WASHINGTON STATE AQUATIC HABITAT GUIDELINES PROGRAM

INTEGRATED STREAMBANK PROTECTION GUIDELINES
2003

ISPG

Integrated Streambank Protection Guidelines

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Washington State Aquatic Habitat Guidelines Program

2002

Washington Department of FISH and WILDLIFE

Washington State Department of Transportation

WASHINGTON STATE DEPARTMENT OF ECOLOGY

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DEPARTMENT OF THE ARMY
SEATTLE DISTRICT, CORPS OF ENGINEERS
P.O. BOX 3755
SEATTLE, WASHINGTON 98124-3755

REPLY TO
ATTENTION OF

Regulatory Branch

Dear Reader:

In concert with Washington State and as a member of the Washington State Aquatic Habitat Guidelines Program Steering Committee, the U.S. Army Corps of Engineers, Seattle District (Corps) is pleased to present to you the *Integrated Streambank Protection Guidelines (ISPG).* The Corps anticipates that the *ISPG* will be a beneficial tool for both the Corps Regulatory Branch and the Corps Civil Works Program. The Corps will be using the *ISPG* in several ways as described below:

The Corps Regulatory Branch will be using the *ISPG* as a tool to assist its staff in the review and evaluation of activities such as stream restoration projects, instream mitigation projects, and riverine bank stabilization projects.

In addition, *ISPG* has been included as a "term and condition" by the National Marine Fisheries Service in the recently issued "Biological Opinion on Corps of Engineers (Regulatory Branch) Programmatic Consultation for Permit Issuance for Four (4) Categories of Fish Passage Restoration Activities in Washington State," dated October 29, 2001. For proposed fish passage barrier removal projects, unavoidable bank stabilization activities are approved if the proponent documents the rationale for the design based on the *ISPG.*

The Corps Civil Works Program sees *ISPG* as an excellent addition to the selection of tools used when designing stream restoration, mitigation, and/or bank stabilization activities. However, the application of these guidelines may not be suitable for all Corps Civil Works projects; i.e., high-risk projects that protect significant infrastructure. In these situations, *ISPG* principles may be considered when practicable for a specific site.

In conclusion, the Corps supports *ISPG* and future Aquatic Habitat Guidelines as valuable methods for the State salmon recovery strategy and as an important effort in moving towards better predictability in decisionmaking for the regulatory arena. For more information on the Corps role in the Aquatic Habitat Guidelines process, contact Ms. Cindy Barger at (206) 764-5526. For more information on the Corps application of *ISPG* in Civil Works projects, contact Mr. Michael Scuderi at (206) 764-7205.

Sincerely,

Ralph H. Graves
Colonel, Corps of Engineers
District Engineer

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WASHINGTON STATE DEPARTMENT OF ECOLOGY

Dear Reader:

We, the chief executive officers of the Washington state departments of Ecology, Fish and Wildlife, and Transportation, are pleased to present to you the *Integrated Streambank Protection Guidelines.* The *ISPG* is the first in a series of Aquatic Habitat Guidelines (AHG). The AHG provide guidance for an integrated approach to protecting and restoring marine, freshwater, and riparian habitat. This integrated approach is necessary to allow consistency in regulatory interpretations, assist with permit streamlining, and ensure that habitat-related projects are based on best available science. The *ISPG* will enable our agencies and the people of Washington to better manage and care for our aquatic habitats and resources, including our endangered salmon species. The *ISPG* was developed using best available science and extensive peer review. For additional information, please visit the project Web site at http://www.wa.gov/wdfw/hab/ahg/

In adopting the *ISPG*, each of our agencies will be using it in various ways, for example:

- At the Department of Ecology, the *ISPG* will be incorporated into the Shoreline Management Guidebook to help implement the Shoreline Management. Additionally, the Aquatic Habitat Guidelines will be incorporated into the state's Water Quality Management Plan to Control Nonpoint-Source Pollution.
- At the Department of Fish and Wildlife, the *ISPG* will serve as a tool to help local watershed groups, lead entities, and agency biologists plan and implement salmon recovery projects that are based on good science. *ISPG* will also serve as best available science and technical guidance in the review of Hydraulic Project Approval applications for streambank protection projects.
- At the Department of Transportation, the *ISPG* will help design and implement mitigation for streambank effects related to construction and maintenance projects, and promote and enhance salmon and watershed recovery work as a part of transportation facility design and construction statewide.

The *ISPG* is an important part of our state's salmon recovery strategy. The ISPG and future releases in the Aquatic Habitat Guidelines series will help us be more efficient and effective as we work toward a healthy environment, vibrant communities and a strong economy. The *ISPG* and future guidelines also will help provide clarity and predictability in decision-making.

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Secretary of Transportation

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To order additional copies of this publication, refer to Appendix A, *Registration Form.*

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Describes how to assess the site-based causes of streambank failure.

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Describes how to assess the reach-based causes of streambank failure.

Chapter 4, Considerations for a Solution
Addresses a multitude of issues that must be taken into account prior to selecting a streambank-protection technique.

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Provides a context and a series of matrices to help select the most suitable streambank-protection technique, and offers several case studies to help illustrate the effects of streambank-protection techniques.

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PREFACE >>>

Preface

Integrated Streambank Protection Guidelines

The Aquatic Habitat Guidelines collection was created by a consortium of public agencies to assist property owners, planners, designers and regulators protect and restore marine, freshwater and riparian fish and wildlife habitat. The agencies involved in developing this series include the Washington Department of Fish and Wildlife, the Washington State Department of Transportation, the Washington Department of Ecology, the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service. The authors of the guidelines are widely recognized experts in their fields. The content and organization of information is based on a set of guiding principles developed by professional resource managers, engineers and other practitioners.

These guidelines provide "how to" guidance that, while scientific in approach, can be understood and used by volunteers, planners, designers and managers of aquatic restoration projects and facilities. Each guideline is based on current best science and technical practice surveyed in topical state-of-the-knowledge white papers or a thorough literature search. Their content includes background science and literature; policy issues; site and vicinity environmental-assessment processes; project-design processes, standards and details; and case studies. Technical-assistance materials produced under the Aquatic Habitat Guidelines program include documents in printed, compact-disc and web-page format, as well as training and outreach workshops. You can obtain additional copies of this and other available guideline documents, downloadable versions of white papers, drafts of guidelines in development and other information about the Aquatic Habitat Guidelines on line by visiting www.wa.gov/wdfw/hab/ahg, or by filling out and mailing or faxing the registration form found in Appendix A of this guideline.

The overwhelming majority of Washington's fish and wildlife species depend on aquatic and riparian ecosystems for all or part of their life cycle. This rich and diverse fauna and the flora on which they depend are irreplaceable elements of Washington's natural resources and are the basis for much of the state's cultural heritage, economy and quality of life. Unfortunately, in our enthusiasm for enjoying and developing land surrounding these aquatic habitats, we have destroyed, degraded and fragmented many of our most precious marine, freshwater and riparian ecosystems. Over time, these adverse impacts have resulted in the federal listing of many marine, freshwater and riparian animal species as "endangered" or "threatened" under the federal Endangered Species Act, and the state of Washington's wildlife protection legislation. Of particular note is the listing of several salmon species under the ESA.

In 1999, Governor Gary Locke and several Washington State agencies adopted a statewide strategy to protect and restore salmon habitat in the state. At the heart of the strategy is the hands-on involvement of landowners and other individuals. Incentives and technical assistance in salmon protection/recovery initiatives are included in the strategy to encourage such participation. In the 1999-2001 biennium, Washington State distributed nearly $50 million to more than 300 salmon protection/recovery projects sponsored by local governments, watershed groups, County Conservation Districts, Regional Fisheries Enhancement Groups, volunteer groups and individuals. For such involvement to be effective, there is an urgent need for increased technical guidance to ensure that these local efforts are strategic in approach, address the source of a problem and not just the symptoms, make the best use of limited funds and are based on the best available science that can be consistently and effectively applied across the landscape. The Aquatic Habitat Guidelines program is designed to help provide this technical assistance.

Each guideline in the Aquatic Habitat Guidelines series is designed in part to provide technical guidance supporting regulatory streamlining; however, it is important to remember that the information in these guidelines is not a substitute for the law. *Current local and state policies, rules and regulations supersede any and all recommendations made in these guidelines.*

The Aquatic Habitat Guidelines Program was created to:

- address habitat requirements and guide recovery projects for marine, freshwater and riparian species listed under the federal ESA;
- facilitate consistent application of good science and technical practice for project designs, construction and operations affecting aquatic systems;
- increase the success rate and enhance the worthwhile expenditure of public funds on protection and recovery projects;
- streamline and reduce costs for environmental review and permitting for activities that affect marine, freshwater and riparian ecosystems; and
- provide a single set of benchmarks for evaluating and prioritizing projects affecting aquatic and riparian habitats.

To carry out such a mission, the program is designed to meet the following objectives:

- make the expertise of professional resource managers available to a wide variety of organizations and citizens who are seeking assistance in habitat protection and restoration activities;
- streamline local, state and federal regulatory review of activities involving aquatic environments by providing guidelines based on best available science;
- provide a scientific basis for any future changes to current local policies or activities associated with aquatic resource in the state; and
- maintain ongoing reviews and updates to the Aquatic Habitat Guidelines to reflect experience and emerging science and technical practice.

GUIDING PRINCIPLES

The Aquatic Habitat Guidelines Guiding Principles summarize current, scientific understanding about how ecosystems work, and they reflect current resource-agency policy and technical approaches to protect ecosystem functions. Documenting this scientific and technical understanding and policy will enable managers and project proponents to assess the effectiveness of the Aquatic Habitat Guidelines in their efforts to protect and restore salmonid habitats as well as other aquatic and riparian habitats. As scientific understanding improves through time, these guidelines will be updated to reflect the evolution of thought.

The guiding principles are organized from general concepts to topical statements. They were developed by the Aquatic Habitat Guidelines Steering Committee, whose membership includes the Washington Department of Fish and Wildlife, Washington State Department of Transportation and the Washington Department Ecology. In addition, Department of Fish and Wildlife Habitat Program technical staff provided valuable input in their development. Some of the principles were taken directly or expanded from other planning documents such as the Wild Salmonid Policy (Washington Department of Fish and Wildlife, 1997), the Statewide Strategy to Recover Salmon (State of Washington, 1999) and Coastal Salmon Conservation: Working Guidance for Comprehensive Salmon Restoration Initiatives on the Pacific Coast (National Marine Fisheries Service, 1996). Links to the websites containing these documents can be found at "Links and References" on the Washington Department of Fish and Wildlife's website at www.wa.gov/wdfw/hab/ahg/.

Guiding Principles for General Ecosystem Function:

1. Ecological processes create and maintain habitat function. These processes include:

    a. Geomorphic processes - the interaction of water, sediment and wood that creates channel and shoreline structure. Geomorphic processes include bank and bed erosion, channel migration and evolution, sedimentation, debris influences, erosion, accretion, sediment transport and fire.

    b. Biological processes (e.g., nutrient cycling, species interactions, riparian and upland vegetation dynamics; and species-mediated, habitat-forming processes such as beaver activity).

   Salmon and other aquatic organisms have evolved and adapted to use the habitats created by these processes. The long-term survival of naturally occurring populations of these species depends on the continuation of these processes.

2. Ecological processes create and sustain a suite of ecosystem characteristics and functions that include:

    a. ecosystem complexity, diversity and change;

    b. ecological connectivity;

    c. riparian interactions;

    d. floodplain connectivity;

    e. species diversity, adaptation and survival;

    f. water quality and water quantity;

    g. invertebrate production and sustained food-web function.

3. These characteristics and functions have biological value as well as economic, social, cultural, educational and recreational values.

4. Because these characteristics and functions vary across and within watersheds, the use of local watershed information in planning and design will often lead to less risk of adverse project impacts. Natural processes that are protected and restored will minimize risk and provide sustainability to ecosystem functions.

   This principle is paraphrased from the State of Washington (1999):

   a. Maintain and restore the freedom of rivers and streams to move and change, especially during floods.

   b. Allow time for natural regenerative processes to occur and provide recovery of river and stream integrity.

   c. Protect the natural diversity of species and restore the natural diversity of habitats within river channels and riparian zones.

   d. Support and foster habitat connectivity.

   e. Tailor actions locally and to the whole watershed in the proper sequence of time and place. Match the system's potential and long-term human commitment to stewardship of the system.

   The principle is also paraphrased from the National Marine Fisheries Service (1996):

   a. To ensure no net loss of habitat functions and to enable natural processes to occur unimpeded, actions should benefit ecological functions. Actions that adversely affect habitat should be avoided.

   b. Maintain habitats required for salmonids during all life stages from embryos and alevins through adults.

   c. Maintain a well-dispersed network of high-quality refugia to serve as centers of population expansion.

   d. Maintain connectivity between high-quality habitats to allow for reinvasion and population expansion.

   e. Maintain genetic diversity.

General Guiding Principles for Project Planning and Implementation:

1. A holistic approach to project planning employs ecologically relevant units of management, such as watersheds.

2. Our limited understanding of ecological processes and engineered solutions is addressed by using the best available science and erring on the side of caution in project management, design, timing and construction.

3. A holistic approach to project planning recognizes and maintains geomorphic processes (e.g., channel migration, channel evolution, hydrologic changes, erosion, sedimentation, accretion and debris influences).

4. Appropriate uses of riparian, shoreline and floodplain systems through responsible land-use practices can maintain natural processes and avoid cumulative, adverse effects.

5. A holistic approach to compensatory mitigation and restoration is desirable; such an approach is based on local watershed conditions, and it strives to maintain or restore historical, ecological functions.

6. Compensatory mitigation for adverse impacts has risk and uncertainty of success. To minimize such risk and uncertainty, adverse impacts are first avoided and then minimized. Unavoidable, adverse impacts are addressed by compensating for losses.
7. Complete compensatory mitigation includes consideration of the project impacts over time (which usually extends beyond the completion of the project) and across the landscape (which often extends beyond the boundaries of the project).
8. Appropriate operating and maintenance procedures are necessary to ensure that project objectives are fulfilled and adverse environmental impacts are minimized.
9. Monitoring and adaptive management are critical components of restoration, mitigation and management activities.

Guiding Principles for Bank Protection:

1. Natural erosion processes and rates are essential for ecological health of the aquatic system.
2. Human-caused erosion that exceeds natural rates and amounts is usually detrimental to ecological functions.
3. Natural processes of erosion are expected to occur throughout the channel-migration zone. Project considerations should include the channel-migration zone and potential upstream and downstream effects.
4. Preservation of natural channel processes will sustain opportunities for continued habitat formation and maintenance.

It is our nature as human beings to live, work and recreate along and adjacent to waterways, whether freshwater or marine. Our lives and histories are inextricably linked to water. How we affect those waterways has long-term survival consequences not only for fish and wildlife, but for humanity. The Aquatic Habitats Guidelines Program is intended to help balance man's need to protect life and livelihood with the need to protect and restore valuable habitat for fish, for wildlife and for ourselves.

Chapter 1

Integrated Streambank Protection

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Chapter 1

Integrated Streambank Protection

A stream's most productive and diverse habitat exists at the water's edge, where the streambank and water intersect. Here, undermined, eroded streambanks, overhanging vegetation, and fallen trees are just a few of the features that allow a diversity of fish and wildlife to find food and refuge from the main channel. The high productivity of this zone is the result of continuous change brought about by disturbance processes such as flood events. During flood events, the high energy of flowing water against the streambank causes erosion. Bank erosion, in turn, results in the introduction of trees to the river, important to the retention of gravels and refuge during high flows; gravels, present in the bank, are washed into the river and later used by salmon for spawning; and erosion introduces nutrients to the river that allows biological growth to occur. Fish and wildlife depend on these processes to provide the diversity of habitat required for their survival. This is a dynamic zone where life is both lost and regenerated. Changes in flow, within seasons and through the years, bring changes to the physical qualities of the river; and the plants and animals that depend on it adapt to and thrive with these changes.

The changing dynamics of a river can be thought of as a metaphor of the human experience. The wearing away of the old often reveals new opportunities for growth and change. Conscious (or subconscious) recognition of this, in many ways, underlies our desire to live near waterways. However, productivity of habitat is based on disturbances, such as flooding, that bring dynamic changes to the bankline. Despite their many benefits in creating productive habitat, these disturbances have also brought destruction to property and life for those living or working within a river's floodplain.

The population living within the Puget Sound basin doubled between the mid-1960s and 1999, and it is projected to reach five million by 2020 - a 78-percent increase since 1999.[1] This trend has exacerbated the conflict between allowing natural processes to occur, such as flooding and erosion, while protecting private property and infrastructure from its damaging effects. Unfortunately, both nature and people have been the losers in our efforts to resolve this conflict.

Within Washington State, between 50 and 90 percent of riparian habitat has been lost or extensively modified by human activities.[1] For instance, the lower Puyallup River, like many of our major rivers, has been so channelized, dredged and diked that it is little more than a large ditch. And, with habitat-forming processes no longer allowed to occur, fish and wildlife habitat is largely gone. While many of the major human disruptions to our river channels occurred almost a century ago, their impact continues, though on a lower scale. For instance, the practice of using rock (riprap) to stabilize eroding banks for the protection of property continues to this day. Riprap fixes the river in place, allowing no bank deformability and, therefore, limiting habitat-forming processes to occur. Riprap often leads to accelerated erosion to adjoining lands, continuing the "hardening" of a river's bankline. Natural resource impacts are primarily the result of the accumulated effects of many small bank-protection projects.

So, what can be done? Is there a way to protect people and property without destroying habitat? Yes, there often is. Indeed, the goal of the Integrated Streambank Protection Guidelines is to educate landowners, state and local governments on alternative ways to protect property and infrastructure from bank erosion while allowing for natural, habitat-forming processes to occur. Sometimes the solution will be in the design of the bank-protection project. Some habitat impacts cannot be mitigated, so sometimes the best solution will be to move infrastructure and development away from the river.

Effective, creative solutions to streambank erosion require a clear understanding of why the erosion is occurring. Integrating this information with habitat considerations, full mitigation requirements, levels and types of risk, project objectives, and design criteria is the most effective way of selecting appropriate, habitat-friendly streambank-protection treatments. These guidelines provide instruction on how to assess these key factors and how to use the results from the assessments to select appropriate streambank-protection solutions.

Prior to selecting and designing a streambank-protection project, three key factors must be considered:

1. the reason for the bank erosion;
2. the fish and wildlife habitat characteristics, needs and potential; and
3. the current and future risks associated with erosion and bank protection to property, infrastructure, fish and wildlife habitat, and public safety.

Assessing these factors from the start is crucial to achieving ecological and structural success in any streambank-protection project. In the past, fish and wildlife habitat needs were often ignored in favor of protecting other floodplain uses. Projects were designed and constructed without a full understanding of riverine and erosion processes. This often resulted in moving erosion problems downstream or upstream and failure to mitigate for the associated ecological impacts. These guidelines will help the reader to assess these factors, develop project objectives and identify design criteria. Detailed design information, for streambank-protection techniques, is also provided.

A graphic representation of the integrated streambank-protection process is shown in *Figure 1-1*.

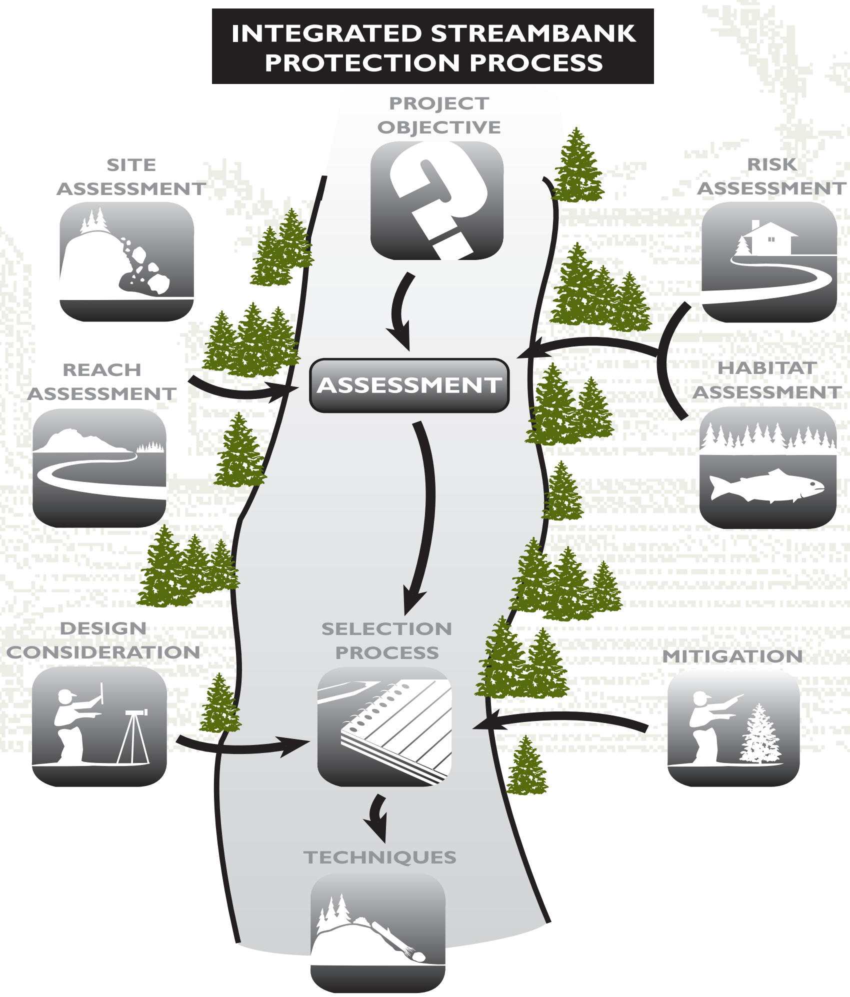

Figure 1-1. Integrated streambank-protection process.

Mitigation is a crucial component in the selection of streambank-protection treatments. Techniques must first be selected that avoid impacts to habitat. Only after exhausting the practicality of applying techniques that avoid impacts can other techniques that may impact habitat be selected. Those techniques that do have impacts must be mitigated.

These guidelines are based on ecological health and guiding principles as described in the Introduction. In 1996, J. R. Karr[2] defined ecological health as:

"An ecosystem is healthy when it performs all of its functions normally and properly; it is resilient, able to recover from many stresses, and requires minimal outside care. Ecological health describes the goal for conditions at a site that is managed or otherwise intensively used. Healthy use of a site should not degrade it for future use, or degrade areas beyond the site."

PROJECT OBJECTIVES AND DESIGN CRITERIA

Addressing a streambank-erosion problem begins with identifying the objectives of the project. The objectives of the project provide the foundation for selecting techniques and establishing design criteria. Objectives are typically stated in somewhat general or qualitative terms. For example, objectives may be stated as "preventing further erosion of the river along the highway" or "stabilizing the streambank to reduce loss of cropland." In fact, for each project there are usually a number of objectives with differing levels of priority. For example, in addition to the two objectives just identified, there may also be objectives such as "maintaining the aesthetic qualities of a streambank environment" or "maintaining or enhancing ecological values of the reach."

The objectives of the project provide the foundation for selecting techniques and establishing design criteria.

Chapter 4, *Considerations for a Solution* includes a discussion of how to develop and use project objectives and design criteria in the streambank-protection selection and design process.

SITE AND REACH ASSESSMENT

Identifying suitable streambank-protection alternatives begins with an understanding of the specific "mechanisms" and "causes" of erosion. Correctly identifying the mechanisms and causes of erosion is critical to selecting appropriate bank protection solutions.

The "mechanism of failure" is the physical action, or process, within the bank that results in bank erosion. There are five mechanisms of failure:

1. toe erosion,
2. scour,
3. mass failure,
4. subsurface entrainment, and
5. avulsion and chute-cutoff potential.

The "cause of erosion" is what activates the mechanism of failure. There are two types of causes:

1. site-based (such as elimination of vegetation at the site), and
2. reach-based (such as a stream that has been confined by dikes).

Identifying suitable streambank-protection alternatives begins with an understanding of the specific "mechanisms" and "causes" of erosion.

Although often difficult to identify, the single cause or combined causes of erosion, can be determined with careful evaluation. Often, reach-based causes generate site-based causes. The mechanisms and causes of erosion may be natural or triggered by human activities. The mechanisms of failure and site-based causes of erosion are described in Chapter 2, *Site Assessment*. Reach-based causes of erosion are described in Chapter 3, *Reach Assessment*.

Site and reach assessments should identify existing habitat conditions and the habitat potential. During site and reach assessments, it is important to recognize that streambank erosion is a natural process essential to habitat function and its creation. For example, an overhanging streambank with exposed plant roots provides cover habitat. Habitat creation (or, conversely, damage to habitat) resulting from streambank erosion is a critical component of site and reach assessments.

During site and reach assessments, it is important to recognize that streambank erosion is a natural process essential to habitat function and its creation.

HABITAT CONSIDERATIONS AND MITIGATION

The first priority of natural resource agencies in reviewing a streambank project is to avoid habitat impacts. If damage to habitat cannot be avoided, then mitigation is required. Direct impacts can be mitigated by restoring the damaged or lost ecological functions of the stream. Indirect impacts, such as the future loss of valuable side-channel habitat, sources of salmon spawning gravel and large woody debris, arise from streambank-hardening practices, which prevent the channel from migrating laterally.[3] A streambank-protection project situated on a previously undisturbed river reach can be problematic, because it can easily cause the need for more streambank-protection projects elsewhere along the river, increasing the chances of further damage to habitat. By recognizing the long- and short-term effects of indirect impacts to the reach, mitigation can be incorporated into the design of the project, either on-site or off-site.

If damage to habitat cannot be avoided, then mitigation is required.

Chapter 4 provides an explanation of various habitat characteristics and how they might be affected by streambank-protection projects. Mitigation, as it relates to streambank-protection projects, is also described. The determination of habitat-mitigation requirements may vary among projects depending upon regulatory jurisdiction of a site and whether species listed under the Endangered Species Act might be affected. The tools provided here are, therefore, general and are intended to assist the designer regardless of the policy and actual mitigation requirement applied. These guidelines support and provide technical guidance for existing regulations and policies in Washington State. While the guidelines help to identify the most appropriate design, it's important to remember that, even with the best science and best project and mitigation design, a project may have habitat impacts that cannot be mitigated.

RISK ASSESSMENT

All streambank-protection projects contain some level of risk. For example, a streambank-protection project may be effective at lower flows, but may fail as a result of a larger flood. Likewise, fish-cover habitat along an undercut, vegetated streambank may be at risk by the placement of certain streambank-protection techniques.[4]

Throughout the design process, it is important to understand and evaluate the many types and levels of risk associated with a streambank-protection project. A risk assessment considers both the risks associated with continued streambank erosion and those of the proposed project with respect to property, habitat and public safety. A more detailed discussion of risk can be found in Chapter 4.

Throughout the design process, it is important to understand and evaluate the many types and levels of risk associated with a streambank-protection project.

SELECTION PROCESS

One of the most important aspects of the design process is moving from the site and reach assessments to the selection of an appropriate solution. Selecting appropriate streambank treatments involves integrating the site and reach assessments, project objectives, risk, habitat considerations, mitigation, and design considerations. The selection process is described in Chapter 5, *Identify and Select Solutions.*

The three screening matrices provided in Chapter 5 will assist the reader in selecting streambank-protection treatments that:

- perform adequately to meet streambank-protection objectives;
- are appropriate with respect to mechanisms of failure and site- and reach-based causes;
- are considered with an understanding of the potential impacts to habitat caused by each technique; and
- are selected in order of priority to first avoid, second minimize, and third compensate for habitat impacts.

These matrices screen treatments based on:

- site conditions,
- reach conditions, and
- habitat impacts.

Within each matrix, streambank-protection techniques and their applicability are listed, assisting the reader to accept or reject a particular technique. With each subsequent matrix, inappropriate techniques are progressively screened out, leaving a suite of feasible techniques. Throughout the process of identifying an appropriate streambank-protection technique, the question should always be posed whether the best course of action might be taking no action at all.

Selecting appropriate streambank treatments involves integrating the site and reach assessments, project objectives, risk, habitat considerations, mitigation, and design considerations.

STREAMBANK-PROTECTION TECHNIQUES

These guidelines provide information about streambank-protection techniques applicable within the state of Washington (*see Table 1-1*). In addition to the streambank-protection techniques, several mitigation techniques are also provided. For each technique, the following information is provided:

- description of the technique;
- typical application, variations, emergency, site and reach limitations;
- effects on geomorphology, habitat and hydraulics;
- design criteria and considerations;
- biological considerations, such as mitigation requirements for the technique or mitigation benefits provided by the technique;

The question should always be posed whether the best course of action might be taking no action at all.

Flow-Redirection Techniques	Structural Bank-Protection Techniques	Biotechnical Bank-Protection Techniques	Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques	Other Techniques
Groins	Anchor points	Woody plantings	Subsurface drainage systems	Floodplain roughness	Channel modification
Buried groins	Roughness trees	Herbaceous cover		Floodplain grade control	Riparian-buffer management
Barbs	Riprap	Soil reinforcement		Floodplain flow spreader	Spawning-habitat restoration
Engineered log jams	Log toes	Coir logs			Off-channel spawning and rearing habitat
Drop structures	Rock toes	Bank reshaping			No action
Porous weirs	Cribwalls				
	Manufactured-retention systems				

Table 1-1. List of streambank protection techniques organized by functional group.

- risk (to habitat and adjacent properties, and level of reliability of the technique);
- construction considerations, such as materials required, timing considerations, cost;
- maintenance needs;
- monitoring considerations;
- examples, such as typical drawings, site examples and photographs; and
- references.

CONCLUSION

There are times when streambank protection is necessary to provide public safety, correct or prevent damage to property, or even to create fish and wildlife habitat. However, the impacts of such protection can have enormous consequence to the health and stability of the stream. The goal of the Integrated Streambank Protection Guidelines is to assist individuals, organizations, and state and local governments with addressing streambank-erosion concerns through an informed decision-making process, and protecting the public and property while avoiding or minimizing damage to fish and wildlife habitat.

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Chapter 2

Site Assessment

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Chapter 2

Site Assessment

This chapter will help the reader determine and define site conditions in order to select the most appropriate streambank-protection techniques. This approach requires identification and assessment of the mechanism of the failure, which, in turn, pinpoints the cause of bank erosion, critical to selecting an appropriate bank-protection treatment.

There are five main categories of mechanism of failure to consider:

1. toe erosion,
2. scour,
3. mass failure,
4. subsurface entrainment, and
5. avulsion and chute-cutoff potential.

The causes of erosion can be divided into two groupings:

1. site-based, or
2. reach-based (including watersheds).

This approach requires identification and assessment of the mechanism of the failure, which, in turn, pinpoints the cause of bank erosion, critical to selecting an appropriate bank-protection treatment.

Mechanisms of failure can have both site-based and reach-based causes. For example, a common mechanism of failure is toe erosion caused by reduced vegetation along the bank (a site-based cause) in a reach that is filling with sediment and debris due to a downstream constriction, such as a bridge (a reach-based cause). Identifying reach-based causes typically requires multiple site investigations as well as broadening the view to a longer reach of the river. Historically, streambank protection has focused on site-specific concerns regarding an unstable bank, while neglecting reach or watershed-wide instabilities. By ignoring reach-based causes, streambank-protection designs can actually cause more damage than good. Indeed, they can cause additional failures such as channel flanking, structure undermining, or sediment deposition and burial of the treatment.

Site-based causes are addressed in this chapter, while reach-based causes are presented in Chapter 3, *Reach Assessment*. Both the site- and reach-based assessments are incorporated into the selection and design of streambank treatments in Chapter 5, *Identify and Select Solutions.*

Site- and reach-based causes affect the flow patterns in a stream, which are quantified using the concepts of "shear" and "scour." The calculation of shear and scour is site-specific, although they are influenced by reach-based causes. Shear and scour calculations can be found in Appendix E, *Hydraulics.* The role of shear and scour in streambank protection technique design is further described in Chapter 5. *Figure 2-1* depicts the assessment approach described in this chapter.

Site- and reach-based causes affect the flow patterns in a stream, which are quantified using the concepts of "shear" and "scour." The calculation of shear and scour is site-specific, although they are influenced by reach-based causes.

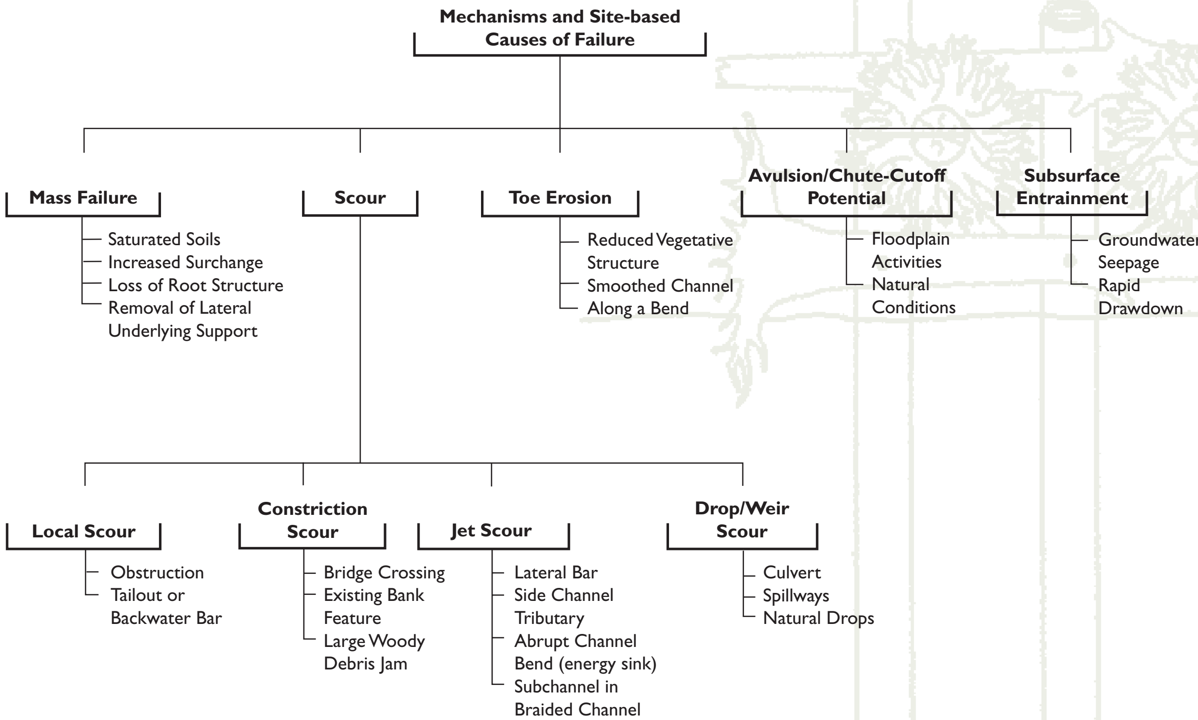

Figure 2-1. Site-assessment approach.

MECHANISMS OF FAILURE AND SITE-BASED CAUSES

A mechanism of failure is the physical process of erosion, which can be thought of as the problem you see on site. Observing the condition of the eroding streambank leads to identifying the mechanism of failure. Is the erosion occurring on one streambank, or on both banks simultaneously? Is the streambank eroding from the toe, causing larger blocks of material above the toe to fall into the river? Is there an obstruction in the channel? Is the erosion attacking the streambanks or is it also deepening the channel? Is the bed of the channel rising from a buildup of sediment? Does there appear to be a gradual shift toward the use of a secondary channel; are channels newly abandoned, or are scars forming where the channel used to go? Determining the mechanism of failure is accomplished by observing and evaluating on-site conditions such as: geologic elements and topography; soil types and horizons; flow patterns and degree of erosional force; vegetative growth, root depth and strength; streambank geometry; and sediment load.

A mechanism of failure is the physical process of erosion, which can be thought of as the problem you see on site.

The mechanism of failure may be due to either site-based or reach-based causes, or both. An example of a site-based cause of streambank erosion would be an obstruction in a stream (e.g., woody debris or an old car) causing localized changes to flow patterns that erode the adjacent streambank (local scour). Or, bank erosion could be due to a reach-based cause such as the migration of a channel bend or channel degradation. Sometimes, reach-based causes for failure contribute to site-based causes (and vice versa), so it's important to be alert to both possibilities, even when a particular cause seems obvious.

Identifying the mechanisms of failure and their causes typically occurs concurrently. Treating the mechanism of failure on site without identifying the underlying cause(s) is like taking an aspirin for a broken leg without examining the injury itself- you may be treating the symptoms, but you're not solving the problem. *Table 2-1* lists mechanisms of failure, site-based causes, reach-based causes and habitat considerations.

The physical process of erosion for most mechanisms of failure is called "entrainment." Entrainment is primarily a surface-erosion concern that can be quantitatively analyzed by using the concepts of shear and scour. This effort will contribute valuable information to the design of a successful streambank-protection project. Entrainment occurs as water flow picks up particles from:

- the entire streambank face or toe,
- the bed of the stream,
- a floodplain (causing rills and gullies), or
- subsurface flows seeping out of the bank (a phenomenon known as "piping").

Mechanism of Failure	Possible Site-Based Causes	Possible Reach-Based Causes (Chapter 3)	Habitat Considerations
Toe erosion	Reduced vegetative bank structure from land-clearing activities Smoothed channel Along a bend (bend scour)	Meander migration Aggradation Degradation	Removal of large trees limits stream-side cover and riparian benefits (food source, shade, nutrients, woody debris, wildlife). Smoothing a channel limits diversity and complexity, pools, spawning habitat, and woody debris. Erosion along a bend or adjacent to a mid-channel bar creates deep pools and overhanging streambanks for cover.
Local Scour	Obstruction Tailout or Backwater Bar	Not applicable	Scour creates deep pools and overhanging streambanks that fish use for cover. Scoured sediments deposited downstream from scour hole may create (or smother existing) spawning habitat.
Constriction Scour	Bridge Crossing Existing streambank feature Large woody debris jam	Not applicable	
Drop/Weir Scour	Weir, ledge or sill	Not applicable	
Jet Scour	Lateral bar Sidechannel or tributary Abrupt channel bend (energy sink) Subchannels in a braided channel	Not applicable	
Mass Failure	Saturated soils Increased surcharge Lack of root structure Removal of lateral/underlying support	Meander migration Aggradation Degradation	Increased sediment load may fill pools or smother spawning beds. May serve as source of spawning substrate.
Subsurface Entrainment	Groundwater seepage Rapid drawdown	Not applicable	Subsurface flows important for maintaining floodplain connectivity, base flows and temperature.
Avulsion/Chute Cutoff Potential	Floodplain activities, natural conditions	Aggradation, channel relocation, downstream constriction, braided channel, large storm event	Removal of riparian corridor limits stream-side cover.

Table 2-1. Mechanisms of failure, site- and reach-based causes, and habitat considerations.

It is important to identify subsurface flows on site as a separate category of entrainment because they require special methods for streambank protection treatment.

Flood events with return intervals greater than 10 years typically cause erosion, and the influence of these events on fish habitat is often overlooked. These events accumulate large woody debris, create scour pools, sort streambed gravel and reorganize habitat components into more complex conditions. The erosion imposed on channel margins through accumulation of woody debris provides channel stability and rejuvenates habitat.

In general, habitat that is reorganized annually or semi-annually fails to provide stable conditions sufficient to support fish and other organisms that have life histories of two to five years.[7,8] Habitat reorganized at a 10-year interval frequency, however, will likely provide each generation with a period of relative stability for growth, reproduction and recovery while also ensuring that natural processes sufficiently rejuvenate habitat conditions. Channel conditions that change frequently under short-return-interval floods are less beneficial to aquatic habitat than conditions that deform less frequently.

The physical process of erosion for most mechanisms of failure is called "entrainment." Entrainment is primarily a surface-erosion concern that can be quantitatively analyzed by using the concepts of shear and scour. This effort will contribute valuable information to the design of a successful streambank-protection project.

Evaluation of stream channels to determine the frequency and magnitude of channel adjustment should be part of any investigation into the causes of streambank erosion. Fish and other aquatic organisms have evolved specific behavioral, physiological and life-cycle adaptations for coping with physical conditions, periodic disturbance, as well as natural processes that occasionally modify and reorganize aquatic habitat. Flow events that cause extensive and widespread reorganization and redistribution of streambed materials, although critical in forming suitable habitats for fish and other aquatic organisms, are catastrophic for most stream benthic communities[1,2] and often affect survival of young stream fishes and colonizing macroinvertebrates.[3,4]

Recovery from these events may take up to several decades, depending upon the magnitude and intensity of the event, although in many cases fish communities are reported to recover in less than ten years.[5] Consequently, it is important that habitat be designed in a manner that replicates the frequency and magnitude of natural processes found in the stream being studied. Under too frequent or too intense of a habitat alteration regime, aquatic organisms will be adversely affected, and the suitability of available habitat for individual species will be diminished.[6]

Each of the five types of mechanisms of failure are described as follows:

Toe Erosion

Toe erosion occurs where water flow removes particles from the streambank and/or bed, undermines the toe and causes subsequent gravity collapse or sliding of overlying layers. In actuality, the term "toe erosion" is not entirely accurate, since the undermining may occur above the toe, depending upon site conditions. However, for the sake of simplicity, these guidelines will use the term toe erosion for all incidents of bank undermining and collapse due to water flow.

Toe erosion occurs either along a meander bend or a straight reach of channel. There are several site-based causes of toe erosion. Site-based causes of toe erosion include:

- Reduced vegetative bank structure: This is a disturbance of woody vegetation along the streambank and in the riparian area affecting the stability of the streambank in resisting erosion (see *Figure 2-2*). Plant roots on a streambank slope bind the soil together in a vertical and horizontal monolithic mass. The roots penetrate through the soil into firmer strata, thus anchoring the soil to the slope.[9] Disturbance of the woody vegetation is a common cause of streambank erosion[10] and is often directly associated with either urban development or agricultural management. It also occurs indirectly when there is a net lowering of the channel over time (a degrading channel). A degrading channel may lower the groundwater table below the root zone, desiccating the streambank, which, in turn, impairs the survival rate of the vegetation. Degradation is a reach-based process and is discussed further in Chapter 3.

Toe erosion occurs where water flow removes particles from the streambank and/or bed, undermines the toe and causes subsequent gravity collapse or sliding of overlying layers.

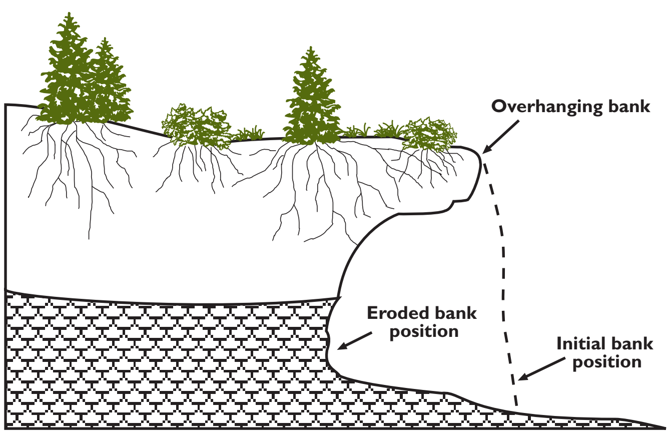

Figure 2-2. Toe erosion.

- Smoothed channel: This is a channel in which roughness elements have been removed, creating a channel with a reduced resistance to flow. Smoothed channels occur where woody debris has been removed, the channel has been dredged, or the streambank has been hardened (see *Figure 2- 3*). Once a channel is smoothed, it will have excess energy that is dissipated on the streambed and banks. The channel will adjust itself to dissipate this energy by increasing its channel length and decreasing its slope, or by degrading the channel bed (see Chapter 3). These adjustments trigger streambank erosion. To protect a streambank in a smoothed channel, it is best to add the roughness elements that were originally lost. Never add smooth structures, such as rock revetments to a smoothed channel. Doing so will further exacerbate the problem.

Figure 2-3. Smoothed channel.

- Along a bend: When flow moves along a bend, the thalweg (the deepest part of the streambed) shifts to the outer corner of the channel and pronounced bend scour occurs at the bend location. Bend scour results from spiraling flow patterns found in the meander bend of a stream (see page 2-18 for a discussion on spiraling flow). Sharper meander bends generate deeper scour than gentle bends. *Figure 2-4* shows the cross section of a channel in a straight reach and a bend. Note that the center of erosive force shifts from the bed of the channel to the outer corner of the channel. The maximum shear stress acting in a bend can be two or more times as high as the shear stress acting on the bed.[11] Therefore, when working along a bend, erosive force of the stream should be taken into account in selecting and designing a streambank treatment.

When flow moves along a bend, the thalweg (the deepest part of the streambed) shifts to the outer corner of the channel and pronounced bend scour occurs at the bend location.

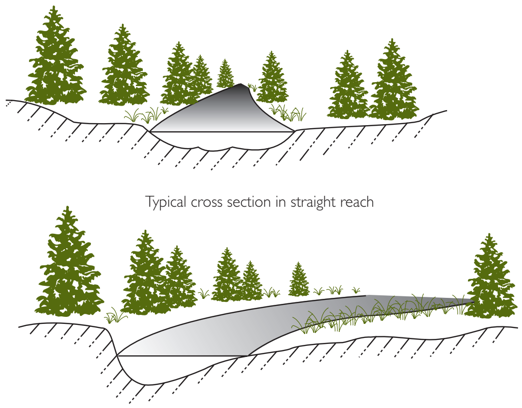

Figure 2-4. Typical channel cross sections in a straight reach and a bend.

- *Figure 2-5* contains a chart used to estimate the increased shear found in a bend, based on the radius of the bend and the width of the river. The method for calculating shear in a bend is to take the bed shear stress and multiply it by the bend factor. It becomes a judgment call based on the shape of the bend and how far up the streambank this maximum erosive force is acting. Each project and site will be different, but the designer will need to ensure that even the least erosion-resistant material used for streambank protection can withstand forces expected in the bend at the elevation of concern.

- Determining where the higher shear stress in a bend begins and ends, or where abrupt changes in the channel create higher shear stress longitudinally, can be identified by:

    - on-site observation of eroded points up stream and downstream,
    - theoretical book examples (*Figure 2-6*), or
    - reviewing sketches from available studies.

- Understanding the greater streambank erosional forces (shear) in river bends and at concentration points in the plan view is also helpful in preparing a streambank design. This information can be applied to selecting the beginning and end points of treatments along the project reach and selecting the point at which treatments can transition from more rigorous to less rigorous (or vice versa). A more detailed discussion about shear can be found beginning on page 2-16.

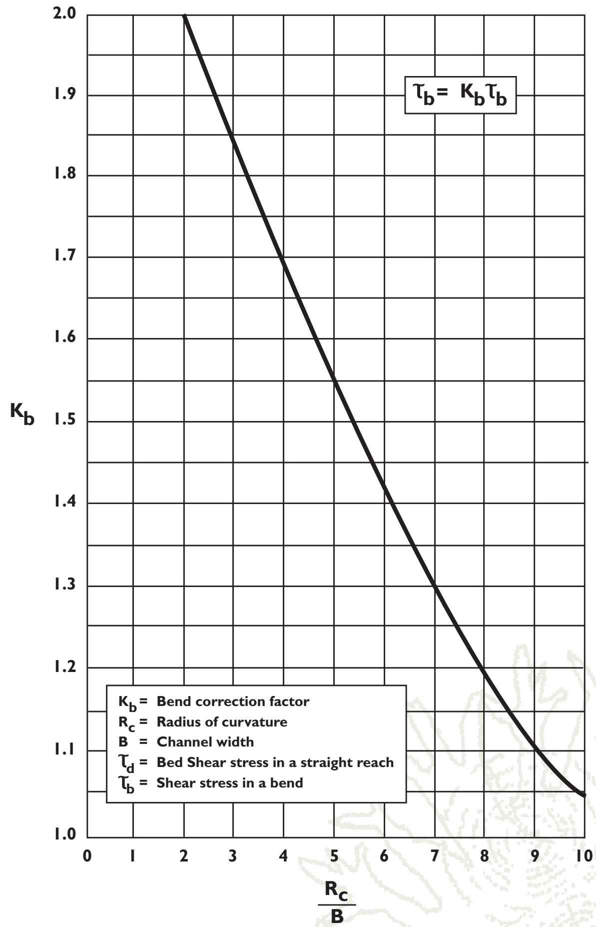

Figure 2-5. Chart showing increase in shear stress with an increase in the tightness of a bend.

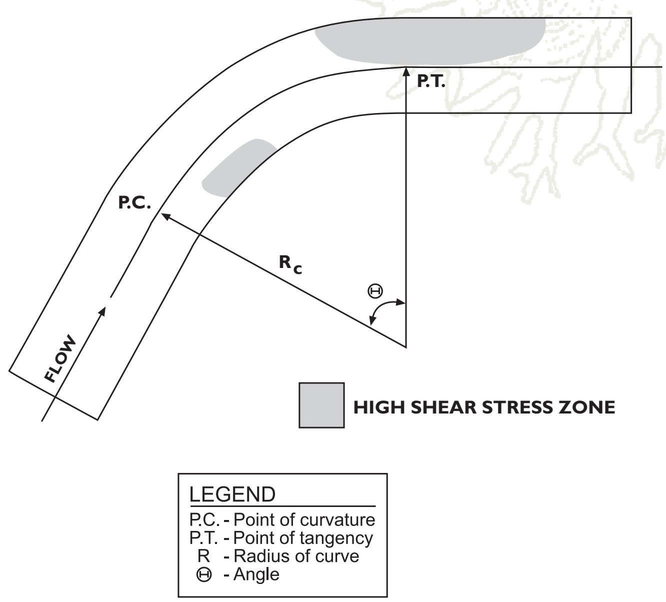

Figure 2-6. Shear stress distribution in a channel bend.

Scour

Scour is erosion at a specific location that is greater than erosion found at other nearby locations of the stream bed or bank. Scour can occur on both the channel bank and bed. Simons and Senturck[12] state that scour is "localized, as opposed to general bed degradation." For the purposes of these guidelines, there are four different kinds of scour to consider:

1. local,
2. constriction,
3. drop/weir, and
4. jet scour.

Scour is an essential contributor to the creation of fish habitat and its maintenance. Many fish-enhancement projects promote scour. It is not the extent or magnitude of the scour that promotes the best habitat, but the frequency of the scour activity. Sites absent of scour tend to provide less habitat than areas subject to moderately frequent scour events, given that intermediate-level disturbances promote aquatic diversity.[13, 14] Sites subject to very frequent scour have less habitat value than areas subject to moderately frequent scour events.

Scour is erosion at a specific location that is greater than erosion found at other nearby locations of the stream bed or bank.

Some scour will occur whenever abrupt changes in channel geometry are introduced to a system. Quantitative methods are available to estimate the depth of scour to be expected from different changes in the flow pattern, but it is first necessary to identify the type of scour. For example, the method for estimating constriction scour depth will not provide a realistic value if the erosion is produced by local scour. Methods for estimating scour depth are presented in Appendix E.

Local Scour: Local scour appears as discrete and tight scallops along the bankline, or as depressions in the stream bed. It is generated by flow patterns that form around an obstruction in a stream and spill off to either side of the obstruction, forming a horseshoe-shaped scour pattern in the streambed (*Figure 2-7*). When flow in the stream encounters an obstruction, for example a bridge pier, the flow direction changes. Instead of moving downstream, it dives in front of the pier and creates a roller (a secondary flow pattern) that spills off to either side of the obstruction. The resulting flow acceleration and vortices around the base of the obstruction results in a higher erosive force around the pier, which moves more bed sediment, thereby creating a scour hole.[15] The location around the pier is being scoured because the bed is eroded deeper at the pier than the bed of the stream adjacent to it. Scour is the key to providing excellent cover and holding habitat for fish.

Scour is an essential contributor to the creation of fish habitat and its maintenance. Many fish-enhancement projects promote scour.

Obstructions can be man-made or natural. Man-made obstructions include bridge piers or abutments. Natural obstructions include boulders, small collections of woody debris or midchannel bars. The extent of local scour

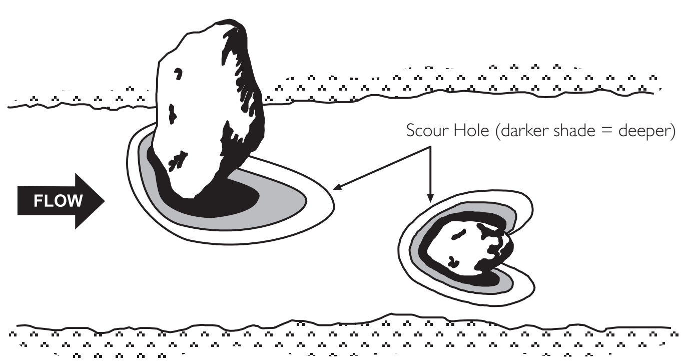

Figure 2-7. Local scour at boulder obstruction (plan view).

depends upon the relative size and location of the obstruction causing the scour. For example, scour formed around a single large tree that has fallen into the river will not extend a significant distance from the tree. As such, local scour is self-limiting and is generally not a high risk to streambank stability. When selecting streambank treatments to control or diminish localized scour, caution needs to be used installing flow realignment techniques (e.g., groins, barbs) upstream from the scoured streambank. Though they realign the flow away from the feature causing the scour, they may redirect the flow to the opposite streambank and cause erosion.

Midchannel bars can also create scour activity. These bars form in the wetted perimeter of the channel during high flow, and they separate the flow into two distinct channels at lower and moderate flows. Flow forced around a bar at low and moderate flows is concentrated against the streambank, increasing bank stress. Scour holes or trenches develop along the bankline, increasing the channel's cross-sectional area while creating spawning and rearing habitat.[16]

Tailout and backwater bars are common types of midchannel bars. (see *Figure 2-8*). Tailout bars typically form directly downstream from a constriction, causing localized bed scour. The scoured sediment is transported and deposited downstream. Backwater bars form directly upstream from a constriction. As the water backs up at the constriction, the velocity decreases and sediment is deposited. Tailout or backwater bar formation is exacerbated when the supply of sediment to the site increases. If the sediment supply is a chronic problem throughout the reach, it is necessary to understand and deal with both the constriction and the upstream sediment supply to provide a long-term solution to the problem (a combination of site-based and reach-based causes). See Chapter 3 for more information about aggradation.

Constriction Scour: Constriction scour occurs when features along the streambank create a narrower channel than would normally form. Often the constricting feature is "harder" than the upstream or downstream bank and can resist the higher erosive forces generated by the constriction. Bedrock outcrops often form natural constrictions. The average velocity across the width of the channel increases, resulting in erosion across the entire bed of the channel at the constriction. The channel bed at the constricted section is deeper than channel bed upstream or downstream (*Figure 2-9*). Large woody debris jams or bridge crossings are common examples of features causing constriction scour. Bank features such as rocky points or canyon walls, overly narrow, man-made channel widths (e.g., with groins), or well-established tree roots on a streambank in smaller channels (sometimes referred to as "hard points") can cause constriction scour.

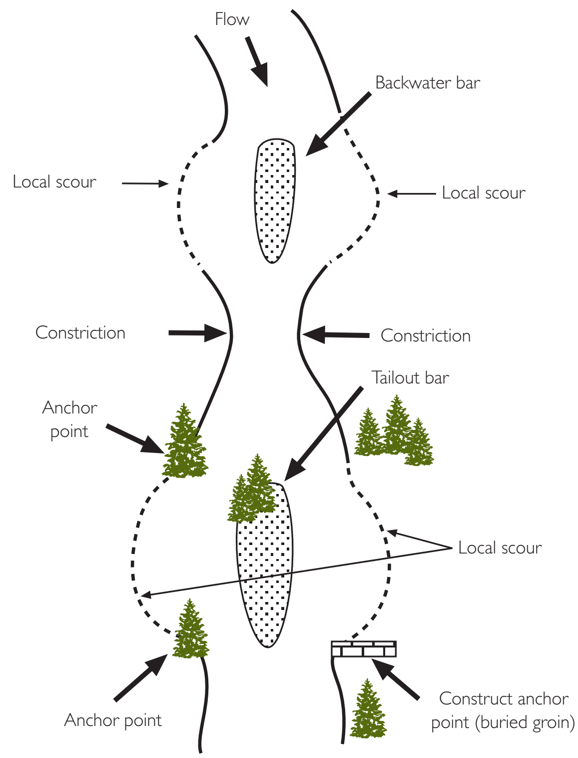

Figure 2-8. Tailout and backwater bars.

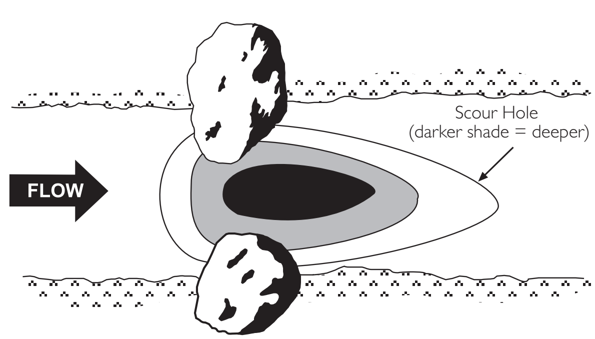

Figure 2-9. Constriction scour (plan view).

Drop/Weir Scour: Drop/weir scour is the result of water pouring over a raised ledge or a drop, creating a secondary flow pattern known as a roller. The roller scours out the bed below the drop (*Figure 2-10*). Energy-dissipation pools may result from drop scour. Perched culverts or culverts under pressure (during a high flow event), and discharge into a pool from spillways and from natural drops such as those found in a high-gradient mountain stream, are all causes of drop scour.

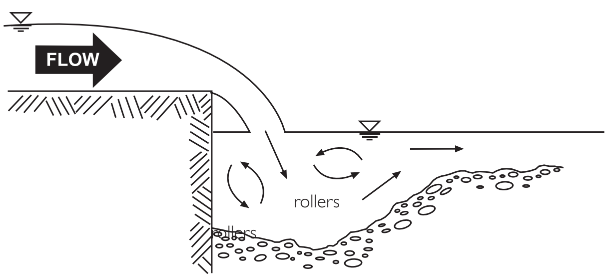

Figure 2-10. Typical drop or weir scour (section view).

Jet Scour: Jet scour occurs when flow enters the stream in the same manner as flow ejecting from the nozzle of a hose. The entering flow could be submerged, or could impact the water surface from above. The impact force from the flow results in jet scour on the streambed and/or bank. Lateral bars, subchannels in a braided or side channel or tributary, or an abrupt channel bend (energy sinks) can also create jet scour.

- Lateral bars are mid channel bars that typically occur directly downstream from a tight bend in the channel and are positioned diagonally in the channel. Jet scour forms when flow is redirected by the bar and focused directly into the adjacent streambank. (see *Figure 2-11*) Lateral bars form during bankfull events and scour occurs during the receding limb of the hydrograph and also during moderate flows. These bars are the result of natural channel processes or increased sediment supply. The cause of lateral bar formation should be determined during the reach assessment. Lateral bars create excellent spawning, cover and rearing habitat.

- Subchannels in a braided stream channel are another cause of jet scour. As water flows through these subchannels during low to moderate flows, the alignment of the subchannel may aim the flow directly at a bankline and cause jet scour (see *Figure 2-11*).

- When a high-energy side channel or tributary discharges into a main channel, the flow can be focused on the opposing streambank of the main channel (see *Figure 2-12*). This cause of jet scour is considered beneficial because the turbulent water attracts migrating salmon to their natal spawning tributaries and side channels.

- An energy sink is another cause of jet scour. When flow piles into the corner of a tight-radius bend, a scour pool forms (see *Figure 2-13*). The scour pool is the energy sink; it dissipates the energy of the entire momentum of the flow. Adequate volume in the energy sink should be provided for energy dissipation. An effective energy sink does not transfer carry-over energy downstream. Instead, it offers some protection to downstream banks and channel.

- Anchor points are a technique that can be used to stabilize an energy sink (see *Figure 2-7*). The use of anchor points requires an understanding of the balance between the need to preserve an energy sink while preventing further erosion. Anchor points are either natural (e.g., a tree or rock outcropping) or artificial hard structures (e.g., a rock trench) at the upstream and downstream end of an energy sink. They fix the upstream and downstream points of the sink, so volume cannot be gained by erosion in the

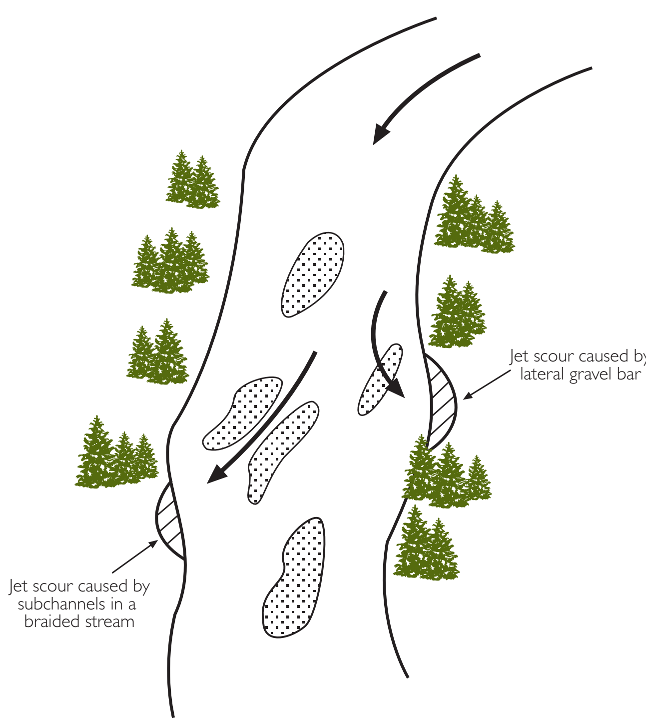

Figure 2-11. Jet scour caused by lateral gravel bar and braided subchannels (plan view).

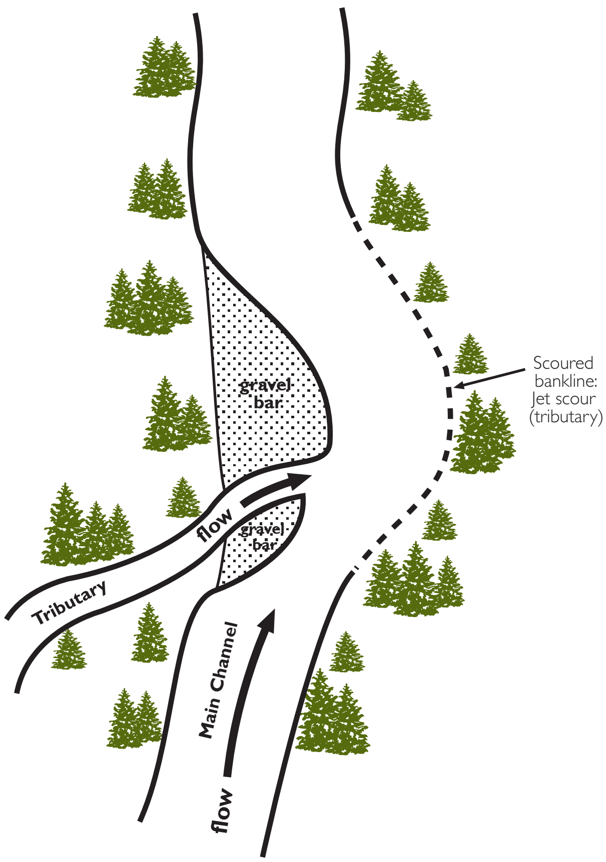

Figure 2-12. Jet scour caused by tributary discharge.

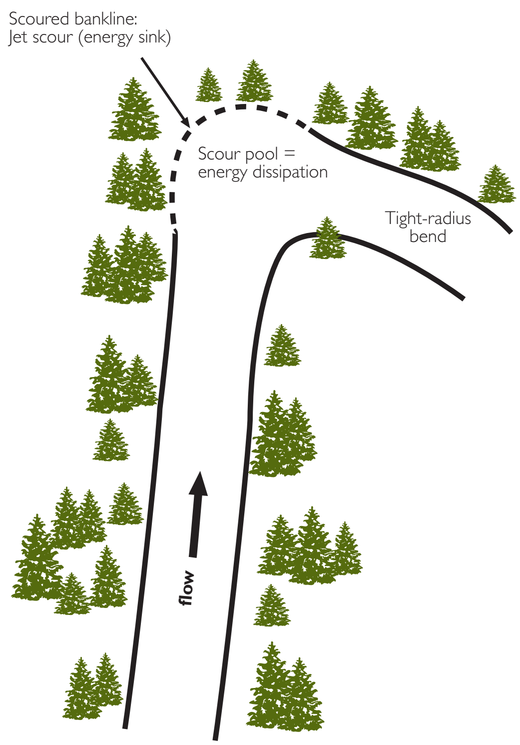

Figure 2-13. Jet scour caused by an energy sink.

upstream and/or downstream directions. By fixing these points, adequate dissipation volume is achieved by forcing erosion to occur either laterally or (preferably) vertically. Vertical erosion of the channel bed creates a deep pool, dissipating energy and creating habitat.

- Roughness elements are not the solution, as their scale often eliminates the energy dissipation volume of the energy sink. Straightening the bankline can destroy energy sinks. Instead, erosion should be allowed to continue until the energy sink has evolved to a mature and stable condition.

Subsurface Entrainment

Subsurface entrainment, or piping, occurs when subsurface flow picks up soil particles until small tunnels develop (see *Figure 2-14*). These tunnels reduce the cohesion of soil layers, thereby causing slippage and switch ultimately streambank erosion. Groundwater seepage and water-level changes, such as rapid draw down, are common causes of subsurface entrainment.

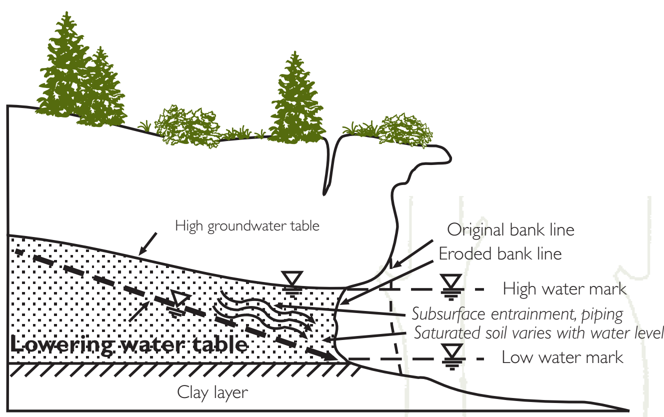

Figure 2-14. Subsurface entrainment, or piping.

Subsurface entrainment, or piping, occurs when subsurface flow picks up soil particles until small tunnels develop.

Mass Failure

Mass failure is the downward movement of large and intact masses of soil and rock.[9] It occurs when the down-slope shear stress (weight) exceeds the shear strength (resistance to weight) of the earth material. Shear stress is the driving force from gravity and/or loads acting on the slope. Shear strength is the characteristic of soil, rock and root structure that resists one unit of material sliding along another. Any cause that increases the shear stress or conversely decreases the shear strength will cause a mass failure. Ninety five percent of all mass failures are triggered by water saturating a slide-prone slope.[17]

Mass failure is the downward movement of large and intact masses of soil and rock.

When water saturates a slide-prone slope, it contributes to an increase in shear stress (it adds weight) and/or a decrease in shear strength (it lubricates). Mass failure results from a number of causes, including:

- rapid draw-down;
- manipulation of stream flows for storage, flood control or power;
- tidal effects; or
- seepage from springs and wetlands.

Bank erosion is also governed by other variables such as topography, geology and vegetation. Furthermore, mass failure can occur in combination with other mechanisms of failure, such as toe erosion or subsurface entrainment.

Understanding and identifying mass failure will assist in selecting appropriate streambank protection techniques. Mass failures are classified into five main groups:

1. falls,
2. topples,
3. slides,
4. spreads, and
5. flows.[17]

The majority of failures in the stream channels of Washington State are slides. There are two common types of slides:

1. rotational, and
2. translational.

Rotational slides have a curved and concave failure plane (*Figure 2-15*) and are generally deep-seated. They occur frequently in slopes ranging from 20 to 40 degrees and in homogeneous materials.[17] Translational slides are shallower than rotational slides and fail along well-defined, nearly planar surfaces (*Figure 2-16*). The failure surface is either soft clay of low strength, a silt layer sandwiched between two clay layers or bedrock.[11]

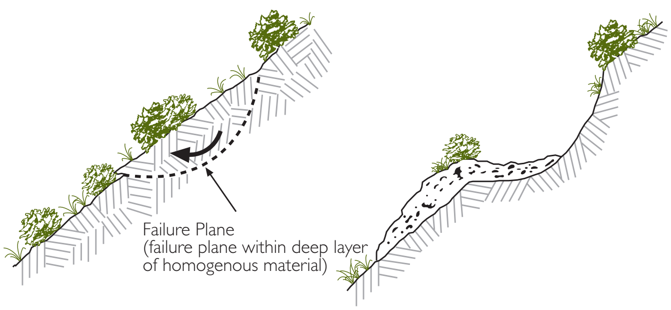

Figure 2-15. Rotational slide.

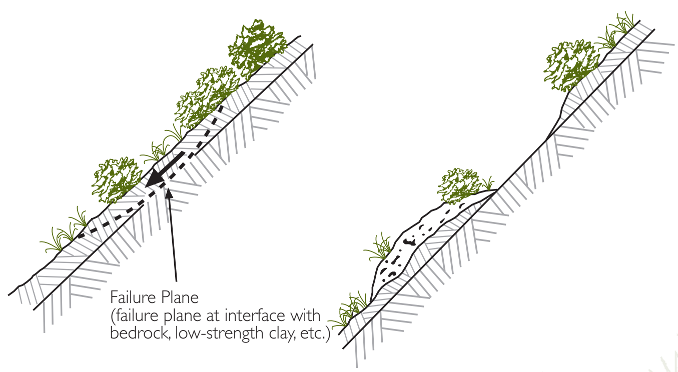

Figure 2-16. Transitional slide.

Slides can occur rapidly or gradually. There are a number of methods available for predicting the stability (or instability) of slopes. Visual indicators of slope stability, such as tilted and bowed trees or scarps, are useful to identify a slide that has been moving gradually over a number of years. Such slides may be reactivated by minor disturbances. Other stability or instability indicators include an over-steepened slope, removal of vegetation, cracks in the ground surface, springs and inherently weak soils.

Because mass failure can be deep-seated in the streambank, surface bank treatments may not solve the problem. For example, although vegetation is an effective surface-protection treatment, it cannot address deep-seated failure because of the limited rooting depth of plants. Therefore, solutions to mass failure along stream channels may involve surface bank treatments based on shear and scour concepts and geotechnical analysis. A geotechnical analysis identifies the need for interior drains, penetrating bank reinforcement, development of channel margins for debris flow chutes, or entire channel relocation. Streambank instability related to subsurface flows often requires additional drainage or corrections addressing the source of internal flows.

Avulsion and Chute-Cutoff Potential

An avulsion is a significant and abrupt change in channel alignment resulting in a new channel across the floodplain (*see Figure 2-17*). An avulsion is caused by concentrated overland flow, headcutting and/or scouring a new channel across the floodplain, leading to a major channel change. Prior to an avulsion, scour holes, headcuts and rills/gullies will be apparent in the floodplain. Avulsions occur during large storm events where there is substantial overland flow to erode the floodplain.

An avulsion is a significant and abrupt change in channel alignment resulting in a new channel across the floodplain.

A chute cutoff is a type of meander cutoff that changes channel alignment on a smaller scale than an avulsion (*see Figure 2-17*). Chute cutoffs occur when the radius of curvature of a meander becomes so small that the flow shortcuts across the adjacent bar or floodplain, resulting in the development of a new meander pattern. Chute cutoffs may occur frequently in meandering river systems, and result in minor alterations to channel alignment which, when considered over time and space, may act to cumulatively change the overall channel pattern.

Chute cutoffs occur when the radius of curvature of a meander becomes so small that the flow shortcuts across the adjacent bar or floodplain, resulting in the development of a new meander pattern.

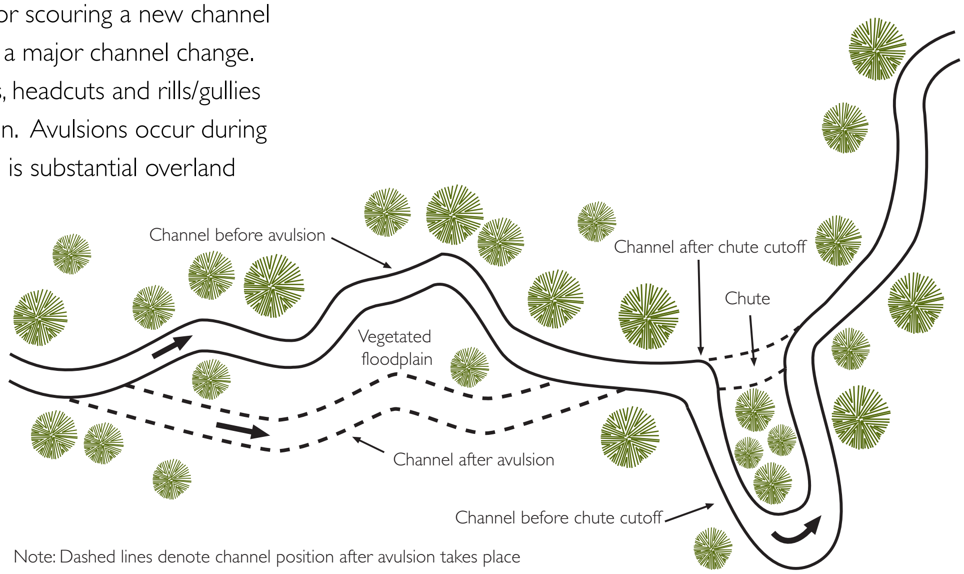

Figure 2-17. Avulsion and chute cutoff.

Though avulsions and chute cutoffs are natural processes, human activities are responsible for an increased frequency of their occurrence. Avulsions in particular may be caused by reach-based activities such as:

- aggradation (increased sediment supply and/or reduced hydrology),
- a downstream constriction,
- a large storm event,
- a braided channel, and/or
- channel relocation.

These causes are discussed in Chapter 3.

Floodplain activities may be a site-based cause of an avulsion. Removal of vegetation on the floodplain and/or in the riparian buffer reduces the shear strength of the soil and the roughness provided by vegetation to dissipate flow and energy. Floodplain mining of gravel is another activity that increases the risk of an avulsion. Placing roughness features in the floodplain, such as tree rows and or large, woody debris, will help dissipate the erosive energy.

Floodplain activities may be a site-based cause of an avulsion. Removal of vegetation on the floodplain and/or in the riparian buffer reduces the shear strength of the soil and the roughness provided by vegetation to dissipate flow and energy.

FIELD VISIT TO IDENTIFY AND CHARACTERIZE SITE CONDITIONS

Gathering data helps with analyzing mechanisms and causes of failure and the selection and design of streambank-protection techniques. An assessment form or information checklist can help cue the observer, and sketching the site conditions will provide geometrical information. Project site visits may be limited by time and season, available access, water stage and available equipment.

Characterizing site conditions involves identifying site conditions, collecting site data, looking for mechanisms of failure, developing a preliminary list of causes of failure, and estimating the frequency of erosion. *Table 2-2* is a checklist to assist in site characterization and to ascertain (or to rule out) the mechanisms and causes of failure.

Photos taken on a site visit should be from several perspectives, and it's a good idea to include objects in the picture that can be used to demonstrate scale of soils, bed material and streambank heights. Photos of the project site boundary can also help when designing transitions between the existing bankline and proposed streambank treatments.

After a site visit, further understanding of the project can be developed, incorporating:

- observation notes, sketches, photos and memories to characterize conditions at the site;
- preliminary identification of mechanism of failure;
- identification of frequency of failure at the site, and the aquatic habitat implications of this frequency; and
- preliminary identification of site-based causes of failure.

Conducting a reach assessment (see Chapter 3) will confirm the mechanisms of failure and identify whether there are any reach-based causes. For example, a site assessment may identify the mechanism of failure as erosion occurring at the toe. The site-based causes are identified as cattle accessing the river, resulting in vegetation disturbance and breakdown of the streambank. The frequency of this disturbance is annual; the habitat impact is deemed chronic. A reach assessment determines the stream reach is relatively stable and confirms there are no reach-based causes responsible for the toe erosion.

Conducting a reach assessment will confirm the mechanisms of failure and identify whether there are any reach-based causes.

Site Characterization Checklist

❑ channel geometry: cross section, streambank height, gradient, pool riffle system.	❑ flow patterns for existing conditions: flow direction, thalweg, angle of attack on streambank, impacts of physical features.
❑ planform: meander bend (how tight?), straight reach, physical features.	❑ approximate flow and stage at time of observation (e.g., during a flood, base flow, at bank-full flow).
❑ over-bank topography.	❑ visualize flow patterns at higher or lower flows (something that may be difficult for the untrained or inexperienced observer).
❑ soils in terrace and bank.	❑ sediment transport indicators: bed-load caliber, bar formation, deposited material in eddies and backwaters, patterns in deposited sizes on bars.
❑ bed materials (bed substrate) and armoring (surficial material).	❑ estimate channel roughness values.
❑ woody debris abundance and location.	❑ man-made features impacting flows: bridges, berms, armored streambanks.
❑ geologic features.	❑ evidence of animal impacts.
❑ vegetation: species, abundance, location on streambank (lower vegetative limit).	❑ high-water features and ice scars.
❑ indication of the height of flood waters, or the peak erosive energy of such high flows; for example, lichen and moss limits on rocks indicating annual high water mark, debris collected in bushes indicating the height of a flood, and the size of cobbles on bars reflecting the maximum flow over the surface.	❑ indicators of historical channel locations in the floodplain: channel scars or meander traces, exposed man-made structures, vegetation locations and deposits on terraces.
❑ location and depth of scour holes.	

Table 2-2. Site characterization checklist.

DESIGN CONCEPTS OF SHEAR

After confirmation of mechanism of failure and reach- and/or site-based causes, the next step is to transition from a qualitative assessment to a quantitative assessment. The erosive forces acting on the streambank are quantified by calculating shear stress and the potential depth of scour (see Appendix E). With scour, we estimate the maximum depth of erosion that can occur; whereas with shear, we determine the magnitude of the erosive force. The calculation of both shear and scour are site-specific, although influenced by reach-based processes.

The shear stress on the streambank provides a measure of the erosive force that can be compared across different sites. Permissible velocity, the velocity a streambank can withstand before erosion occurs, has also been used as a quantitative measure. An advantage to working with shear, as opposed to velocity, is that it reflects the influences of the velocity and depth of the flow on erosion. If two channels with similar geometry, planform and gradient are flowing at the same velocity, the channel with the greater depth of flow will be subject to a greater erosive force at the bed and toe. A shear value will reflect this difference, while permissible velocity will not.

With scour, we estimate the maximum depth of erosion that can occur; whereas with shear, we determine the magnitude of the erosive force.

Fish are affected more by velocity than shear, as most fish do not live at the streambed surface; they seek areas of low velocity for residing. As shear increases to the point of moving particles, areas of low velocity diminish and eventually become areas of particle bombardment. It is valuable to recognize the role that shear stress distributions have on fish habitat utilization.[11] As shear increases, fish migrate to areas of lesser velocity or depth to avoid displacement downstream.[11] Thus, fish require habitat components along the stream channel margins.[19] When evaluating shear stress, consider the need for margin habitat equivalent in area to that lost to excessive shear. Refuge habitat is limited during flood events. Fish survival during high flows is dependent upon the hydraulic conditions that promote refuge habitat development.

VERTICAL DISTRIBUTION OF SHEAR

When designing streambank treatments, it is important to analyze both vertical and longitudinal distributions of shear. Once shear stress on the streambank has been calculated, this information can help select potentially successful streambank-protection techniques.

When designing streambank treatments, it is important to analyze both vertical and longitudinal distributions of shear.

Not all streambank-protection techniques have clearly quantified shear ranges, but there is adequate information available to assign a general range to many techniques.[20] Furthermore, since the erosional shear stress decreases progressively up a streambank (i.e., there is less shear higher up a bank), composite streambank treatments of various resistances can be applied at appropriate locations upstream on a streambank profile. Less rigorous techniques could be assigned to the upper streambanks, with more rigorous techniques applied in the lower streambanks.

Because depth and velocity vary in a channel, the shear stress acting on a channel bed and banks will also vary. In 1955, E.W. Lane[21] published the graphical representation shown in *Figure 2-18*. The figure shows how shear stress varies around the perimeter of a channel in a straight reach. The figure delineates erosive force decreasing higher up the streambank, which is a reflection of the reduced depth of flow over the streambank area. The understanding that shear stress is less at a higher elevation on the streambank is a key concept for bioengineering because it explains why it is not always necessary to armor a streambank from top to bottom. Bank-protection techniques that are less rigorous can be combined with hard-surface solutions when appropriate. In other words, riprap is not always necessary from toe to top of bank.

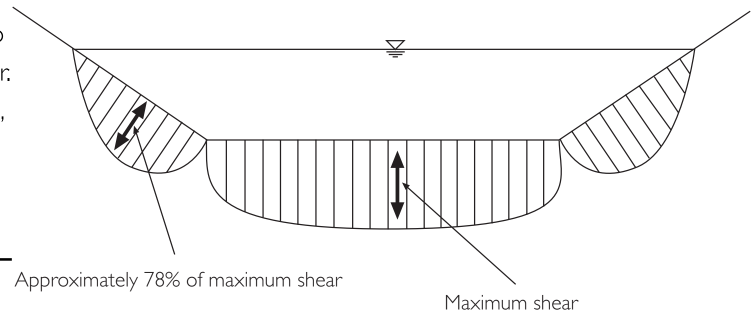

Figure 2-18. Typical shear-stress distribution in a channel.

Figure 2-18 illustrates why toe erosion is often subjected to greater forces than higher up the streambank and will exhibit more erosion. This diagram shows that the greatest shear on the streambank is approximately 78 percent of the shear acting on the bed, and the maximum streambank shear occurs up to the lower one-third elevation of the streambank.[11] This distribution of stress is known for a trapezoidal channel in a straight reach of the stream. A more recent and similar diagram is shown in *Figure 2-19*.[22] The bed shear stress calculations presented in the Appendix E can be transformed into the maximum streambank shear stress (acting approximately one-third of the distance up the bank) by multiplying by 0.78.

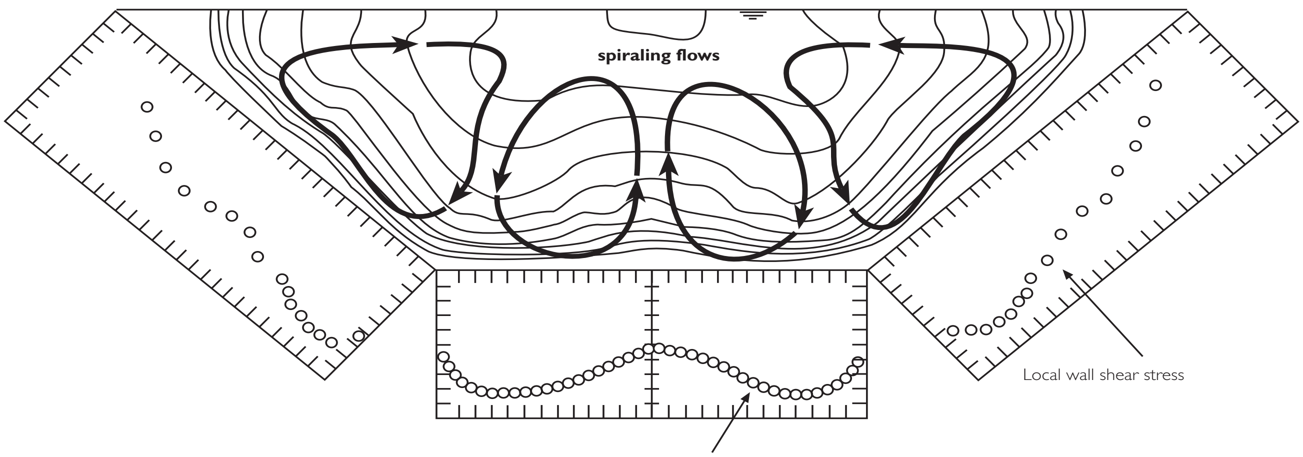

Figure 2-19. Shear-stress distribution in a channel, with primary velocities and secondary flow currents.

A geometric change in the channel shape causes a change in flow patterns, thereby varying the levels of shear stress. When flow goes around a bend or over an object, it no longer moves in a consistent pattern directed downstream in the channel. Flow moving around a bend begins to rotate sideways to the channel, generating a spiral motion. Established flow patterns not moving consistently downstream are described as secondary currents. In the bend, flow is moving sideways (spiraling), not moving prominently downstream. Surprisingly, the velocity of flow in this spiral motion exceeds the average velocity for flow moving consistently downstream. Since the flow velocity is higher, the flow has more erosive force and the capacity to move more sediment from the bed and banks of the stream.

CONCLUSION

In Chapter 2, we explored the various mechanisms of failure and their respective site-based causes. In Chapter 3, we'll examine the role that reach-based causes can have in mechanisms of failure and how they interact with site-based causes.

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Chapter 3

Reach Assessment

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Chapter 3

Reach Assessment

Chapter 3 describes reach-based processes that typically result in bank erosion. It provides guidance on how to characterize the basic physical conditions of the channel in order to better identify potential reach-based causes. The reach-based assessment should be used in tandem with a site-based assessment, since both may be contributing to the erosion of the bank. Indeed, without working through the site-based and reach-based assessment processes described here and in Chapter 2, *Site Assessment,* selection of the most appropriate solutions (as described in Chapter 5, *Identify and Select Solutions*) will not likely occur.

A reach assessment attempts to answer the following five questions:

1. What are the basic physical conditions of the stream channel?
2. What are the natural and human-induced processes that are occurring?
3. Do these processes indicate a stable channel?
4. Do these processes indicate an unstable channel? If so, what is causing the instability?
5. How can the streambank be protected in order to achieve long-term ecological success?

This chapter is organized by first providing guidance on how to characterize the basic physical conditions of the channel (*see Figure 3-1*). With this information, reach-based processes can be identified. There are two basic categories of reach-based processes that cause bank erosion:

1. channels in equilibrium (stable), and
2. channels in disequilibrium (unstable).

For each of these categories, there is a range of processes that may occur (e.g., natural meander migration or aggradation). Reach-based causes responsible for triggering each process (e.g., downstream constriction causing aggradation) are described, in addition to bank-protection treatment considerations.

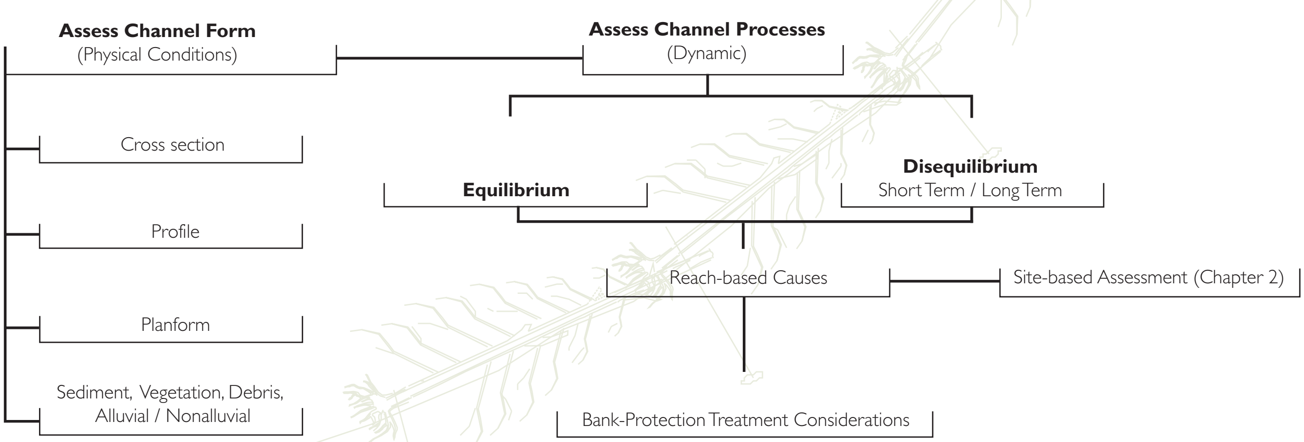

Figure 3-1. Reach-assessment approach.

CHANNEL FORM: BASIC PHYSICAL CONDITIONS OF THE CHANNEL

The basic physical conditions, or channel form, of a stream should be characterized in the initial reach assessment in order to understand the reach-based processes that are causing bank erosion. This is essential before selecting bank-protection techniques. Selecting techniques without identifying and understanding the reach-based processes can result in bank-protection techniques that fail to protect the bank and/or that trigger additional erosion.

A series of eight questions that will help characterize the physical conditions are described in *Figure 3-2*. Standard approaches to quantifying these conditions are presented in Appendix F, *Fluvial Geomorphology*.

The basic physical conditions, or channel form, of a stream should be characterized in the initial reach assessment in order to understand the reach-based processes that are causing bank erosion.

1. Is the channel alluvial or nonalluvial? Alluvial channels transport and deposit their own bank materials. As a result, they have erodible bank and bed boundaries. Nonalluvial channels have relatively nonerodible materials (e.g., bedrock or concrete), limiting erosion of the bank or bed boundaries.
2. What is the average channel slope? The channel slope represents the vertical descent of a river over a given distance, reported as percent (ft/ft) or as feet of drop per mile (ft/mile) (*Figure 3-3*).
3. What is the general sediment load? The sediment load of a stream reflects the size and quantity of sediment delivered to a given stream reach. Sediment size is commonly expressed in terms of gradations of sediment measured, where D_n equals the particle size, of which n percent is finer. For example, D_{50} refers to the particle size, of which 50 percent of the particles sizes are finer. Sediment can be measured either by weight via sieve analysis,[1] or by number via pebble count.[2] Sediment quantity is generally referred to as tons per year of sediment delivered to (transported by) a reach.
4. What is the shape and size of the channel cross section? The cross section of a channel can be expressed in terms of active width and depth, bankfull width and depth, and floodplain width (*Figure 3-4*). A useful parameter in the evaluation of channel cross section is the determination of bankfull discharge, which, in equilibrium channels, is the discharge that just fills the channel to the top of its banks and at a point where overbank flow begins.
5. What are the planform characteristics of the channel? Planform refers to the two-dimensional condition of a river as seen in map or aerial view, which is generally expressed in terms of pattern, sinuosity (channel length/valley length), and individual meander attributes such as amplitude, wavelength and radius of curvature (*Figure 3-5*). Channel planform is commonly characterized as braided (multi-channeled), meandering (sinuosity > approximately 1.5), or straight.[3] Other planform characteristics include the width of the floodplain. Channels in urban and rural watersheds are often modified by humans and have a highly altered planform.
6. What are the banks composed of? The variability in bank materials within a reach will affect bank erosion. Bank materials are often variable both horizontally and vertically.
7. What is the distribution of vegetation? The distribution, vigor and types of vegetation on the streambank can affect rates of channel change and the degree of channel stability/instability.[4]
8. What is the distribution and function of large woody debris? Large woody debris aids in the formation of pools and riffles, increases sediment storage, and creates steps in the longitudinal profile of the streambed.

Figure 3-2. Questions to ask when characterizing the physical conditions of a stream reach.

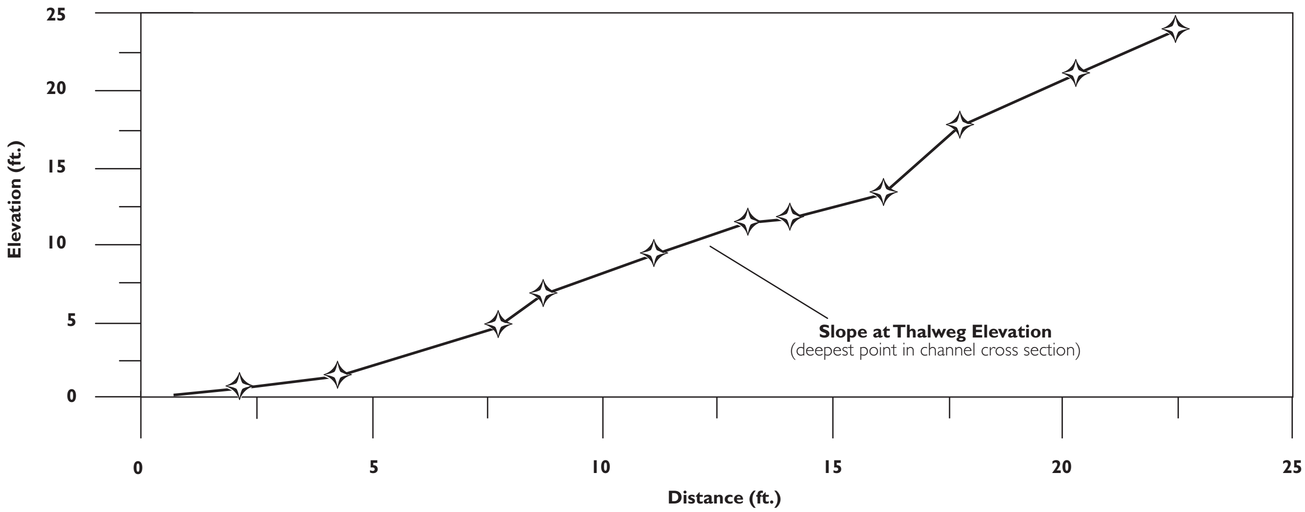

Figure 3-3. Typical channel profile.

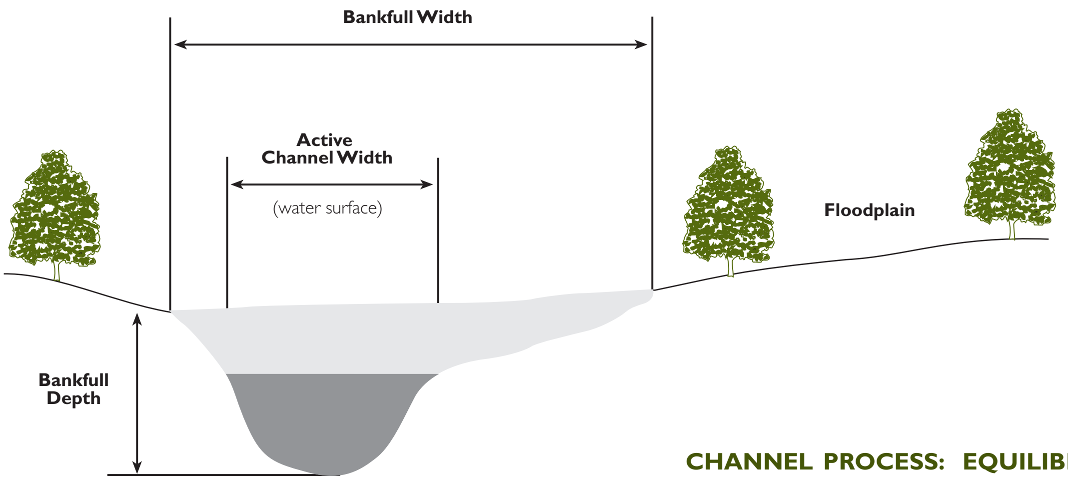

Figure 3-4. Channel cross section.

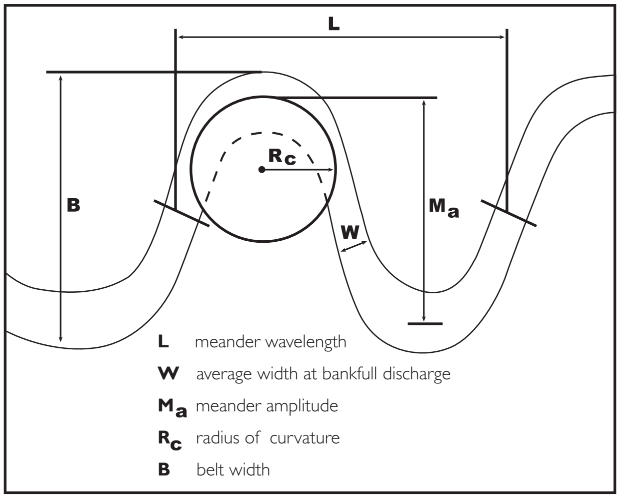

Figure 3-5. Channel planform characteristics.

CHANNEL PROCESS: EQUILIBRIUM AND DIS-EQUILIBRIUM

Collectively, channel forms describe a wide variety of channel conditions, ranging from meandering to braided. The next step in a reach assessment, then, is to determine how these components collectively reflect channel processes.

A fundamental concept in the assessment of channel process is geomorphic equilibrium (also referred to as channel stability). The concept of geomorphic equilibrium refers to a general condition of "sediment transport continuity," where the quantity and size of sediment transported into a reach is approximately equivalent to the quantity and size of sediment transported out of the reach.[5] Similarly, the sediment transport energy present within a reach is in balance with the sediment load. E.W. Lane[6] presented this concept graphically (*Figure 3-6*) as a balance scale. Tipping the scale in one direction or the other (by changing either hydrology or sediment inputs) produces an

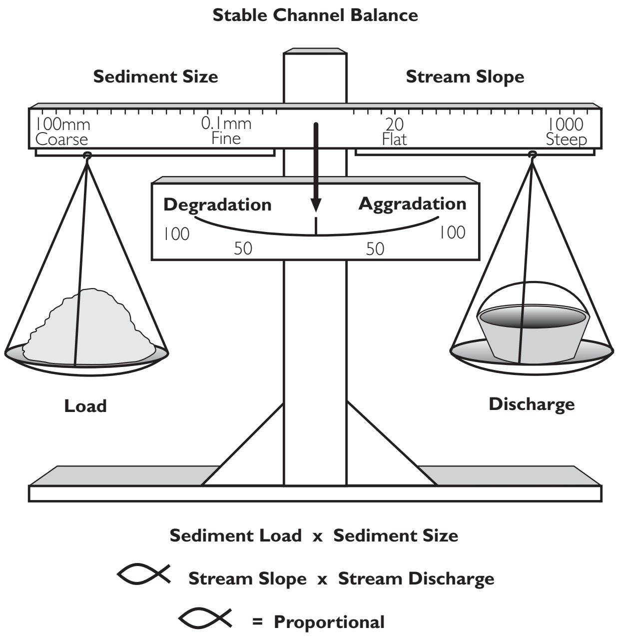

Figure 3-6. Conceptual diagram of geomorphic equilibrium.

opposing response. Geomorphic equilibrium exists when the processes of bank erosion and channel migration occur gradually. In contrast, rapid bank erosion, driven by changes in sediment load or hydrology, reflects a state of geomorphic disequilibrium, referred to as channel instability.

Identifying the reach-based causes of disequilibrium is critical in selecting long-term bank-protection solutions. The reach-based causes are summarized in *Figure 3-7*. They may indicate short-term impacts, from which the channel recovers naturally at a relatively rapid rate (such as following a flood event), or they may indicate long-term changes that will cause significant channel adjustments as part of natural recovery (for example, following dam construction or urbanization).

Geomorphic equilibrium exists when the processes of bank erosion and channel migration occur gradually. In contrast, rapid bank erosion, driven by changes in sediment load or hydrology, reflects a state of geomorphic disequilibrium, referred to as channel instability.

Table 3.1 shows mechanisms of failure and their possible reach-based causes. These relationships link the results from the site-based assessment provided in Chapter 2 to reach-based processes in this chapter. For example, the mechanism of failure called toe erosion may be triggered by site-based causes (e.g., reduced vegetative bank structure) and/or reach-based causes (meander migration, aggradation or degradation). Only by doing both a site and reach assessment can the actual cause(s) be identified.

By answering the following four questions, the reader will be able to proceed directly to the discussion on identified reach-based processes:

1. Is the channel migrating laterally? If so, at what rates? Predictable patterns of channel migration, coupled with a stable bed profile, are typical of stable alluvial channels. Accelerated migration rates or unusual erosion patterns reflect channel instability. Channel migration rates can be estimated from historic aerial photographs, channel survey data, visual observations, anecdotal information, and/or from bankline migration monitoring. Migration rates typically occur during flood events in excess of a five- to 10-year return interval. Toe erosion (see Chapter 2) is the mechanism of failure resulting from lateral channel migration.

Only by doing both a site and reach assessment can the actual cause(s) be identified.

2. Is the channel aggrading? Channel aggradation refers to the accumulation of sediment within a channel when the quantity of sediment entering a reach is more than what is leaving the reach. Aggradation is determined through repeat surveys, observations of pool in-filling, changing river pattern from single-thread to multiple-thread, widening and shallowing of channel cross section, or burial of infrastructure. Aggradation is discussed in more detail on *page 3-13.*

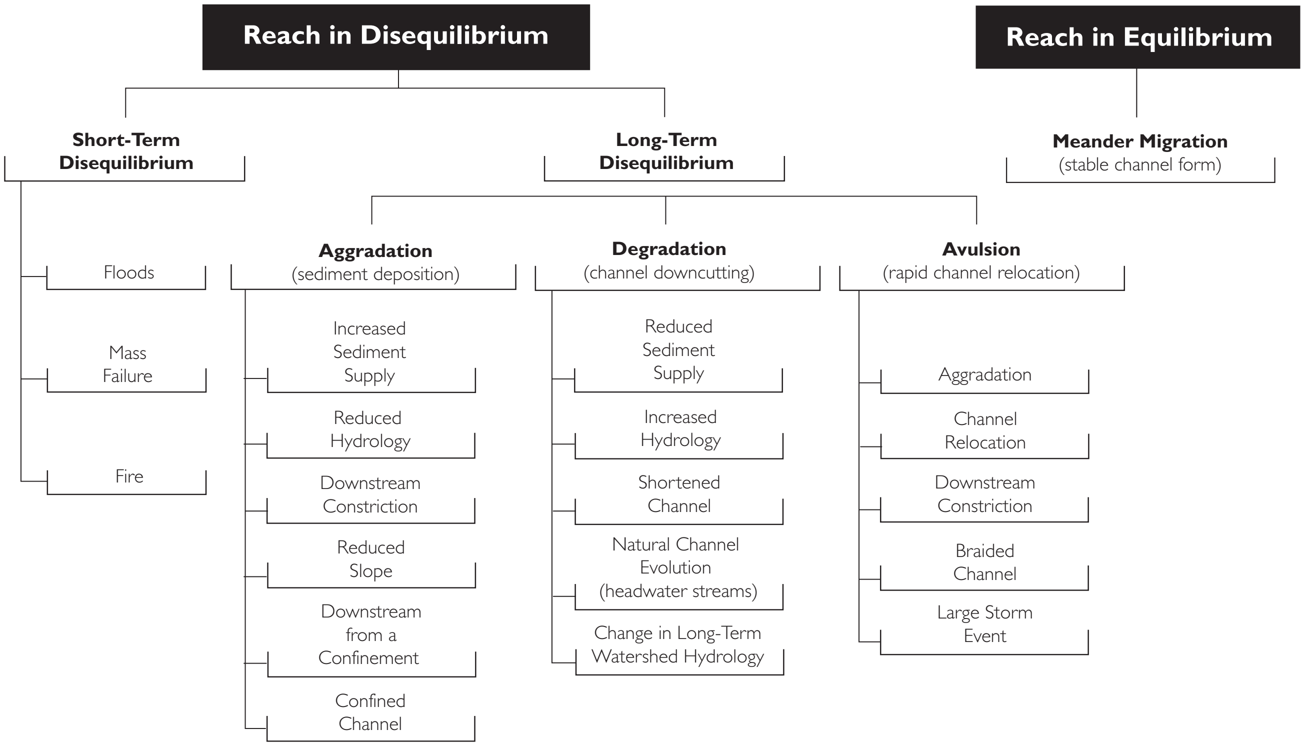

Figure 3-7. Reach-based causes of erosion.

Typical Mechanisms of Failure	Possible Reach-Based Causes
Toe erosion Neck/Chute cutoff Mass failure	Meander Migration
Toe erosion Scour: constriction jet (at a tributary) Avulsion Mass failure	Aggradation: reduced hydrology increased sediment supply confined channel downstream constriction reduced slope downstream from a confinement
Toe erosion Mass failure Drop/weir scour Subsurface entrainment	Degradation: increased hydrology reduced sediment supply shortened channel natural channel evolution change in long-term watershed hydrology

Table 3-1. Reach-based causes and associated mechanisms of failure.

3. Is the channel degrading? Channel degradation occurs when the quantity of sediment transported out of a reach exceeds what is being delivered. Degradation is recognizable through repeat surveys, observations of increased bank height (increased vertical bank exposure due to lowered channel), deepening and narrowing of channel cross section, or exposure of infrastructure foundations. Degradation is discussed in detail on *page 3-14*.

4. Has the channel avulsed? Avulsion is a rapid change in channel location and reflects channel instability in single-channeled (meandering) and multichanneled (braided) streams. Channel straightening or relocation, through constructing dikes or levees are common causes of channel avulsions. Avulsion is discussed in more detail on *page 3-16*.

For detailed information regarding geomorphic principals, methodologies for quantifying geomorphic assessment, and typical human impacts and associated physical responses of channel systems, see Appendix F.

Equilibrium Channels

Equilibrium channels are most commonly located within undeveloped watersheds, where sediment and flow inputs remain relatively constant through time. However, equilibrium can eventually be achieved even in highly urbanized settings through long-term channel adjustments to altered watershed conditions.[7] Alluvial channels in equilibrium can be identified by determining the following six questions:

1. Does the channel have a historically consistent cross section shape and size for a given channel slope and channel feature (pool or riffle)? The cross section size and shape are maintained in equilibrium channels.

2. Does the channel have a historically consistent profile and pattern? Consider the human modifications of the channel as well as the geomorphic adjustments through time.

3. Does the channel have access to its floodplain, such that over-bank flows occur during floods to dissipate excessive flow energy? Alluvial channels that are in equilibrium will have access to the floodplain during high flow events.

4. Are there predictable channel patterns, such as pool/riffle sequences in phase with the general channel planform? Meandering channels in equilibrium display features related to the channel planform (e.g., point bars on the inside and pools on the outside of bends and riffles at crossings).

5. Does the channel geometry satisfy established empirical regression equations developed for similar streams? Regression equations compare morphological relationships in stable-to-potentially-unstable channels[8, 9] (see Appendix F). These empirical equations reflect channel conditions such as slope, vegetative vigor or sediment gradations. Their application should be made cautiously, such that equations applied are appropriate for the channel.

6. Is there an absence of indicators that the channel is in disequilibrium? Field indicators of channel disequilibrium are discussed in subsequent sections of this chapter (*see page 3-11*).

One of the greatest concerns that arise when bank erosion occurs in equilibrium streams is that the stream will naturally meander into a migration corridor that contains man-made infrastructure or agricultural lands. In such cases, it may be tempting to use rigid bank-protection techniques in order to protect the property at risk. However, such an action will modify the stream's natural corridor configuration and may alter meander migration dynamics to the detriment of other properties (as discussed in the following section).

Meander Migration: Meander migration occurs in equilibrium channels. It occurs as water flows through a channel and develops spiraling flow patterns (see Chapter 2). These spiraling flows cause bank erosion along the outer bank (bend scour) and deposition on the inner bank. As a result, meander migration occurs as the outer bank erodes and the inner bank accumulates sediment. The rate of bank erosion is dependent upon

Meander migration occurs as the outer bank erodes and the inner bank accumulates sediment. The rate of bank erosion is dependent upon the shear resistance of the outer bank materials relative to the shear stress imposed on that bank.

the shear resistance of the outer bank materials relative to the shear stress imposed on that bank. Bank shear is a combined function of the flow magnitude and duration, as well as the shape of the bend and channel cross section (see Chapter 2 and Appendix E, *Hydraulics*).

Meander migration has three patterns (*Figure 3-8*)[10] :

- meander translation (downstream migration),
- meander extension (migration transverse to the valley axis), and
- meander rotation.

An example of downstream meander migration is shown in *figure 3-9*.

Vegetation increases bank-shear resistance. The ability of vegetation to add shear resistance and thereby reduce bank erosion rates depends upon the relationship between the bank height and vegetative rooting depth. Where banks are low and root densities are high, removing bankline vegetation will weaken the bank toe and increase erosion.[11] Bank vegetation disturbance is a common cause of increased erosion rates and meander migration.

Vegetation increases bank-shear resistance. The ability of vegetation to add shear resistance and thereby reduce bank erosion rates depends upon the relationship between the bank height and vegetative rooting depth.

Figure 3-9. Downstream meander migration, Washington State.

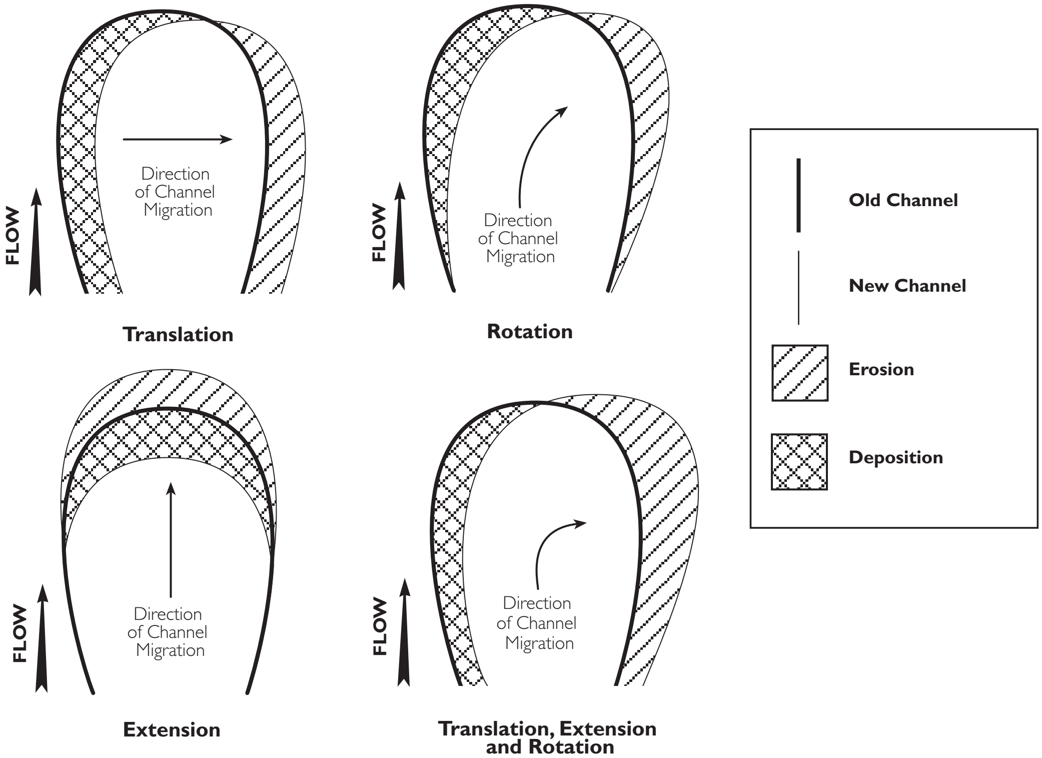

Figure 3-8. Migration patterns.

Meander Cutoffs - Chute and Neck Cutoffs:
Meander cutoffs can occur as either chute or neck cutoffs (*Figure 3-10*).[10] Neck cutoffs occur when two limbs of a bend meet due to gradual bank erosion and meander compression. Chute cutoffs occur when a bend in the stream becomes so tight that it causes sediment and debris to deposit and creates backwatered flow conditions in the upstream limb of the bend. The backwatered conditions increases the frequency of over-bank flows. As the flow shortcuts across the bar and reenters the channel on the downstream limb of the bend, erosion and the development of a new channel or "chute" results. An example of chute cutoff is shown in *figure 3-11*.

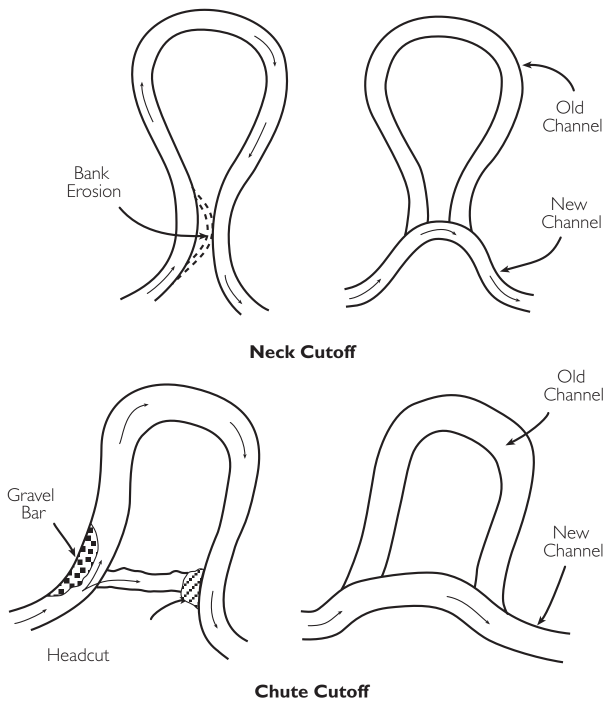

Figure 3-10. Chute and neck cutoffs.

Treatment Considerations: Channel migration and erosion patterns need to be considered during the selection of bank-protection techniques, paying careful attention to their effects on upstream and downstream channel dynamics. When short segments of migrating meanders are prevented from shifting (either by natural or artificial means), the adjacent, unprotected bankline may continue to migrate beyond the hard point, distorting the channel planform and threatening the stability and performance of the bank protection. It is critical to consider the appropriate locations and lengths of erosion control protection on a migrating meander to ensure proper performance and to prevent the exacerbation of adjacent erosion problems.

Meanders tend to migrate downstream. When a meander migrates downstream and encounters rigid bank protection (or bedrock), the meander extends across the valley, resulting in a widened migration corridor upstream.[12] The hardening of the downstream meander limb also results in meander compression, as the upstream limb continues to migrate down the valley. The meander bend will compress until it eventually cuts off and creates a new channel, resulting in rapid downcutting through the new channel for significant distances upstream. As other migrating meander bends downstream reach the same hard point, the sequence of events repeats, with successive bends extending, compressing and cutting off, as

Figure 3-11. Chute cutoff, Washington State.

shown in *Figures 3-12 and 3-13*. "Train wreck" meanders such as these (so named because the bends compress like derailed train cars) cause rapid and extensive adjustments in pattern and profile over an entire reach. In natural settings, such as at the entrance to a narrow canyon, this response results in a dynamic and unusually wide migration corridor.

Construction of rigid bank-protection techniques within the migration corridor disrupts natural meander migration and patterns of erosion. This commonly results in the need for even more bank protection, ultimately creating a rigid bankline throughout an entire reach. On alluvial channels, continuously rigid bank protection severely reduces geomorphic and habitat functions. The allowance of gradual bankline erosion and meander migration within the natural migration corridor will provide for geomorphic diversity and habitat evolution. Erosion also recruits raw substrate required for the regeneration of riparian vegetation.

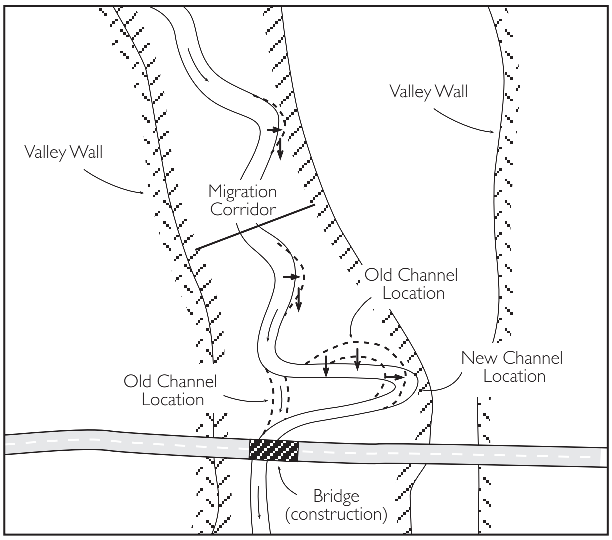

Figure 3-12. Typical meander extension and compression upstream of a constriction.

The allowance of gradual bankline erosion and meander migration within the natural migration corridor will provide for geomorphic diversity and habitat evolution.

Where gradual erosion is acceptable, but short-term, rapid erosion is not acceptable, bank-protection techniques may be appropriate if they allow eventual bank deformability (*Figure 3-14*).[13] One such technique uses degradable, erosion-control fabric wrapped around a gravel toe, overlain by a sloped, planted upper bank (see Chapter 6, *Techniques,* called *Soil Reinforcement*). It is designed to provide stability during a range of flow events, allowing upper-bank vegetation to become established prior to fabric degradation. The selection and design of these techniques are described in more detail in Chapter 5.

Where gradual erosion is acceptable, but short-term, rapid erosion is not acceptable, bank-protection techniques may be appropriate if they allow eventual bank deformability.

Nondeformable techniques, such as buried groins or rock toes, are best used along or near the edge of (and parallel to) the migration corridor to allow for natural channel migration and associated habitat evolution (*Figure 3-14*).[14] Channel stabilization along or near the edge of the migration corridor is less vulnerable to flanking and failure than similar treatments applied within the corridor. The migration corridor concept can be applied proactively, such that acceptable migration limits can be defined before addressing specific erosion threats.

Disequilibrium Channels

All streams are subjected to periodic changes. Shifts in contributing factors such hydrology, sediment load, valley slope or riparian vegetation collectively control channel morphology. However, changes do not necessarily result in channel disequilibrium. The tendency for a channel to be in disequilibrium depends upon the magnitude of a natural- or human-caused disturbance relative to the resilience of the channel. If conditions are such that the channel is just barely able to stay in its equilibrium state, a sudden change could be the last straw to throw it into

Figure 3-13. Meander extension and compression, Teanaway River, Washington State.

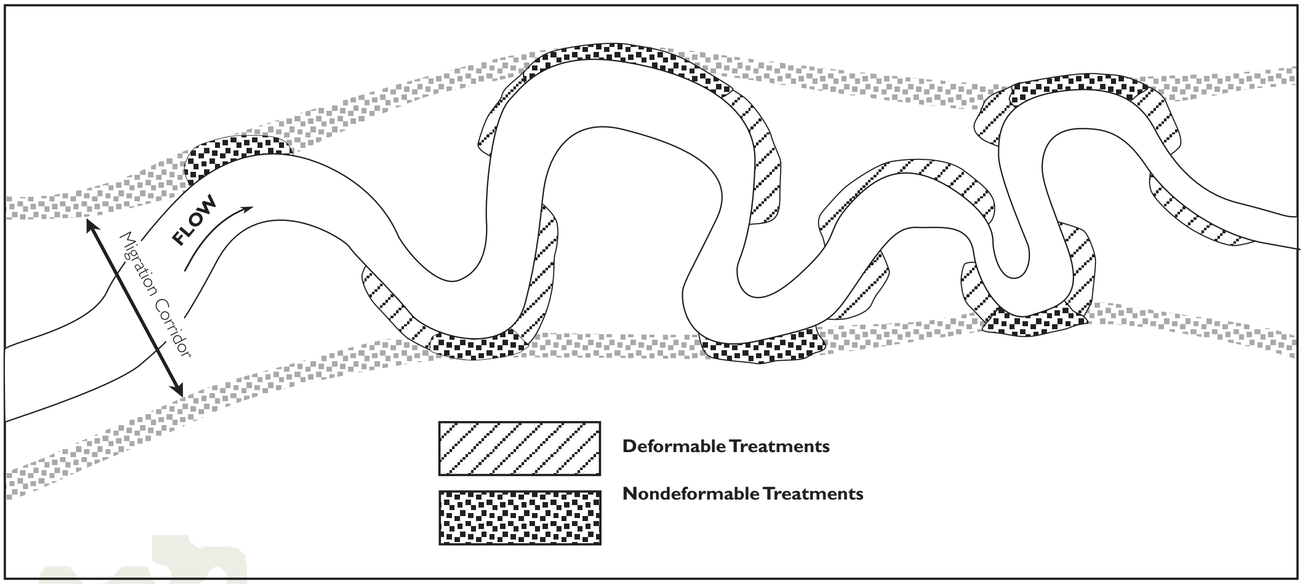

Figure 3-14. Conceptual application of deformable/nondeformable treatments across a migration corridor.

disequilibrium. If conditions are such that the channel is well within its equilibrium range, it will be more resilient, more able to accommodate a sudden change without dramatic shifts in channel shape and dimensions. (See Appendix F). For example, a slight increase in sediment load on a meandering stream that is approaching its geomorphic threshold may be all it takes to force the stream into a braided condition.[15] Such a system is prone to disequilibrium. In contrast, a stream that is already naturally braided is more resilient; its more dynamic condition enables it to accommodate and adjust to constant disturbances without requiring dramatic shifts in channel shape or dimension. Appendix F provides detailed information on disequilibrium channels.

With respect to geomorphic disequilibrium, sediment supply and hydrology must also be considered (*see Figure 3-6*).[16] When observing what appears to be a channel adjustment, it is important to remember that such adjustments may be in response to a long-term change in sediment or hydrology or may reflect a recovery from a short-term disturbance, such as a flood event. Determining the magnitude of such disturbances (short-term or long-term) and the causes of disequilibrium (*Figure 3-7*) is essential for selecting the most appropriate bank-protection solution.

Long-Term Disequilibrium:
Where a channel is subjected to changes in hydrology and/or sediment inputs, the channel will adjust (*see Lane's diagram, Figure 3-6*). Such adjustment can result in a significant change in overall stable channel form.

A major river-management challenge is to recognize that a channel is in disequilibrium, identify the causes, and develop a strategy that will promote recovery. Where the causes of disequilibrium are identifiable, a strategy should involve the

Determining the magnitude of such disturbances (short-term or long-term) and the causes of disequilibrium is essential for selecting the most appropriate bank-protection solution.

direct treatment of those causes. For example, treatment may involve removing or redesigning instream structures (e.g., weir, culvert or dam) that disrupt the natural transport of sediment, or reconfiguring a channelized stream reach. Where the causes are untreatable, such as in an urban, harvested or agricultural watershed, the strategy may involve creating a new condition of equilibrium. In these systems, an altered hydrology and sediment load may not support native-species vegetation or habitat for fish and wildlife. The ability for native species to adapt to these changes is limited; and, when those limitations are exceeded, extraordinary amounts of restoration and continual management will be required to foster recovery of native vegetation and habitat.

Altered hydrology and/or sediment load can lead to aggradation, degradation or avulsion. These are the most common reach-based processes driving bank erosion in a disequilibrium channel. These processes are triggered by one or more causes. For example, a downstream constriction (such as an undersized bridge) may cause aggradation, or shortening a channel may cause degradation.

Figure 3-7 shows the processes and causes of long-term channel disequilibrium. What follows is a discussion of each, along with treatments to consider.

Aggradation: A reach aggrades when more sediment is transported into the reach than out of the reach. Channel aggradation may occur naturally; or it may be induced or accelerated by human activities. Where a channel is in disequilibrium due to an excessive sediment supply of sediment or reduced flow energy, deposition (aggradation) occurs.[17] Aggradation will continue until the channel evolves to accommodate changes in sediment supply and hydrology (*see Lane's diagram Figure 3-6*). Localized aggradation can also occur upstream of woody debris jams, rock outcroppings or infrastructure elements (e.g., culverts and bridges) that create backwater during high flows. *Figure 3-15* shows a severely aggraded stream.

A reach aggrades when more sediment is transported into the reach than out of the reach. Channel aggradation may occur naturally; or it may be induced or accelerated by human activities.

Figure 3-15. Aggrading Channel, East Fork Grays River, Washington State.

Identifying whether a reach is aggrading can be achieved by answering the following seven questions:

1. Has the average bed elevation increased through time? Aggradation is identified by an increase in the elevation of the channel profile.
2. Has there been a demonstrated loss of channel asymmetry and associated habitat due to pool in-filling? Aggrading channels tend to shallow and widen.
3. Has the channel capacity and bankfull discharge been reduced? Has the frequency of overbank flow increased? Aggrading channels tend to flood more frequently than stable channels.
4. Has there been an increase in meander cutoff frequency? Aggradation increases the frequency of overbank flows, which increases the chances of more frequent meander cutoffs.

Altered hydrology and/or sediment load can lead to aggradation, degradation or avulsion. These are the most common reach-based processes driving bank erosion in a disequilibrium channel.

5. Has the channel shifted from a single-thread meandering pattern to a multichanneled, braided pattern? Braided channels are characteristic of streams with high sediment loads.
6. Has the channel avulsed (changed course) due to deposition within the main channel? Do avulsions commonly occur within the reach? Avulsion, common in braided channels, also occurs in meandering channels due to aggradation (*see page 3-16*).
7. Is human activity or maintenance required to maintain the desired channel condition? Channels that require human intervention to prevent changes may be aggrading.

Reach-Based Causes: The most common reach-based causes of aggradation are:

- Increased sediment supply -
    - Upstream bank erosion, mass failures, or scour can recruit excess sediment into the channel. An upstream, degrading reach is another source of excess sediment;
    - Sand and gravel stockpiling in the active channel or floodplain is a source of excess sediment recruited during flood events; and
    - Removal of instream structures, such as dams or culverts or even collections of large woody debris, can unleash an accumulation of sediment stored behind the structures.
- Reduced hydrology from upstream flood-control structures or diversions can decrease flows and the energy needed to transport sediment.
- A decrease in channel slope corresponds to a reduction in energy to transport sediment. The flow of a stream into another body of water, or the abrupt change in slope as a steep channel emerges into a valley, creates an alluvial fan or delta.
- Localized backwater effects due to constriction points at bridges, culverts, or natural hard points (e.g., bedrock) can reduce the hydraulic energy.
- Channel confinement by dikes or berms limits or prevents overbank flood flows from depositing sediment in the alluvial floodplain, resulting in deposition of sediment in the channel.

A channel will respond to these impacts by making significant adjustments to restore sediment transport continuity. These adjustments may include channel steepening, or changing channel pattern and cross-section shape. Consequently, natural recovery often results in a significant change in channel form. Some alluvial environments are naturally aggradational, such as alluvial fans, deltas and tidal environments.[10]

Treatment Considerations: Applying bank-protection treatments will not stop aggradation, and risk of flooding along the floodplain area will continue to exist. Indeed, the risk of flooding may even increase if the bank protection fails. Bank-protection treatments may also result in other highly undesirable impacts such as:

- the burying of bank protection,
- a major channel shift,
- a change from a single-thread meandering to a braided channel, or
- the widening and shallowing of the channel cross section.

Instead, reducing the sediment load or increasing the transport capacity of the reach should be considered. This can be achieved by adjusting the channel slope and cross-section (Chapter 5). Identifying and selecting a migration corridor that extends beyond the current active channel should also be considered. Broadening the channel's migration corridor will allow aggradation and recovery to occur naturally.

Degradation: A reach degrades when energy in the channel exceeds that which is required to carry the incoming sediment load (*see Lane's diagram, Figure 3-6*). It appears as a net lowering of the bed elevation over time. It may occur as a gradual, continual lowering of the entire profile (in highly erodible materials such as a sand bed channel) or as episodic lowering and formation of steep channel segments (nickpoints or headcuts) that migrate upstream.[18] A degrading channel will follow an evolutionary sequence of down-cutting to a new stable profile, followed by widening due to the collapse of over-steepened banks. The widened channel has less flow energy, so deposition and formation of a new floodplain surface occur. This new surface is below the elevation of the pre-degraded floodplain (*Figure 3-16*) and the perched, old floodplain becomes the new terrace (see Appendix F for further discussion).

Figure 3-16. Degrading channel, Washington State.

A reach degrades when energy in the channel exceeds that which is required to carry the incoming sediment load.

A degrading reach can be identified by answering the following eight questions:

1. Is there evidence of reach-wide down-cutting and lowering of the channel profile? A continual lowering of the channel profile is the clearest indicator of channel degradation.
2. Are headcuts or nickpoints evident in the channel bed? Headcuts or nickpoints are short, steep channel segments recognized as small drops or waterfalls or abnormally over-steepened channel segments.
3. Are banks consistently over-steepened and collapsing? Degrading channels tend to result in over-steepened banks that collapse. The erosion results in overall channel widening, rather than localized erosion on the outside of bends.
4. Are channel features such as bars and riffles disappearing or becoming coarser? Degrading channels erode sediment from channel features, such as spawning riffles, until they disappear. Coarsened material that is resistant to erosion remains.
5. Has the channel become detached from its floodplain? Degradation results in the perching of the floodplain above the channel bed and water table, until the floodplain eventually becomes an abandoned terrace. Side channels also become detached from the channel, destroying fish passage to side channels.
6. Has there been a loss of root penetration in the banks? Lowering of the groundwater table below the root zone will impair the survival of vegetation and reduce vegetative bank structure.
7. Have there been activities that would result in degradation? Activities such as upstream channelization or dam construction are common causes of degradation.
8. Has the hydrology of the watershed changed? An increase in impervious area (such as paved lots) and changes to the natural drainage system alter the peak and duration of flows.

Reach-Based Causes: Causes of channel degradation are shown in *Figure 3-7* and are related to either a reduction in sediment supply or an increase in hydrology. The most common causes of degradation are:

- Reduced sediment supply -
  - Sediment trapped behind instream structures, such as dams or culverts, limits the sediment transported downstream;
  - Upstream sand and gravel removal will limit sediment transported downstream;
  - Hard bank protection upstream restricts the natural recruitment of sediment; and
  - Capping floodplain sediment sources by impervious surfaces prevents the natural recruitment of sediment during flood events.
- Increased hydrology from land use changes such as past flood hazard management efforts, urbanization, agriculture and forest practices cause both an increase in peak flows and frequency and a decrease in runoff duration.[19] Changes in long-term watershed hydrology (magnitude and duration) from climatic and/or geologic events may also cause an increased hydrology.
- A channel that has been artificially shortened and straightened will have excess energy, since planform roughness has been eliminated and length has been shortened, which steepens the grade. A channel in this condition will attempt to regain a natural pattern (e.g., increase length and decrease slope) through erosion of the banks and bed.[19] Channels that are shortened and/or straightened are often confined using berms or levees, which inhibit meander migration and disconnect the channel from the floodplain. Energy is not dissipated out of the channel, because flows do not spread out across the floodplain.

- Natural disturbances operating at varying time scales are part of the sequence of natural channel evolution, where the channel changes gradually over time, leading to increased flow energy, and subsequent channel degradation. Natural causes of degradation may be related to stream and valley geology (e.g., uplift or faulting), geomorphology (e.g., lowering of base level or increased gradient), climatic change (e.g., a wetter period), and hydrologic change (e.g., increase in peak flows).[20]

Treatment Considerations: The primary concern to be aware of if applying bank-protection treatments in a degrading channel is the potential for the river to undermine the treatment by lowering its channel bed. Consequently, the design of a bank-protection technique applied at the toe of a bank must be sufficient to withstand down-cutting. This resistance is critical to project performance (in addition to depth of scour calculations based on existing conditions). Instead of using bank-protection treatments, consider using grade-control structures, which can stabilize the bed elevation. Also consider reducing the hydrology and increasing sediment storage by adjusting the channel size and shape. The size and shape of the channel can be adjusted by recreating meanders within the reach or by modifying the cross section and constructing a floodplain surface that will dissipate flow energy during flood events. Another treatment to consider is placement of large woody debris which provides storage of sediment by creating a low-velocity zone downstream for sediment to settle out and stabilize.

Avulsion: An avulsion is a significant and abrupt relocation of a new channel. (*Figure 3-17*). Avulsions are caused by concentrated overland flow, headcutting and/or scouring a new channel in the floodplain, leading to a major channel change. Avulsions typically occur in braided or aggrading channels.[12] Avulsions are different from chute or neck cutoffs in that they are not related to the predictable patterns of meander migration. Rather, they result from random channel events that vary dramatically in length and point of occurrence.

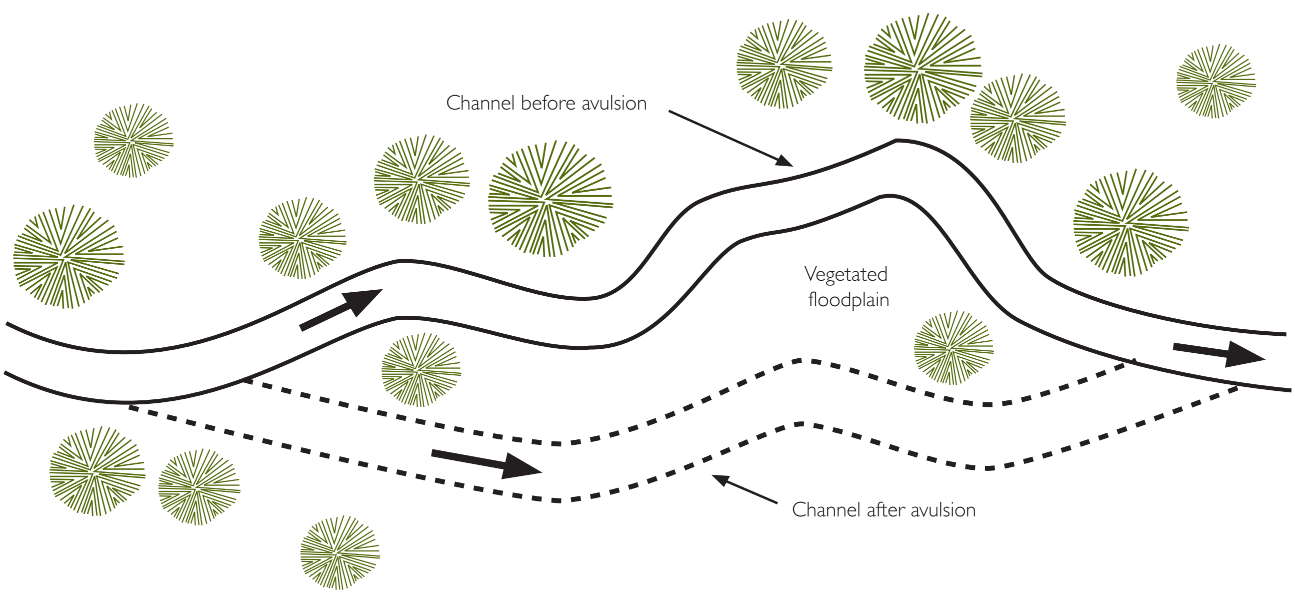

Figure 3-17. Avulsion.

An avulsion is a significant and abrupt relocation of a new channel. Avulsions are caused by concentrated overland flow, headcutting and/or scouring a new channel in the floodplain, leading to a major channel change.

An avulsion takes place sequentially as surface erosion in the floodplain progresses from small channels (rills) to gullies, to eventually cutting a new channel. After an avulsion, erosion progresses upstream in the new channel (as headcutting) and/or downstream. An obvious indicator of a potential avulsion is a nick point or headcut downstream from where the stream flowed over its banks and onto the floodplain. *Figure 3-18* shows a newly formed avulsion.

Figure 3-18. Avulsion, Quillayute River, Washington State.

An avulsion can be identified by answering the following questions:

1. Has a new channel formed over the old floodplain surface? Is it lengthening in the upstream direction and does it have a headcut on its upstream end? This reflects the fundamental process of avulsion.
2. Have large flood events recently occurred? Has the hydrologic regime changed such that the frequency of large runoff events has increased? An avulsion typically occurs during large storm events where overland flows erode the floodplain. Large storm events are extreme events that are unlikely to recur in the foreseeable future. However, in watersheds that have had their natural hydrology altered, more frequent, milder storm events may cause flooding and erosion similar to a large storm event. Hydrology is commonly altered by watershed activities (e.g., urbanization, forest and agricultural practices, and past flood-hazard management efforts) that directly change the natural hydrologic response.
3. Is the floodplain extensively eroded? The onset of the avulsion process includes the progressive erosion of the floodplain and formation of a new channel.
4. Has the main channel aggraded? A common cause of an avulsion is reduction of conveyance in a channel due to aggradation, resulting in more frequent over-bank flows.
5. Has the channel been relocated? If the channel has been relocated, the channel may avulse back to its original location.
6. Are abandoned channels common on the floodplain? Walk the site and review aerial photos. If there is evidence of abandoned channels, this reach may have historically or recently avulsed. If there are a series of scroll-shaped channels parallel to a newly formed channel, it is more likely meander migration and not an avulsion.
7. Has the floodplain been cleared of all vegetation or mined? Avulsions may occur where floodplain roughness, naturally provided by the riparian corridor, has been cleared. Also, sand and gravel mining activities are depressions in the floodplain, increasing the risk of an avulsion.

Reach-Based Causes: Reach-based causes of an avulsion are shown in *Figure 3-7* and are related to either aggradation in a meandering or braided channel or relocation of a channel from its natural location. Floodplain activity (e.g., removal of vegetation on the floodplain or in the riparian buffer) were discussed in Chapter 2 as a site-based cause of an avulsion (*see page 2-14*). An aggrading reach may result in an avulsion if the bed and water surface elevations increase the frequency of overbank flow across the floodplain. Avulsions are a common occurrence in naturally braided channels. See *page 3-13* for more information about aggradation.

Historically, many channels have been relocated due to land-use activities such as agriculture or infrastructure development. These channels were often relocated to the edge or outside of their migration corridor. In areas where this has happened, an avulsion is possible as a relocated channel attempts to reclaim its historic location within the migration corridor.

Treatment Considerations: As long as large storm events occur, avulsions will also occur. After large storm events, the human response is often to "fix" the avulsion problem (e.g., put the channel in its pre-avulsion location and armor the bank) to withstand the next large event. These "fixes" are often structural and are designed to withstand these few large events; but, more often than not, they unintentionally exacerbate bank erosion along downstream and upstream properties.

Treatment of avulsed channels is most effective if the root cause, rather than the secondary cause, is addressed. For example, if the root cause is aggradation, and the secondary cause is floodplain activities, selecting techniques that correct the root cause will most effectively reduce the avulsion risk.

The formation of backwatered, off-channel habitat within the abandoned channel increases habitat value within a reach. These abandoned channels provide winter and spring flood refuge for fish and cool, spring inflow conditions during low summer flows. Loss of these habitats is common in developed watersheds. Maintaining or fostering vegetative recovery of avulsed channels should always be considered following such an event.

Short-Term Disequilibrium:

Short-term, catastrophic impacts including floods, rapid mass failures and fires drive rapid channel change and are a fundamental component of stream dynamics. Channels affected by such events require a period of time to recover and return to geomorphic equilibrium. The recovered channel may or may not resemble the pre-impact channel. Short-term instability is valuable to fish habitat and riparian vegetation, both of which have evolved and adapted to natural channel disturbances.[21,22]

Short-term, catastrophic impacts including floods, rapid mass failures and fires drive rapid channel change and are a fundamental component of stream dynamics.

Large Flood Events: The geomorphic impact of large flood events depends on the magnitude and frequency of the events and how the channel recovers between floods.[23,24] The significance of floods in terms of channel morphology is related to climate, lithology, vegetation and the timing of the events; and their impacts vary dramatically, depending upon the geomorphic setting. For example, in semi-arid settings of sparse vegetation and thunderstorm-driven flooding (e.g., eastern Washington), channel recovery is slow, and floods commonly dominate channel form. In contrast, channels in more temperate environments (e.g., western Washington) tend to recover rapidly from flood impacts.

Floods can cause rapid changes in channel form, such as changing a single-thread, meandering channel into a braided channel, especially if a meandering channel is nearing its geomorphic threshold (Appendix F). Other effects of floods include channel widening and deepening, avulsion and extensive transport and rearrangement of sediment and woody debris.

Channels generally undergo a period of recovery following flood events. Sediment deposition and vegetative regeneration will narrow over-widened channels. Floods benefit riparian regeneration due to deposition of new substrate along the bank and in the floodplain, and a number of plant species have evolved to respond to these conditions.

Mass Failure: Rapid, mass failures from hill slopes into stream channels, including rockfalls, landslides, debris flows and slumps, can significantly alter channel dynamics.[25] Mass failures cause large plugs of sediment to enter stream channels, which can degrade fish spawning substrate and habitat.[21] The ability of the channel to transport excess sediment from hill-slope failure depends upon the size of the sediment and the energy of the stream. Increased sediment supply generally results in an altered channel slope and, potentially, a shift from a meandering to a braided channel. Mass failure events that dam a channel (either with sediment or vegetative debris) can have major downstream impacts on channel morphology if a flood spills over the top of the dam.[26] For a more detailed description of how and why mass failure occurs, review Chapter 2.

Once the excess sediment erodes, the channel will readjust to background sediment loads. However, if the excess sediment is too coarse to be mobilized, evidence of the mass failure will remain as a steep, coarse channel reach. This appears as rapids on large river systems. Mass failure contributions of large amounts of woody debris to a channel will be routed downstream and, with time, serve as valuable aquatic habitat. Some debris, however, will remain, providing stability to the bank and bed of the channel.[27, 28]

Fire: The destruction of large amounts of hill-slope vegetation by wildfire impacts stream channels by increasing runoff and soil erosion, especially in steep drainage basins,[29] mass wasting on hill slopes (through the loss of vegetation root strength,[25] and sediment deposition in the stream channel. The increased sediment load consists primarily of fine-grained soils that may degrade habitat function for many years, causing channel disturbance from stream reaches all the way up to entire drainage.[30]

Treatment Considerations: Channel restoration within areas that are damaged by short-term impacts often focus on restoring the original channel condition. In many cases, these efforts simply accelerate the natural recovery process and may, therefore, not even be necessary to achieving channel stability. Indeed, a "no action" option may be optimal if the predicted extent and time frame of recovery are acceptable. Additionally, it's important to remember that short-term disturbances such as floods create excellent aquatic and riparian habitat. Restoration efforts should be undertaken with great caution, weighing carefully the potential adverse effects on the extent, quality, or longevity of habitat created by the initial disturbance against the potential adverse effects of the proposed restoration treatment.

Where the magnitude of short-term impacts is such that a channel is likely to remain unstable for long periods of time, human interaction might be necessary. For example, where floods or mass failures result in the deposition of a new size of sediment (such as large boulders in a gravel-dominated stream), extensive channel modifications may recover channel equilibrium, to the benefit of human needs and habitat quality.

Indeed, a "no action" option may be optimal if the predicted extent and time frame of recovery are acceptable.

CONCLUSION

The variety of reach-based causes of streambank erosion makes assessment of their presence and influence challenging, but essential, in determining appropriate treatments. Evaluating reach-based causes should always occur in tandem with evaluation of mechanism of failure and site-based causes, since each can profoundly affect the other. In Chapter 4, *Considerations for a Solution* we will explore how to weave our site and reach assessments with the engineering considerations necessary to determine risk and mitigation needs for potential treatment(s).

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Chapter 4

Considerations for a Solution

This chapter links the building blocks of site and reach assessments described in Chapters 2, *Site Assessment* and Chapter 3, *Reach Assessment* with the engineering considerations involved in risk assessment and mitigation procedures when dealing with lost habitat (Chapter 5, *Identify and Select Solutions*). The information contained in this chapter will help establish project* objectives and design criteria, which include consideration of habitat mitigation, risk, the emergency nature of the work and project management. Developing design criteria involves integrating various project elements, including technical performance, cost, acceptable risk, mitigation requirements and maintenance needs.

* In this context, the term "project" refers to the actual protection treatment used, not just the effort to construct or install the treatment.

OBJECTIVES AND DESIGN CRITERIA

Integrated Streambank Protection is a strategic approach to managing erosion on streambanks and channels that protects lives, properties and structures while also protecting or restoring a stream's ecological value. It may involve structural or nonstructural solutions, or both, integrated with ecological functions. It may also result in solutions that allow continued erosion. The desire to stabilize a streambank may be driven by the need to protect a physical structure or to protect land from being consumed through bank erosion or instability. A number of objectives may be imposed on such a project, some of which may even be in conflict with each other.

Describing Objectives

Selecting an appropriate bank treatment requires identifying all the objectives associated with the project, including ecological functions associated with the site. Objectives are usually described qualitatively. For example, a project might have an objective such as: "to stabilize the streambank for 500 feet upstream of the bridge at Highway 50 so the bridge isn't undermined," or "to stop the streambank erosion that is threatening private residences."

Objectives should be stated in terms of the desired outcome to be achieved. Do not include methods in the stated objectives. Doing so may create unintended problems, such as causing certain solution options to be selected or rejected prematurely, and risks may not be accurately characterized or evaluated. For example, although erosion caused by a large flood appears to threaten property, focusing on the erosion risk may place the property in further danger if the real risk (and solution) has to do with the probability of large flood events in the future. Rather than stating the objective as "stabilize the streambank to protect property and lives," state the objective in terms of outcomes: "take action to minimize the risk erosion poses to property and lives." Doing so enables all solution options to be considered, selected and/or rejected based on their individual potential for success. Folding the concepts of *Integrated Streambank Protection* into the picture, the objectives might also include something like, "... while protecting the aquatic productive capacity of the site." The objective might even include other factors such as protecting recreational or scenic values.

Defining Design Criteria

Design criteria are specific, measurable attributes of project components developed to meet objectives. Put more simply, they describe how a successful outcome would function if the objective were met.

Design criteria are target standards or performance measures set for individual components of a design, providing numeric, allowable limits of performance and tolerance for bank-protection components and mitigation features. These performance measures relate to reversing, preventing or minimizing the mechanisms of failure described in Chapters 2 and Chapter 3, as well as achieving the proper function of mitigation features.

Design criteria are a key to establishing mutually understood expectations for the property owner, project sponsor, designer and regulatory agencies. They also form an agreed-upon, objective basis of evaluation to determine whether the fix was effective or not. While an objective might be stated in general terms, such as "minimize erosion" and "maximize stability during high flood events," design criteria are more specific; they describe what it means to meet the objective. For example, a set of design criteria for bank stabilization might include*:

- The bank-toe stabilization measures taken shall resist scour forces up to and including a 25-year discharge.
- The bank protection above the water level that occurs at the five-year discharge shall resist shear stresses of 0.5 pounds per square foot.

*the design-criteria examples listed in this chapter may or may not be appropriate for any given project. Specific criteria must be determined for each individual project.

Selecting an appropriate bank treatment requires identifying all the objectives associated with the project, including ecological functions associated with the site.

- Stabilization measures shall account for potential bed degradation of two feet in the event channel degradation continues.
- Bank-toe woody material shall resist buoyancy and shear forces up to and including those that occur during a 10-year recurrent flow.
- Shoots from grasses planted on the upper bank shall cover 80 percent of the ground surface at the end of the second year following project implementation.
- At least 80 percent of the woody plant material shall survive three years after placement.
- Scour pools created by each mitigation debris jam shall result in an average of at least 600 cubic feet of pool volume covered or within 10 feet of the major debris jam elements.

Design criteria are what make it possible to achieve the stated objective. They help the project participants describe what the objective means, figure out how to achieve the objective and measure whether or not the strategy to meet the objective succeeded. When applied in conjunction with design analysis, design criteria might answer questions such as:

- What type of bank-surface protection is appropriate, if any?
- How big should the toe foundation material be, and how deep should it be placed beneath the existing stream bed?
- What specific mitigation features will be required, and how secure must they be?
- What type of erosion-control fabric, if any, should be used on the upper bank, and how should it be installed?
- What trees and shrubs should be used for revegetation; how large should they be when planted, and how should they be cared for?

The number and focus of design criteria for any given project depend upon the scale and extent of the particular project itself. Simple, uncomplicated projects with little ecological effect may require only a few design criteria, whereas more complex or risky projects may require a more extensive suite of criteria. Depending upon the problem to be solved, design criteria may take into account any number of components. For example:

- Vertical Stability: bed-material gradations and distribution, grade-control-structure rock size, structural dimensions and placement details.
- Lateral Stability: deformable or nondeformable bank, composition and character of bank toe (including depth, width and angle, upper-bank backfill or soil material and slope) and surface protection.
- Floodplain Surface Stability: time required to achieve vegetative stability and allowable shear forces on the floodplain surface.
- Aquatic Habitat: function, description, quantity, location and durability of various habitat types after initial construction and as affected by subsequent flood events.
- Revegetation Success: vegetation zones and landscape position, lower limit of vegetation, species composition, plant density and performance, irrigation needs, weed control and maintenance requirements.
- Constructability Considerations: construction time window and sequencing needs, dewatering methods and protection of fish, erosion- and sediment-control measures, staging areas for materials and equipment, heavy-equipment capabilities, access requirements and site restoration.

RISK AND COST ASSESSMENT

Assessing risk is a highly subjective yet critical process in evaluating bank erosion and considering management steps. Risk is the product of consequence and probability. A high-risk situation is one in which the probability and/or the consequence of failure is high. A lower-risk situation is when the probability of occurrence or the nature of the outcome is less severe. Determining the nature and degree of risk depends upon the point of view of those who have a stake in the outcome. For instance, weighing risks to habitat, property and safety against each other will likely result in differing conclusions, depending upon whether one is a property owner, a recreationist or a resource manager. Assessment should always weigh the risks of bank protection as well as the risks of bank erosion. Just as the nature of stream activity should be assessed in terms of site conditions and reach conditions (as discussed in Chapter 1, *Integrated Streambank Protection*), the nature of risks should also be considered within such a context.

Assessment should always weigh the risks of bank protection as well as the risks of bank erosion.

Site risks to consider in terms of both erosion and steps to correct erosion include impacts on:

- property and infrastructure,
- habitat, and
- public safety.

Reach risks to consider in terms of both erosion and steps to correct erosion include impacts on:

- channel stability, and
- habitat.

While some risks are difficult to quantify, due diligence in addressing all certain and potential financial and resource costs will only contribute to a more successful outcome in resolving the streambank or channel issue.

Cost considerations for both bank erosion and bank protection should include:

- repair of damage to property and infrastructure;
- relocation of at-risk facilities;
- compliance with legal requirements for habitat rehabilitation;
- restoration of the channel to prevent further habitat losses associated with a bank-stabilization project;
- design (including appropriate geomorphic and hydrologic analyses), construction and maintenance of the bank-protection treatment; and
- habitat mitigation for the duration of the impact, including any required monitoring and mitigation adjustments.

Assessing Risk Associated with Bank Protection

The selection of streambank treatment is often guided by the assessed risk of failure. The use of "soft" bank-protection techniques, such as revegetation, can be used if either the probability or consequence of continued bank failure is low. In their early stages, purely vegetative bank-protection techniques often provide less guarantee of protection than more structural techniques. However, they can act as a buffer initially, and they provide secure protection once vegetation becomes established and bank strength is restored.

An eroding bank is not usually a risk to habitat. Erosion is a natural process that can recruit large woody debris and sediment necessary for a healthy stream and riparian ecosystem; but accelerated erosion, especially of fine-grained material, can be a risk to habitat by filling pools and contaminating spawning beds. Additionally, steps to stabilize streambanks can have a habitat-restoration value by restoring channel geometry.

Relating Risk to Hydrologic Probability

The selection of design criteria is guided by the risk of failure. Since the success or failure of bank stabilization is dependent on flood events, design criteria and risk are defined by the probability of occurrence of a flow of a given size. Some design criteria need to relate to a specific, limited time window. For example, revegetation might require five years of development before it succeeds in its objective of bank stabilization, and establishing measurements for the success of that treatment will need to take this into account. Other criteria may take into consideration longer return periods, depending upon the need. For example, a design might include a criterion such as, "vegetative bank protection shall resist erosion with 70-percent assurance during the first five years and 80-percent assurance over the next 50 years."

Design criteria can be established that consider the erosive forces exerted during a flow of a particular magnitude, also referred to as the "design flow." By using the probability of a flow occurring during a limited time frame, variable levels of risk can be considered. Design flow (that is, a flow of a defined level) is described by the likelihood of recurrence over time. A "100-year flood" is the flow that has a one-percent probability of occurring in any given year. Although such a flow could occur in two consecutive years, the statistical probability is one percent in any given year. The statistical probability of occurrence of a specific level of flood is typically related to an unlimited time frame. When the statistical probability of a specific flow happening within a limited time is calculated, for example within the next ten years, the likelihood of recurrence is lower than it would be for an unlimited period and is calculated as:

$$P = 1-(1-1/T)N$$

where:

- **P** = probability that a given flow will occur at least once during the next N years;
- **T** = recurrence or return interval; and
- **N** = specified number of years in time window.

In many cases, design criteria for the same project may relate to different design flows. For example, a bank toe of rock might be designed to withstand forces up to the 25-year flow, whereas surface protection of a floodplain against potential avulsion might be designed to the five-year flow. A reason for this difference might be the expectation that the immediate risk of avulsion is acceptable and natural vegetation growth on the floodplain will reduce the risk over time.

There are two approaches to determining appropriate design flow. The first is quite simple and involves selecting a suitable risk level based on probability. For example, a common standard for protecting infrastructure is to design for a one-percent-probability flow, recognizing that such a flow may actually occur in any year or sequence of years. However, application of that standard may be overly simplistic and inappropriate. Design standards for a project take into account the risk, cost and habitat implications associated with adhering to them.

The second method of determining appropriate design flow is an integrated and iterative approach, where methods, risk, mitigation, sequencing and costs are considered. Risk can be viewed in the context of limited and/or unlimited time frames. One can evaluate the forces at various flows, consider the methods required to provide stabilization at these flows, evaluate the costs and habitat mitigation requirements of the different levels of stabilization and choose a design flow that achieves the objectives of the project at the best value.

HABITATS COMMONLY AFFECTED BY BANK PROTECTION

This section explains various habitat characteristics and how bank-protection efforts might affect them. See Appendix G, *Biological Considerations* for a more complete description of habitats.

Spawning

Spawning habitat is created by the interaction of high flows with channel geometry, sediment and substrate as well as other variables and complexities at the site. Habitat requirements depend upon the fish species in question. Some species are "broadcast spawners" that freely spawn over the substrate. Other species construct and deposit their eggs within nests or "redds" in the substrate. Some species' spawning habitat is present in riffle-pool channel morphology associated with debris accumulations or in pool tailouts and other localized accumulations of gravel. Other species depend on wide gravel beds with uniform cross section and profile, known as "runs."

Spawning habitats are directly created by and depend on channel characteristics and complexities that cause hydraulic sorting and accumulation of gravel into bed forms appropriate for spawning. These beds, if well established, are relatively resistant to scour during periods of egg incubation. Changes to the bank can cause the thalweg to scour gravel accumulations and create uniform channel beds that eliminate spawning habitat. Where banks are smoothed by natural or man-made influences, riffle-pool sequences and other spawning habitats are lost forever. Spawning-habitat losses are difficult, if not impossible, to recreate without regenerating the channel characteristics they depend on. This is especially true in channels that are too narrow to include large roughness elements or debris accumulations.

Spawning habitats are directly created by and depend on channel characteristics and complexities that cause hydraulic sorting and accumulation of gravel into bed forms appropriate for spawning.

Mitigating the loss of spawning gravel includes recreating and/or maintaining channel dimensions and complexity. Depending upon the species, the scale of the channel and associated impacts, channel-complexity mitigation might include adding debris jams, debris catchers, channel constrictions, drop structures and roughness elements. Even under the best of circumstances, however, it is not always possible to recreate spawning habitats.

An important source of spawning gravel is the material eroded from its banks. Successful bank-protection projects often block the ability of channels and banks to continue supplying spawning gravel. Spawning sites in channels whose supply of gravel is lacking are particularly sensitive to these impacts. Lack of spawning gravel might be a natural situation or may be due to previous unmitigated bank-protection projects or dams. Artificially supplementing the channel with spawning gravel allows the channel to redistribute it during floods.

Cover

The term "cover" refers to juvenile rearing and adult holding habitats provided by large woody debris, live tree roots, deep pools, shallow water (refuge for juveniles), undercut banks, overhanging vegetation, turbulence and large interstitial areas in cobble or boulder substrate. Fish use and value of these habitats vary with different species and life stages. Especially important in lower river reaches, fish-migration corridors provide holding areas for fish that are not ready to enter saltwater or that are migrating at night and holding during the day.

Cover provided by complex debris structures is the habitat preferred by most fish. Deep, low-velocity pools resulting from scour around debris structures, debris, snags and jams in or near the water should be left in place. If they must be moved to facilitate construction, they must be replaced in their entirety either in the original position or a location where they would naturally occur in order to maintain the original habitat function. An alternative to replacement is to install debris collectors that capture and retain floating debris. It may be tempting to use boulders or groins to create pools in the stream for fish. The problem with such a solution is that fish tend to use these pools less than those created by wood. Therefore, boulders or groins alone are not a good substitute for wood. However, when groins are combined with substantial accumulations of wood, they have been shown to provide comparable habitat to that created by naturally accumulated woody debris.

Armored revetments create a continuous, deepened thalweg, an uninterrupted, high-velocity pool, along the treated bank. Placement of dense clusters of large wood in the channel and along the banks will break up the current. The track record for attaching large woody debris to riprap, particularly for single pieces, has been poor, except when specifically designed for the shear stress at the site and buoyancy of the wood. Log jams and pile structures as debris catchers have been successful when designed to fit natural channel processes. Shallow water is an important cover feature for juvenile fish use where more complex cover habitat is not available. Juveniles use shallow water to escape predatory fish. Shallow-water cover is not a replacement for cover provided by debris and scour, however.

Habitat Complexity and Diversity

Habitat complexity and diversity is the mix of in-channel and hydraulic features important to the survival, growth, migration and reproduction of salmonids. Complex and diverse channels are more productive for salmonids than simple channels. Vegetated banks and floodplain, cover, off-channel rearing, flood refuge and spawning are habitat components that partially define complexity and diversity of a stream channel. Variations in bank and bed topography, substrate, depth and velocities are all elements of diversity.

Riparian Function

Riparian corridors serve a vital role in fish and wildlife habitat. Riparian benefits include food contribution in the form of leaf litter and insects, shade, nutrients, cover, large-woody-debris accumulation, attraction of wildlife and a high level of water quality. Riparian corridors also provide energy dissipation, bedload retention, pool formation, flood-refuge habitat and critical habitat diversity. To maintain and protect the riparian function, it is important to preserve a natural riparian buffer within and beyond the bank protection.

All bank-protection projects should have a riparian preservation or restoration component. Riparian function is partially mitigated at armored banks by planting vegetation that will grow through the hardened bank armor. This is not always feasible depending upon the thickness of the rock and filter blankets, as well as water conditions in the bank. If the bank armor cannot be vegetated because of materials or maintenance requirements, another style of bank protection should be considered, or the loss must be mitigated by establishing a riparian buffer in the area above the rock, including large trees and native under-story plants. Controlling invasive, noxious weeds is critical in re-establishing native riparian vegetation.

Every linear foot of bank that has received protection treatment should have the riparian function restored, including trees, other woody species and under-story vegetation. Be sure to integrate plantings into the bank treatment or create or enhance a riparian habitat area in a bank terrace and above the bank face. Part of the mitigation design and management is to assure a specific plant survival rate over a specific period of time. For example, a mitigation plan could stipulate that 80 percent of the intended riparian vegetation survives and develops to specific dimensions within three years.

Flood Refuge

Riparian habitat often provides refuge for juvenile and adult fish during floods. It can be created by installing debris collectors (such as rows of pilings) or mature, woody vegetation on the upper bank and in the floodplain.

When armored revetments are put in place, they create smooth banks that limit floodplain and bank roughness features. Debris collectors and vegetation create current breaks, which provide flood refuge, juvenile rearing habitat and holding cover for adult fish. Planting trees in the riparian buffer creates refuges and is also effective in roughening the channel. Vegetating rock armor and/or building a terrace into the revetment above the ordinary high-water line will also provide some mitigation. Large-woody-debris structures anchored into rock armor above the ordinary high-water line will provide some refuge as well.

Sediment and Debris Sources

Sediment and woody-debris sources are lost if a channel is fixed in place and not allowed to gradually erode and recruit material.

Trees removed from rights-of-way or streambanks for safety purposes and debris removed from reservoirs should be relocated or placed within the stream channel so they can function as habitat. Artificial feeder banks can be developed for a reach to mitigate the cumulative loss of sediment sources due to bank protection. Gravel bars and gravel bluffs have proven effective when constructed and maintained as gravel sources downstream of reservoirs.

Off-Channel Rearing Habitat

Off-channel rearing habitat, including wall-based channels, flood swales, side channels and floodplain spring channels, is often a limiting factor to salmonid productivity in channelized rivers. Common functions of these habitats include spawning, rearing and holding habitats, and refuge for adults and juveniles of many fish species.

In-kind mitigation should be required for any project that eliminates off-channel habitat or reduces the opportunity for the creation of off-channel habitat in the future. If no on-site opportunities for habitat restoration exist, or land ownership precludes their use, the project owner should contribute to the creation of such habitat elsewhere. If land is not available for off-channel work, then an off-site restoration effort on other river stretches may fulfill this habitat need.

Lost-opportunity impacts can be avoided by selecting a bank-protection technique that is deformable and provides for natural rates of lateral erosion, such as a log or vegetated bank toe or debris jam to restore the channel processes to their natural rate. Construction or restoration of off-channel habitats and providing an artificial supply of debris and sediment can also help mitigate the loss. However, mitigation must be provided in perpetuity and a long-term commitment is required for mitigation which precludes natural fluvial processes. Off-channel habitats are a logical application of mitigation banking.

Funding for off-channel habitat mitigation can be accomplished by consolidating the impact fees of multiple small projects. Diking districts can combine their funding into projects of reasonable and effective scale, distributing the cost among off-channel beneficiaries through their taxing structure. Fees can include administrative costs, and cost matches from other programs should be encouraged.

DURATION AND EXTENT OF IMPACTS

It is important to understand the specific potential impacts that bank-protection treatments have on stream function and fish habitat. Without this level of understanding, treatments may be selected that have unintended but severe consequences to the ability of the stream or river to support life. There are five types of impacts associated with bank-protection projects:

1. construction activity impacts;
2. direct loss of habitat;
3. channel response impacts, both on- and off-site;
4. lost opportunity; and
5. increased risk by perception of protection.

Construction-Activity Impacts

Construction-activity impacts to the riparian corridor and the channel can often be avoided. Construction activity that causes impacts is often short-term, though impacts to a mature riparian area may take decades or centuries to recover. Short-term impacts can usually be addressed and minimized by construction timing and sequencing, water-quality protection techniques, work-site isolation, re-vegetation, and erosion- and sediment-control practices. The impact that heavy equipment has on a streambank construction site is often significant, depending upon the type of equipment used, care of equipment operation, site-access design, project sequencing and the care equipment operators take in conducting their work. Long-term construction impacts are caused when riparian vegetation is removed along the bank or in the water, when soil is compacted, when surface drainage is changed or when heavy equipment is repeatedly used for maintenance.

Impacts include tree removal, erosion of bank and disturbed soils, release of sediment to the water, road construction, soil compaction, channel and bank reconfiguration and debris removal. Construction impacts must be mitigated at the time of project construction. Mitigation is usually covered with standard Hydraulic Project Approval provisions that usually include construction timing, project sequencing, water-quality protection, equipment type and operating procedures, revegetation, and best-management practices for erosion and sediment control.

Direct Habitat Loss

Direct habitat loss is the immediate and permanent alteration of habitat by a project. It is also the lost ability of a site to naturally restore the habitat functions associated with it. Direct loss of habitat may include loss of cover, spawning beds, individual pieces or accumulations of debris, riparian function and alterations to the channel that decrease the complexity or diversity of habitat. It may also include interference with the hyporheic function of the stream. Treatments that prevent a channel from naturally restoring itself include placement of permanent structures that eliminate habitat-forming dynamics such as pool scour, debris accumulations, and overhanging trees and/or debris.

Channel Response Impacts: On Site, Off Site

One of the most unpredictable impacts of bank-protection projects is their off-site effect on stream function upstream or downstream. Channel-response impacts include effects of redirecting flow, modifying energy dissipation through the project reach and/or disrupting natural meander migration patterns. The impacts are to the adjacent channel upstream and downstream of the project. Impacts can be positive, depending upon the mechanisms and causes of failure. However, they can also negatively impact not only fish habitat, but also property and public safety.

Indicators of potential off-site impacts include changes in flow alignment, energy or sediment delivered past a project site or changes in backwater conditions upstream and, therefore, a change in sediment deposition and channel stability and hyporheic function. These changes may not be obvious or immediate. They are created by the influence of the project on the channel over time and during future floods. Channel confinement, constriction, smoothing or roughening, alignment changes and channel shortening may jeopardize adjacent habitat and properties. Indirect, off-site impacts are the most difficult to

Channel-response impacts include redirecting flow, modifying energy dissipation through the project reach and/or disrupting natural meander migration patterns.

predict and mitigate and may take years before they are discernable or they may occur during the next flood event. Once they occur, however, they are typically persistent and create even more channel instabilities. Despite the difficulty of identifying the potential off-site consequences of different bank-protection techniques, an attempt must be made during the reach analysis and design phase.

Mitigation should be conducted concurrently with the bank-protection project. Mitigation for off-site impacts avoids the indirect loss of habitat in adjacent reaches as a result of a bank-protection project. The best mitigation, again, is to avoid the impacts altogether by not constructing the bank protection or by selection of an appropriate treatment that avoids the impact.

Mitigation for upstream and downstream channel-stability impacts can include acquisitions, protective covenants, conservation easements and restoration of natural banklines in adjacent reaches to minimize impacts from the project. While there is an equity issue in asking for mitigation of lost opportunity when the perpetrator of the problem (e.g. upstream land owner) was not required to mitigate for their previous actions, that issue does not relieve the responsibility of project mitigation.

Lost-Opportunity Impacts

Lost-opportunity impacts result from projects that adversely alter natural fluvial processes important to the ongoing creation of fish and wildlife habitats. Habitat diversity for a variety of life-cycle stages of fish and wildlife depends on natural rates of lateral channel erosion.

Habitat diversity for a variety of life-cycle stages of fish and wildlife depends on natural rates of lateral channel erosion.

Debris, sediment sources and sorting, habitat complexity, pools, and side channels are examples of habitat components that depend on erosion. Preventing a channel from naturally migrating across the floodplain usually eliminates sources of woody debris, sediment and side channels; these losses are defined as "lost opportunities." Natural channels evolve over time and migrate across their floodplains. When a channel naturally moves to a new alignment, it leaves behind vital habitat, such as floodplain sloughs and side channels. Those habitats have a finite productive longevity, some likely less than 20 years. If the natural fluvial processes of a stream are restricted or interrupted, these side-channel habitats will diminish in productivity and will not be replaced. These habitats cannot be mitigated by the design of a project. They are lost when a channel is fixed in a specific location, regardless of the bank-protection technique. Lost-opportunity impacts last as long as channel migration is halted (see *Figure 4-1* for an example of lost-opportunity assessment).

Mitigation for lost opportunity requires mitigation for channel processes affected by a project. In some situations, off-site mitigation may be the only option. It may be more efficient and cost-effective for small landowners in a watershed to consolidate their mitigation work.

Mitigation for lost opportunity requires mitigation for channel processes affected by a project.

Though it is recognized that, to achieve no loss of habitat, lost-opportunity impacts must be mitigated, there are currently no tools for universal and consistent application of the concept. Tools are needed to assess the lost opportunities in order to ensure that appropriate mitigation is provided. The concept of mitigation for lost opportunity should only be applied when consistent, acceptable, assessment methods or specific site information are available.

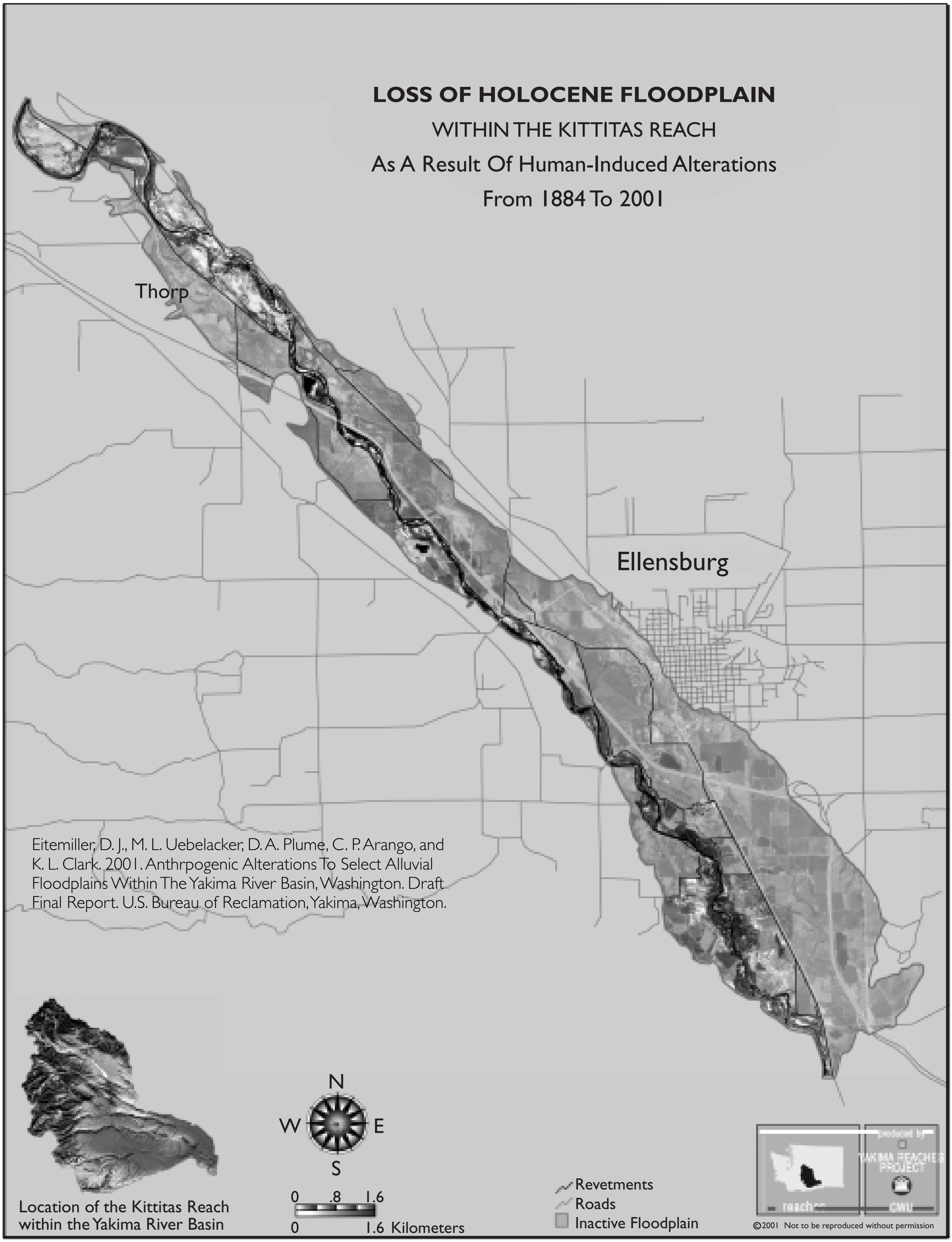

Figure 4-1. An example of lost-opportunity assessment, in this case, loss of floodplain.

Management of Lost-Opportunity Impacts

Lost-opportunity impacts should be recognized early in the scoping of all projects, especially those projects that are large and complex. Recognizing and mitigating lost opportunities within the context of an entire stream reach is far more efficient, practicable and preferable than focusing only on individual projects. This approach is most feasible for property owners and public agencies that have access to extensive lands along the stream basin or in areas with cooperative planning among landowners.

The process of identifying lost opportunities and determining their mitigation includes conducting a corridor analysis, studying the overlay of existing infrastructure, studying projected land use, and identifying ecological characteristics that might be affected by the interaction of the river and the proposed work (*see Figure 4-1*). An alternatives analysis could then identify treatment options for the entire corridor. This brings additional partners into the assessment process such as neighboring property owners and other interests in the basin. It allows efficient use of combined resources and allows a proactive approach to stream corridor management when designing both projects and mitigation.

Different protocols might be appropriate for assessing different scales and levels of lost-opportunity analysis. For example an analysis using typical channel characteristics might be used in the planning phase of a large project. That analysis might be expanded and/or verified as part of the project development through a geomorphic analysis of the reach and site.

Recognizing Lost-Opportunity Impacts

There are three key elements to identifying lost opportunity:

1. expected duration of impact,
2. geomorphic/riparian basis, and
3. the action/treatment being considered.

Expected Duration of Impact

The expected duration of the impact establishes the timeframe through which mitigation must be considered. Channel processes by definition are time dependent; over time, a channel may continue to move and create habitat. Lost-opportunity impacts, therefore, should also be considered continual and changing; cumulative impacts may continue to occur as long as a treatment is present.

Impacts of a project might also last beyond the project's existence. If a bank-protection treatment is removed, its impact of altering the channel form, shape, slope and location may continue until the channel regains its natural character and process. It is important to pay close attention to the concept of "life of project" discussed later in this section.

Geomorphic/Riparian Basis

The geomorphic/riparian basis of lost opportunity is the physical setting and the natural processes that might be affected by a project.

There are four parameters in the geomorphic/riparian basis:

1. channel and floodplain characteristics;
2. current, natural and expected rates of erosion;
3. extent of area affected; and
4. opportunities affected.

The character of a channel in which work is proposed will help determine the impacts expected. For example, stabilizing a channel in a ravine that migrates very little laterally over the life of the project may result in little or no lost opportunity. On the other hand, stabilizing a channel that once meandered freely across an alluvial floodplain may present substantial lost opportunities. Meandering reaches produce valuable oxbows and cutoff channels, and avulsing reaches create beneficial side channels.

The channel-migration zone, relative to the expected life of the protection treatment, generally defines the aerial extent of the actual or potential impact, though additional hyporheic zone impacts may extend even further.

The channel-migration zone, relative to the expected life of the protection treatment, generally defines the aerial extent of the actual or potential impact.

Lost-opportunity analysis should include time averaging to identify issues such as habitat types, diversity and presence, debris and sediment recruitment rates, successional stages and growth rates of riparian vegetation, life cycles of various fish and wildlife, water quality, and channel processes. It should also identify lost opportunities as if the floodplain were in a natural condition. "Natural condition" is described in terms of presence of side channels and forests as well as in terms of rate and pattern of erosion and channel migration. This is because a floodplain would be less developed if it were not for the presence of bank-protection work. In other words, clearing and developing the floodplain is at least partially the result of bank-protection work rather than a pre-existing condition. It also provides a simple and common baseline for assessing the condition of the watershed, hydrology and sediment inputs that might affect the site.

A dichotomous key or flow chart such as the example below can be used to analyze the potential for lost-opportunity impacts: (see *Figure 4-2*)

Action/Treatment Being Considered:

The third element of lost-opportunity analysis is the design and scale of the project or action being considered. A project that is designed to be deformable, so that the channel can eventually return to a natural rate of erosion, will likely have very different lost-opportunity impacts than a project that rigidly and permanently fixes a migrating channel in place.

Bank-protection treatments installed in inappropriate locations more often than not create the need for further bank protection and ultimately result in loss of opportunities for the entire reach. Those responsible for initiating the first bank protection along a reach may be liable for impacts to the entire reach. On the other hand, whoever

What floodplain and channel processes might be impacted by the project?

- Are there remnant side channels present or anticipated?
  - ❑ Yes. Consider lost opportunity of off-channel rearing and/or spawning habitat.
  - ❑ No. Further lost-opportunity assessment is needed.
- Could the riparian area to be affected by the project be a source of debris?
  - ❑ Yes. Consider lost opportunity of debris source.
  - ❑ No. Further lost-opportunity assessment is needed.
- Could the riparian area be a natural source of sediment that could be important to spawning habitat function?
  - ❑ Yes. Consider lost opportunity of debris source.
  - ❑ No. Further lost-opportunity assessment is needed.

For all "yes" conditions, consider the extent of lateral migration relative to the expected life of the project, and the frequency and nature of expected off-channel habitat, debris and sediment sources that contribute to the lost opportunity.

Figure 4-2. A dichotomous key used to analyze the potential for lost-opportunity impacts.

installs bank protection along the last remaining unarmored section of a river reach might be considered the victim of previous actions and may therefore be held to a different standard of mitigation liability. They may be held liable for no more than the direct impact at the site of their bank-protection treatment.

Impacts of Perceived Protection

Bank-protection treatments often create a false perception that properties adjacent to the channel are now safe from flooding or erosion. This false sense of security can buoy confidence to increase land development, which in turn may increase the risk associated with future bank erosion. Special caution needs to be taken in land-development planning and streambank management to account for such a risk.

MITIGATION

This section describes appropriate fish-habitat mitigation measures. The following concepts are intended specifically for bank-protection projects but might also be appropriate for other types of projects.

Bank erosion is a natural process that is often accelerated by human influences. Mature, overhanging trees, shrubs and exposed roots in a gradually eroding bank are important for creating and maintaining habitats. The recruitment of debris and gravel also perform vital habitat- and erosion-protection functions. Although a bank-protection project may control the introduction of excessive sediment, armoring a streambank stops ongoing development of a healthy and dynamic riparian ecosystem. The habitat-creation benefits of debris from an eroding bank can be more important to biological processes than the reduction of the sediment source. Bank-protection projects may preclude the possibility of restoration of the natural bank and riparian functions.

The first priority of mitigation is to avoid impacts to habitat. Where all impacts are avoided, mitigation is complete. On the other hand, where a bank-protection project causes impacts to habitat, compensatory mitigation (rectifying, compensating or correcting) will be required.

The first priority of mitigation is to avoid impacts to habitat.

Legal and Policy Basis of Mitigation

The required level of mitigation is described in Washington Department of Fish and Wildlife regulations, Washington Administrative Code (WAC) 220-110-050: *Bank protection projects shall incorporate mitigation measures as necessary to achieve no net loss of productive capacity of fish and shellfish habitat.* Mitigation is defined in the WAC as actions taken *to avoid or compensate for impacts to fish life resulting from the proposed project activity.*

The Washington State departments of Ecology, Fish and Wildlife, and Transportation, as well as Tribes in Washington have worked together to develop policy guidance for mitigation alternatives within a watershed context. This guidance has been compiled in a document called *Alternative Mitigation Policy Guidance - Interagency Implementation Agreement (AMPG-IIA),* published February, 2000. Additionally, the Washington Department of Fish and Wildlife has developed a mitigation policy (POL-M5002, Jan. 18, 1999).

The concepts presented in this section are intended to provide further explanation and detail to existing mitigation policies and regulations. If there is any discrepancy between these policies and regulations and the information related in the *Integrated Streambank Protection Guidelines,* the policies and regulations prevail.

The AMPG-IIA defines mitigation as:

"...actions that shall be required or recommended to avoid or compensate for impacts to fish and other aquatic resources from a proposed project. Mitigation shall be considered and implemented, where feasible, in the following sequential order of preference. Use of the word 'mitigation' is comprehensive of all three parts of the following sequence and is not to be considered as synonymous with compensatory mitigation.

Complete mitigation is achieved when these mitigation elements ensure no net loss of ecological functions, wildlife, fish and aquatic resources. Avoiding the Impact altogether by not taking a certain action or parts of an action. Minimizing the Impacts by limiting the degree or magnitude of the action and its implementation. Compensating for the Impact by replacing and providing substitute resources or environments through creation, restoration, enhancement or preservation of similar or appropriate resource areas."

This sequence of mitigation decision making is the basic foundation of the bank-protection design process described in the text and matrices of Chapter 5.

The most elegant bank-protection solution mitigates by avoiding habitat impacts and, in fact, restores or enhances habitat.

Mitigation success is evaluated based on the *biological productive capacity and opportunities reasonably expected of a site in the future* (Washington Department of Fish and Wildlife Mitigation Policy, 1999). This statement recognizes that an eroding channel is not static; in the process of erosion, habitats are formed. Likewise, mitigation measures should be allowed to evolve as the channel evolves.

The stream's biological capacity and habitat potential should be incorporated into the project design. An understanding of the stream's biological characteristics and the effects of a bank-protection project are essential in order to assess the habitat impacts and habitat potential of a site and reach. A detailed discussion of these needs for various species of fish and wildlife and at various life stages is provided in Appendix G. An annotated bibliography, prepared by the U.S. Army Corps of Engineers, is also included in Appendix K, *Literature Review of Revetments*. It describes biological effects due to stream channelization and bank stabilization.

The most elegant bank-protection solution mitigates by avoiding habitat impacts and, in fact, restores or enhances habitat.

Avoiding the Impact

If a project requires a federal permit from the Corps of Engineers, the Federal Memorandum of Agreement called, "Memorandum of Agreement between the Environmental Protection Agency and the Department of the Army Concerning the Determination of Mitigation under the Clean Water Act, Section 404(b)(1) Guidelines," will apply. The memorandum states "*the determination of avoidance requirements will not be based on characteristics of the proposed projects such as need, societal value, or the nature or investment objectives of the project's sponsor*." It is important to note that the Federal Clean Water Act and Memorandum of Agreement require that the "*least environmentally damaging and practicable alternative (as determined by the Corps and EPA) may be permitted.*"

Avoidance of impact requires relocation of the proposed project if:

- alternatives are available for nonwater-dependent activities that do not involve special aquatic sites, or
- alternatives are available that have less adverse impacts on the aquatic environment than the proposed impact site (AMPG-IIA).

When applying for state permits, a project proposal should have all aquatic resources delineated, and project proponents should examine avoidance alternatives (AMPG-IIA).

Minimizing the Impact

Minimization refers to actions taken on a site to reduce impacts that will occur to aquatic resources. An applicant must first demonstrate to the permitting agencies that complete avoidance of impacts is not practicable.

Compensating for the Impact

For those impacts that are determined to be unavoidable, The Washington State Department of Ecology poses seven questions when planning compensation of unavoidable impacts (AMPG-IIA):

1. What are the species, habitat types or functions being adversely affected?
2. Is replacement or reintroduction of the species, habitat type or functions vital to the health of the watershed? If so, do they need to be replaced on site to maintain the necessary functions?
3. If it is determined that on-site, in-kind replacement is not necessary, are there higher-priority species, habitat types or functions that are critical or limiting within the watershed?
4. If both on- and off-site compensatory mitigation is available, will the species, habitat type or functions proposed as off-site compensatory mitigation provide greater value to the health of the watershed than those proposed as on-site?
5. How will the proposed compensatory mitigation maintain, protect or enhance impaired functions or the critical or limiting functions of a watershed?
6. Will the proposed compensatory mitigation have a high likelihood of success?
7. Will the proposed compensatory mitigation be sustainable in consideration of expected future land uses?

For those impacts that are determined to be unavoidable, the Washington Department of Fish and Wildlife mitigation policy states that priorities for compensatory mitigation location and type, in the following sequential order of preference, are:

- on-site, in-kind;
- off-site, in-kind;
- on-site, out-of-kind; and
- off-site, out-of-kind;

The department's preference for sequencing alternatives does not prohibit project proponents from initiating off-site and/or out-of-kind actions if they are better than on-site, in-kind actions. Off-site and/or out-of-kind compensatory-mitigation activities might be appropriate for specific mitigation targets as described later in this chapter under *Compensatory Mitigation Target.*

Mitigation Concepts for No Loss-of-Habitat Functions

The following concepts are essential to avoiding loss-of-habitat functions and values when compensatory mitigation is required. The concepts in this section relate to compensatory mitigation; they are about *rectifying, compensating or repairing* habitat impacted by a project. The concepts described here have common requirements related to habitat function, performance standards, monitoring and adaptive management.

Mitigation for the Duration of the Impact

To avoid loss-of-habitat functions and values, impacts of a project must be mitigated for as long as they persist. Many habitat features have finite lives, regardless of whether they are naturally occurring or constructed as mitigation. Some specific mitigation features may not be expected to persist as long as the bank-protection project that they are intended to mitigate. A habitat feature may fail structurally or functionally. Ideally, mitigation should be "deformable," or adaptive, just as the natural channel is. If compensatory mitigation fails or deteriorates in function, it should be modified, replaced or supplemented unless the failure is due to unanticipated watershed conditions. If full compensatory mitigation is provided and it continues to succeed, no additional mitigation is needed. If the natural character and function of the river or stream return to an impacted site, mitigation is complete for those elements of the impact.

To avoid loss-of-habitat functions and values, impacts of a project must be mitigated for as long as they persist.

Mitigation plans should include clear mitigation objectives and project-impact and mitigation-monitoring procedures, as well as a process by which mitigation can modified, replaced or supplemented as necessary. Monitoring plans should evaluate the success of mitigation and its duration, as well as performance standards and adaptive measures for correcting inadequacies in the mitigation.

For example, a piece of woody debris placed as a mitigation feature may over time either be buried in sediment as the channel migrates away from it, or it may be washed downstream and become stranded on a gravel bar. In either case, is the mitigation still effective? The essential question is whether the presence of the bank-protection project precludes the habitat from recovering and whether or not the debris performed as intended. The buried piece of debris will still be in place and be effective when and if the river moves back to it. Whether the mitigation for the displaced piece of debris is effective or not depends on its initial purpose and as defined by the mitigation plan. If it had been placed to supply the channel with debris that is precluded by the bank protection, then its specific location is not essential. In fact, it may be more appropriate in its relocated position. If, on the other hand, the displaced debris was intended as mitigation for the on-site loss of overhanging structure and complexity in the bank, then its function may have failed. Clear objectives of mitigation activities are essential to the determination of success or failure of the mitigation.

Reopening Mitigation for Life of the Project

The success and effectiveness of mitigation measures should be evaluated throughout the design life of the project. Since mitigation is normally applied for the expected life of a project, the mitigation should be "reopened" for consideration and revision if the life of the project is extended. In such a case, mitigation is evaluated and reconsidered almost as if it were a new bank-protection project.

For the purpose of these guidelines, the "life of the project" is concluded when the impact, frequency and scale of maintenance, repair or reconstruction activities exceed a predetermined threshold. This threshold can be exceeded even though the project itself may still functional satisfactorily for its primary objective.

This means that repair or reconstruction that exceed a threshold, or replacement of the structure, will reopen mitigation considerations. This does not mean that additional mitigation will be required for impacts that occurred earlier in the life of the bank-protection project. The assumption is that mitigation was provided for the previous impacts caused by the existing structure. It does mean that mitigation may be required for impacts of the project continuing into the future.

The mitigation reopener determines whether the initial mitigation for the presence of the project and directly related development is still effective for the proposed extended life of the project. If the mitigation is not adequate, complete mitigation should be a requisite of the current activity. It's often not realistic or practical to get full mitigation for the presence of a facility before repairs must be made to protect life, property and infrastructure.

The following activities would not normally trigger a mitigation reopener:

- activities that have insignificant impact over time;
- normal maintenance and repair, defined as structural activity that returns the facility to as-built condition as long as there is no change in course, current or cross section; and
- repair of damage due to watershed conditions that were reasonably unanticipated.

There are two key reasons for reopening mitigation:

1. project reconstruction, and
2. chronic maintenance or repair.

Major project reconstruction and chronic repair of a project are actions that extend the duration of a project. They are also logical points at which to reopen the mitigation plan in order to re-evaluate and/or revise it as appropriate. Reopening the mitigation plan determines whether the initial mitigation for the presence of the project is still effective for the extended life of the project. If the mitigation is not adequate, complete mitigation should be a requisite of the current activity. This step isn't intended to evaluate the adequacy of the mitigation for past impacts; it considers the adequacy of mitigation only for the future extended life of the project.

There currently is no detailed protocol for universal and consistent application of the concepts described here as "life of the project" and "mitigation reopener." Development of specific thresholds as described in this section and a clear expectation of the action expected at the end of the life of the project are needed. The concept of mitigation for the duration of the impact should only be applied at this time where consistent, acceptable methods are available. There are habitat-assessment tools that can help estimate the duration of impacts and the longevity of mitigation function. Specific monitoring protocols are described and evaluated in *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia,* published by the Washington Department of Fish and Wildlife.[1]

Three project timeframes should be included as tools and methods are developed:

1. existing projects,
2. projects in the planning and development pipelines, and
3. new projects.

Design criteria for new projects are generally more conservative and should include mitigation for duration of the project. It is essential that designers of new projects incorporate a realistic and thorough environmental analysis into the early cost/benefit analysis.

Mitigation for Project Reconstruction

Project reconstruction can be a cause for reopening mitigation. What qualifies as project reconstruction is a matter of scale of both the project and the impact of its presence.

The following examples define reconstruction that would cause a mitigation reopener:

- a repair or modification that measurably confines or constricts the channel beyond the original design or changes the course, current or cross section of the channel beyond the original design;
- work that extends the design life of the project, including reconstruction of the project;
- repair work or structural replacement that is required as a result of damage from a flood that is greater than the project was designed to withstand. Hydraulic structures are commonly designed to withstand a specific flood recurrence level. They are not expected to be fully functional or to survive at flood events greater than the design flow. Such repair and/or replacement work can be considered to be a new project.; and
- work that exceeds a specific design or maintenance threshold or criteria for the type of facility. For example, a current standard for new bridge piers is that they will not require scour protection in their lifetime. If scour protection becomes necessary, the design life of the bridge would be over, and mitigation would be reopened.

Increased peak events, increased sediment loads due to upstream land uses or hydraulic influences of nearby projects may affect the life of a project. The concept of *Integrated Streambank Protection* requires that future watershed conditions be considered in any project design. Project mitigation should consider the presence of the project in current and future channel and watershed conditions. If future conditions were predictable, those conditions should not lessen the mitigation responsibility or prevent the mitigation reopener. Anticipation of watershed conditions more than about 20 years into the future is not likely practical. A project that does not define and design for watershed conditions reasonably expected to occur in the future should not be exempt from mitigation reopener triggered of damage due to changes in watershed conditions. Anticipated future conditions must be clearly defined in mitigation plans.

It is recognized that there are both expected and anticipated conditions, and there are unanticipated and unpredictable future conditions. The further into the future that conditions are projected, the less certain the predictions are. Projects would only be expected to design for anticipated and expected conditions that are likely to occur within 20 years. City and county planning departments can assist in providing projections for future conditions, based on expected rates of growth and development. In addition, the Washington State Department of Natural Resources and private timber companies have long-term timber harvest projections, and many are now committed to 50-year Habitat Conservation Plans, which can be used to determine expected land-use actions.

Mitigation for Chronic Maintenance or Repair

Some level of normal maintenance and repair activity is expected during the life of most bank-protection projects and, except for the operational impacts of maintenance activities, should be mitigated as part of the initial project. A "chronic" level of repair is defined as that which exceeds expectations of frequency and magnitude as identified in the initial project and may indicate that the life of the project is exceeded. Mitigation should be considered in this case as if it were a new project.

The following activities should *not* trigger a mitigation reopener as chronic activities:

- normal maintenance and repair, defined as structural activity based on a normal frequency of work for that type of facility;
- normal maintenance and repair, defined as structural activity that returns the facility to as-built condition, as long as there is no change in course, current or cross section; or
- damage from large flood events, even if they are frequent.

Some projects may have maintenance plans that specifically define normal maintenance expectations. Maintenance plans encourage good design.

When the frequency of an activity exceeds an acceptable threshold established for a specific types of facility, it should be considered to be chronic, triggering a mitigation reopener. Tracking maintenance and repair activities at facilities is helpful in defining which maintenance activities are chronic. Chronic levels of some types of activities should be defined by reach rather than specific location. For example, a road that encroaches on a channel migration zone for some distance may be threatened by bank erosion at multiple individual locations. The activity that might be chronic in that case would be the bank-protection activity along a distance of the road and include multiple individual erosion sites.

The Washington State departments of Ecology, Fish and Wildlife, and Transportation are jointly developing thresholds and examples to help define chronic activity.

In addition to these options, large-property owners or public agencies might maintain a chronic repair list and a rotating budget to resolve projects on the list. Chronic repair projects would automatically be added to the list. Additional project tracking will be needed to maintain chronic repair lists. Such lists might also include chronic needs for maintenance of habitat mitigation features. Mitigation maintenance would increase the importance of resolving a chronic problem.

Probability of Mitigation Success and Delayed Mitigation

Like bank-protection projects, mitigation work has inherent uncertainties of success. Some portion of compensatory mitigation projects will fail structurally; others will fail in function. Success or failure depends partially on the quality of design and construction, the ability of the design to accommodate fluvial processes and the type and extent of mitigation required. Many mitigation activities also have a delay until they are fully functional or may function with varying degrees of success over time. For instance, vegetation planted as mitigation for loss of cover and food source habitats take years to develop and become fully functional. This time lag results in an interim loss of habitat function. A stream may migrate to or from the mitigation site, resulting in varying degrees of performance for a specific function.

There are several methods of dealing with the uncertainty of success and delay of mitigation function:

- mitigation banking,
- monitoring and corrective action,
- mitigation ratios, and
- experimental mitigation techniques.

Mitigation Banking

In some situations, mitigation is required prior to project construction to ensure its completeness. Successful mitigation banking eliminates reduces mitigation risk and delay and might be appropriate to adequately mitigate project-related impacts.

Sometimes, the mitigation habitat benefit achieved is actually more than 100 percent. In other instances, it is impossible to adequately mitigate a project. When mitigation exceeds success requirements, the project may receive credits for mitigation and would be considered mitigation banking.

Monitoring and Corrective Action

It will be necessary to monitor the success of mitigation and take appropriate corrective action to ensure its success. Monitoring requirements may be more prevalent in the future under federal consultation through the Endangered Species Act. More is included about monitoring in the section titled, "Maintenance, Adaptive Management and Monitoring" of this chapter. Specific monitoring protocols are described and evaluated in *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/ Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia*, published by the Washington Department of Fish and Wildlife.[1]

Mitigation Ratios

Another way to deal with uncertainties and time lag is by using mitigation ratios. A project proponent can provide compensatory mitigation at a rate greater than the anticipated impact of a project with the expectation that a portion of the mitigation may not be functional. For example, twice as much habitat might be constructed as mitigation replacement for the quantity of habitat lost by a project with the expectation that half of the new habitat may fail either structurally or functionally. It is not possible to quantify appropriate ratios for every type of mitigation activity. Mitigation ratios are applied to wetland mitigation projects and are based on the proportion of functional success of previous wetland construction projects. Applied ratios need to start conservatively. Their accuracy will be more assured if restoration monitoring is increased and if there is a high motivation for success. The ratio can also vary with the construction technique and care of construction, monitoring and follow-up work.

Mitigation ratio considerations for a specific impact might include the following questions:

- What is the level of certainty of success of the mitigation feature for the duration of the impact?
- Is the proposed mitigation technique proven to be successful or is it experimental?
- What is the level of certainty that the mitigation feature will be constructed as intended?
- Is the mitigation feature self-maintaining, and what is the certainty of follow-up or corrective actions necessary to maintain full mitigation function?
- What is the time lag between the initial project impact and the full maturity of the mitigation?
- Will the mitigation function variably over its life?
- What is the importance of the impacted habitat to the fish and wildlife that depend on the mitigation? Is the habitat unique or does it limit productive capacity?
- What is the status of impacted fish or wildlife?
- What is the mitigation target of the project (see *Compensatory Mitigation Target* later in this chapter).

It is important to understand that none of the concepts in this section constitute habitat restoration or enhancement; they are meant to provide full and complete project mitigation. In other words, the intent of mitigation banking and ratios is to prevent loss of existing habitat, rather than to improve habitat beyond original condition. The section in this chapter on *Compensatory Mitigation Target* may lead to mitigation objectives of habitat restoration.

Experimental Mitigation Techniques

Some habitat mitigation measures, including some described in this document, are considered experimental. Their experimental nature might either be in their basic concepts or in their specific applications. Either the structure or its habitat function may be considered experimental. Experimental measures are encouraged as long as the risk of structural and mitigation functional failure are appropriately addressed. These risks are addressed by applying experimental mitigation to low-risk projects (e.g., retrofits, restoration, low-resource-value sites, small projects) and by providing guarantees of mitigation success (e.g., experimental plan, financial guarantee). The resource regulatory agencies have final approval for application of experimental measures.

The Washington Department of Fish and Wildlife Mitigation Policy requires that if experimental techniques are used, they must be constructed and proven successful before they can be counted as mitigation. This essentially says that experimental mitigation techniques can only be used in mitigation banking situations.

If an experimental mitigation technique is applied before it is proven, an experimental plan must be approved by appropriate resource agencies to eliminate the risk of partial or complete failure. Such a plan must include:

- a *contingency plan and a commitment to upgrade, replace, or supplement the mitigation* (if it fails in function or structure). Specific contingency mitigation and a commitment of funding and schedule must be described. The plan must also include mitigation for the time lag in case a mitigation technique fails in function. The commitment must be legally binding such as with a bond or contract;
- a *study plan, which should include specific experimental goals and objectives* and clear success criteria that will be used to measure success of the mitigation and further the development or acceptance of the concept. The study plan should include specific performance standards, contingencies, experimental process and schedule to address expectations and actions to address failure;
- a *commitment to a monitoring plan*, including baseline information, reporting and peer critique of findings; and
- a *closure to the experiment.* At the conclusion of the study, the mitigation should either be accepted or not accepted as adequate by regulatory agencies agreeing to the experimental application. The contingency plan is activated for projects that do not have complete and accepted mitigation.

Before a technique is accepted as a standard method and specific design details are provided, a history of monitoring experimental installations is needed. In the meantime, details of current design principles of some experimental technique are provided in these guidelines. Design and mitigation recommendations are likely to change as new observations and data become available.

Integrating Mitigation into Bank-Protection Projects

As described earlier, compensatory mitigation is required when a project causes damage or risks cauding damage to or loss of habitat or the opportunity for habitat to form is impaired. Compensatory mitigation involves the restoration, repair or replacement of habitat that has been damaged. It also is called for when the opportunity for habitat to be created is lost due to project activities.

Compensatory Mitigation Target

A compensatory mitigation target is the condition or measurable level of performance that must be achieved as a result of doing the mitigation. Such targets must be provided for projects that call for compensatory mitigation. Compensatory mitigation targets are to be set and implemented only after the avoidance and minimization mitigation approaches have been exhausted.

A compensatory mitigation target is the condition or measurable level of performance that must be achieved as a result of doing the mitigation.

There are four general targets for compensatory mitigation:

1. improvement of factors within the watershed that limit fish and/or wildlife production,
2. restoration of properly functioning habitat,
3. replication of current natural conditions, or
4. restoration or replacement of preproject conditions.

The sequence of the list reflects a decreasing extent of analysis and needed information.

Mitigation targets vary in scope from an entire watershed down to specific site conditions. Mitigation targets might also vary depending upon the objectives and authorities of the agencies that issue the permits to work in stream channels. The ability to take action based on concepts like channel processes, lost opportunity and potential productive capacity differ depending on the mitigation target applied to a project.

Improvement of limiting Factors

The Revised Code of Washington (RCW 75.46) defines limiting factors as "conditions that limit the ability of habitat to fully sustain populations of salmon." Taking steps to reduce the effects those limiting factors have on habitat can increase the functionality and restore the productivity of a reach or basin. Considering limiting factors in mitigation design allows innovative mitigation that can affect productive capacity. Enhancement of limiting factors would increase the function that is limiting to productive capacity of a reach or a basin.

The Washington State Conservation Commission is doing formal analyses of limiting factors for salmon in Washington watersheds.[2] Completed analyses are available for a small number of watersheds. Limiting factors are often identified as a suite of factors rather than a single factor that limits productivity. Limiting-factor analyses are key to a successful mitigation design but not all that is needed. Limiting factors might change over time as conditions change and new information is gained.

There are several ways limiting factors might be applied to mitigation planning, including directing mitigation at the limiting factor regardless of the type of habitat affected by a project. For example, impacted spawning habitat might be compensated through buying water rights that will result in lower water temperatures. Alternatively, mitigation for impacts to limiting factors might be at a ratio greater than what is applied to factors that are not limiting since the risk to productive capacity is greater. Limiting factors tends to focus on a single genus or species instead of broader ecological values and multiple species. Even if just one species or species habitat is targeted, impacts to other species should be addressed as well. Mitigation that supports natural channel processes is by far preferable to mitigation that forces a stream channel into an unnatural pattern or creates artificial conditions.

The implications of off-site mitigation should also be understood. There is some risk of not mitigating for specific habitat lost until eventually that habitat becomes a limiting factor itself. Any compensatory mitigation done off-site has the likelihood of impacting habitat and must also be part of the project mitigation requirement.

This type of mitigation might be off-site and/or out-of-kind. This target works best in the following circumstances, adopted from the Alternative Mitigation Policy Guidance - Interagency Implementation Agreement (AMPG-IIA):

- limiting factors are understood either by formal or informal analyses,
- greater limiting or critical functions can be achieved off-site than is possible on-site,
- adversely affected functions are of low quality,
- there are no reasonable on-site opportunities,
- on-site opportunities do not have a high likelihood of success due to development pressures or adjacent impacts to the compensatory mitigation area, or
- off-site enhancement and restoration opportunities have a higher likelihood of success than on-site options.

Mitigating limiting factors requires a way of valuing one habitat type relative to another. What is the value (habitat value as well as cost) of a unit of nonlimiting habitat (e.g., spawning habitat) compared to the value of a unit of limiting habitat (e.g., water temperature) that is built as mitigation? Providing additional rearing habitat that currently limits productive capacity might compensate impacted spawning habitat. It also requires specific methods of quantifying existing habitat. Both of these issues are explained later in this chapter, in the section, *Quantifying Mitigation Needs*.

Properly Functioning Habitat

An analysis of properly functioning habitat focuses on the specific reach or site affected by a project. This concept is included in these guidelines because the National Marine Fisheries Service suggests using a similar process in its assessment of whether a project will "take" (contribute to elimination of) an endangered species.[3] The process evaluates each component of the existing habitat compared to numerical standards that define the habitat as functional or nonfunctional. It is expected that a project will not have an impact if it doesn't move the characteristic out of the preferred range. A project design is said to be preferred when it moves a characteristic into the desired range. For example, a project might not be allowed that would increase the fine-sediment composition of a spawning bed to a level greater than the defined deleterious threshold.

Mitigation might be done by increasing the function or quantity of a habitat. In effect, lost habitat is mitigated by replacing it, resulting in properly functioning habitat. Where water quality does not comply with properly functioning habitat standards, water-quality improvements might be made as mitigation for loss of spawning habitat.

Just as in the limiting-factors analysis, this process implies understanding a relative value of one habitat type in relation to another; providing additional rearing habitat where it is not functioning properly might compensate impacted spawning habitat. It also requires specific methods of quantifying existing habitat.

This type of mitigation is out-of-kind and may be either on-site or off-site mitigation. This target might be appropriate in the following circumstances adopted from the AMPG-IIA:

- when the resources adversely affected provide minimal desirable function, and they are neither limiting for a special species nor determined limiting within the watershed (Special species are identified in the AMPG-IIA as "*plants or animals listed by the state or federal government as threatened or endangered and those that are candidates for listing. It also includes the priority habitats and species designated by the Washington Department of Fish and Wildlife and those species designated as species of local concern under the [Washington State] Growth Management Act.*"); or
- when out-of-kind functions are critical or limiting within the watershed and provide a net gain for the resources of the watershed.

As discussed with limiting factors, mitigating functional habitat require methods for quantifying habitat and a way of valuing one habitat type in relation to another. Both of these issues are explained in this chapter under the section of this chapter titled *Quantifying Mitigation Needs*.

Replication of Current Natural Conditions

This is the process of copying at the project site the channel of a nearby undisturbed reach. A reach is identified with the same or similar hydrologic, sediment, geologic and climate conditions and it is replicated at the project site.

"Undisturbed" habitat is assumed to be noneroding, which may not be possible at the project site. If the entire reach is evolving to a changed hydrology, erosion might be the natural condition. It's important to capture channel function when characterizing a representative reach. To fully characterize the representative site, physical features that are characterized and replicated might include rates of channel migration and rate of recruitment of sediment and debris.

This target is useful where land uses at the project site have obliterated the natural channel characteristics or where there is not information regarding condition of the habitat or habitat limiting factors.

This type of mitigation is on-site and out-of-kind. This process might be appropriate in the following circumstances adopted from the AMPG-IIA:

- when resources adversely affected provide minimal desirable function and are not considered limiting, or
- when out-of-kind functions are critical or limiting within the watershed and provide a net gain for the resources of the watershed.

Restoration or Replacement to Preproject Conditions

A traditional approach to mitigation is to restore a habitat feature of the same type that is lost as a project impact. This approach is commonly used because it requires the least amount of information for application. There is no need to understand the habitat loss of a project; the same physical features are simply mapped and replicated in the mitigation.

Exact duplicate features are not necessarily created. Restored features should include substrate, channel shape, unique features, and depth and flow of water. They must be mitigated to be naturally self-maintaining and/or self-generating as the initial habitat was. The intent is to restore or replace *functions* rather than replacing specific features.

This concept does not account for potential productive capacity or future conditions by consideration of either limiting factors or functional habitat. It tends to perpetuate existing degraded habitat.

Such an approach is, however, useful for simple and small-scale projects or where there is not information regarding condition of the habitat or habitat limiting factors. No information is needed other than characteristics of the preproject channel that can be restored at the site within the project. If not applied appropriately, this concept leads to static constructed habitat with little regard to the natural channel function. If applied appropriately, it is applicable in pristine habitat. Application of this at sites that were affected directly or indirectly by development or land use is usually not appropriate since it only preserves a deteriorated condition.

This type of mitigation is on-site and in-kind. This target applies but is not limited to the following circumstances adopted from the AMPG-IIA:

- the on-site location is critical for protecting or replacing important location-dependent functions that are lost due to project impacts;
- the location or natural conditions on a site play a key role in larger watershed functions and health, or they are important to a special species;
- the on-site location has a high likelihood of success and will not be influenced by adjacent development pressures;
- adversely affected functions are limiting within the watershed and are vital for replacement;
- adversely affected functions are critical to the continued health of the watershed or of a special species; or
- adversely affected functions are of high quality and should be replaced.

On-site and in-kind mitigation may be required in other circumstances as determined by site-specific needs or at the discretion of the permitting agencies.

Quantifying Mitigation Needs

Several of the targets described in these guidelines require methods of assessing the quality and quantity of existing habitat at a site, habitat and channel characteristics of a representative reach and monitoring constructed habitat. The methods developed under the Timber-Fish-Wildlife (TFW) management system in Washington State for ambient monitoring are probably among the most recent and most quantifiable. The TFW Monitoring Program at Northwest Indian Fisheries Commission and the Washington State Department of Natural Resources Forest Practice Division publishes methods manuals.[4] The AMPG-IIA recommends "*project impacts and mitigation success should be measured with the Habitat Evaluation Procedure, the Washington State Wetland Functional Assessment Method, photographic documentation, or other methods acceptable to the permitting agencies.*" The physical surveys the Washington Department of Fish and Wildlife uses for habitat assessment above fish-barrier culverts may be acceptable as a minimal approach for smaller projects. That method is described in the agency's *Fish Barrier Assessment and Prioritization Manual*.[5] Specific habitat-monitoring protocols are described and evaluated in *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia*, also published by the Washington Department of Fish and Wildlife.[1]

None of these methods identify concepts such as future conditions, lost opportunities and habitat diversity. For bank-protection projects, habitat-assessment methods should identify debris and sediment sources, flood refuge, and habitat complexity and diversity.

There are recognized standard methods for assessing biological diversity. Biological diversity is the number of species in an area and includes a measure of the variety of species in a community and the relative abundance of each species. These methods might be modified to provide mitigation evaluation tools but will not provide the right information for habitat assessment for the purpose of mitigation design.

Several of the mitigation targets described in these guidelines require a way of valuing one habitat type relative to another. What is the value (habitat value as well as cost) of a unit of habitat that does not limit productive capacity compared to the value of a unit of limiting habitat that is built as mitigation? For instance providing additional rearing habitat where productive capacity is currently limited might compensate impacted spawning habitat.

One way to assign mitigation a financial value is to state it in terms of avoided costs. In other words, what actions were avoided by doing the mitigation, and what would those avoided actions have cost? The estimated cost of mitigating for the specific habitat lost could be applied to another habitat type. For example, the cost of replacing spawning habitat could be estimated and then that amount could be applied to the acquisition of water rights if that action were appropriate for either limiting factor or functional habitat mitigation.

EMERGENCY BANK PROTECTION

There are two types of emergency bank-protection projects. The first is the flood fight–actions taken during a flood to address the immediate threat of erosion during a flood. The second activity is bank repair after the flood–often with the risk of additional floods in the near future.

Most emergencies involving bank failure along streams and rivers occur during floods, when water levels are high and erosion occurs. Inundation and poor weather reduce visibility and complicate access for people and equipment. When a stream or riverbank is failing during such conditions, the key questions that arise are:

- Are immediate bank-protection actions during the flood prudent, necessary and effective?
- What bank-protection measure will work best to solve the emergency problem and can be implemented during high water conditions, safely, without high cost and impacts to the site?
- What materials are immediately available for bank-protection work?
- What are the best ways to physically implement the bank-protection measures during high water and poor weather conditions?
- What permits are required to do bank-stabilization work, and can they be expedited?

What Constitutes an Emergency?

Federal, state and local regulatory and resource agencies have differing jurisdictions and regulations for emergency bank stabilization during floods. The differing definitions and authorities can be especially confusing while in the throes of a flood fight.

Most agencies require approval of activities prior to constructing emergency bank protection. Washington State law (RCW 75.20.100(5)) regarding Hydraulic Project Approvals (HPAs) issued by Washington Department of Fish and Wildlife has specific language defining emergency situations and response to them:

> "(a) *In case of an emergency arising from weather or stream flow conditions or other natural conditions, the department, through its authorized representatives, shall issue immediately, upon request, oral approval for removing any obstructions, repairing existing structures, restoring stream banks, or to protect property threatened by the stream or a change in the stream flow without the necessity of obtaining a written approval prior to commencing work. Conditions of an oral approval to protect fish life shall be established by the department and reduced to writing within thirty days and complied with as provided for in this section. Oral approval shall be granted immediately, upon request, for a stream crossing during an emergency situation.*
>
> *(b) For purposes of this section and RCW 75.20.103, "emergency" means an immediate threat to life, the public, property, or of environmental degradation.*
>
> *(c) The department or the county legislative authority may declare and continue an emergency when one or more of the criteria under (b) of this subsection are met. The county legislative authority shall immediately notify the department if it declares an emergency under this subsection.*

The Washington Department of Fish and Wildlife has adopted specific procedures to deal with emergency HPAs:

> *Verbal request.* Determine if an emergency per 75.20.100(5) exists; if it does, make site visit if possible and issue a HPA on site, otherwise gather details over phone, and give verbal conditions for limited amount of work that are specifically necessary to address the emergency; put verbal conditions into written HPA within 30 days for record; if no, determine if the situation meets requirements for an expedited HPA per 75.20.100(3). If yes, require written application (may receive at site visit) and issue HPA within 15 days.

Written request - Determine if it meets emergency or expedited requirements. If it meets emergency requirements, contact person, make site visit, and issue an HPA on site; if the request meets expedited HPA requirements, visit site and issue within 15 days.

Designing and Installing Bank Protection During Emergency Conditions

Design and installation of bank protection during high water is difficult. Emergency installation is more costly than during low-water conditions because access is more difficult, timing is more immediate, there are fewer options for treatment and use of materials is generally less effective. Emergency situations can also cause an increased cost for mitigation since damage from an emergency project is usually greater, and equipment remobilization is required for post-project mitigation. Project impacts for emergency work have to be mitigated just as they are for projects with normal timing. It is, therefore, important to minimize impacts during project installation because it is likely that mitigation will already be more difficult and costly. Under emergency scenarios, the tendency is to act to protect a bank regardless of the existing trees and other vegetation. Keep in mind, however, that these same trees and vegetation may naturally provide bank protection once the emergency subsides. Such vegetation also reduces the future need for bank stabilization. When it comes to habitat, preserving existing vegetation also assists in mitigation efforts because it provides important riparian habitat. Therefore, vegetation should be protected even if it offers no immediate stabilization value.

Project impacts for emergency work have to be mitigated just as they are for projects with normal timing.

Since many bank-instability problems show initial evidence during low flow, it's a good idea to develop a contingency plan prior to the advent of an emergency.

Safety of those installing bank stabilization is another important aspect of emergency protection. Working adjacent to flood waters is dangerous. Deep water; fast, unpredictable currents; rapidly rising water levels; floating (or subsurface) debris and woody material all contribute to the extreme hazard.

Emergency Bank-Protection Techniques

Floods tend to impose their own set of complexities and limitations on bank-protection projects:

- Placement, anchoring and constructability during high flows;
- visibility below the water surface is obscured;
- equipment access may be limited;
- the site can't be drained; and
- safety issues are very real but unpredictable.

A typical bank-protection request during a flood is to dump large rock from the top of a bank. Such actions get in the way of other immediate and future creative solutions such as composite banks or vegetated revetment unless they are permitted strictly as temporary emergency work, with the requirement to remove and replace the work with more appropriate measures at the next appropriate work window. Deep water doesn't allow visibility below the water surface. Thus, when working in deep water, it is difficult to know where the dumped rock landed, how it is oriented and what its effect is. Another problem that arises in taking this type of emergency action is that, often, more rock is used than is necessary. To complicate installation, saturated bank conditions make heavy equipment access difficult, if not impossible.

Techniques suitable for emergency conditions are discussed in Chapter 5 and in the descriptions of specific techniques in Chapter 6, *Techniques*. Those featured include exposed and buried groins, anchor points and avulsion-prevention techniques in the floodplain, such as placement of debris or roughness. Dumped rock is also feasible but should be considered only after all other options have been ruled out, including those that would disturb the riparian zone less or require less rock and/or are easier to modify during the project follow-up. Placing bank-protection measures that immediately fail can exacerbate the problem, increasing the extent or rate of additional bank failure.

Follow-Up Work After Installation of Emergency Bank Protection

Some level of follow-up work is after required after installation of emergency bank protection and after floodwaters have receded. Follow-up can range from simple (such as re-seeding of disturbed areas) to extensive (removing dumped rock and replacing it with a more suitable and environmentally acceptable alternative). Every project built under an emergency HPA should be studied after the flood has receded, and a follow-up report should be developed by the applicant and interested agencies. The following are questions to ask following emergency bank-protection actions:

- Is the bank-protection technique consistent with concepts described in these guidelines?
- Are fish and wildlife habitat impacts fully mitigated? What is necessary for full mitigation?
- What site cleanup is needed? Are there unused materials left around the site?
- What should be done in terms of revegetation of disturbed ground, either by seeding or planting of shrubs and trees?
- Should the bank-protection measure be adjusted to function better or reduce habitat impacts, for example, to change the shape and extent of placed rock?
- Are the transitions of the treatment into adjacent stable banks adequately installed?
- Can habitat and vegetation be added to the treatment to reduce any adverse environmental impacts?
- Overall, will the bank protection continue to function in the future, or should it be adjusted, redone or removed? If, after-the-fact design analyses were undertaken, would the bank protection meet the stabilization objectives and design criteria?

MAINTENANCE, ADAPTIVE MANAGEMENT AND MONITORING

Streambank stabilization requires maintenance. Because streams are dynamic and many bank-protection measures include living plants and biodegradable material, the potential is high for stabilization measures to change in some way over time and through flood events. The only way that such changes can be observed is through a monitoring program (see Appendix J, *Monitoring*).

Streambank-protection measures do not function in a static setting. Typical changes might include: migrating meander forms; adjustments to water and/or sediment supply from upstream; and impacts to vegetation survival from on-site land use. These changes are gradual and sometimes imperceptible to the casual observer, until a high-flow event occurs, when change may be sudden or even catastrophic. To ensure that bank-protection measures do not fail, it is important to establish a formal monitoring program.

Monitoring of bank-protection measures typically involves an intensive period of evaluation during the first few years after a project has been installed. After that, a less intensive evaluation is acceptable. Monitoring a project site two or more times during the first few years, when vegetation is re-establishing and the protection measures are less tested, is especially important where the bank-protection measures rely heavily on plants to provide long-term stabilization. After vegetation has been established, monitoring once a year, or every other year is adequate.

The level of cost and risk associated with a project dictates the appropriate level of monitoring. Costly, high-risk projects require a detailed monitoring plan that identifies what should be measured, and how and when it should be measured. A small-scale project might simply involve developing a photographic record from one or more established photo points. A monitoring plan might include: taking photos, measuring bank and channel cross sections, measuring plant densities and species composition, assessing fish habitat, and estimating fish use. For a more detailed discussion on monitoring, see Appendix J.

If monitoring indicates that a bank-protection measure is not meeting design criteria, then adjustments can be made to ensure the continued long-term function of the treatment. Such maintenance is called "adaptive management," because it identifies over time what changes might have occurred and what needs to be done. Adaptive management for streambanks involves maintaining appropriate vegetation, ensuring that toe protection remains intact and watching transitions from treatment to non-treatment along a bank to make sure they do not weaken and become prone to failure. It may involve planting trees, or pruning trees that have become too big. Severe pruning and tree felling to prevent tree throw should only be done where there is a limited riparian corridor, no opportunity for the corridor to be widened and a high risk of further erosion. Adaptive management may involve installing a different kind of bank protection should the original treatment fail. For example, if an attempt to rely solely on vegetation did not work, then a treatment with more rigid materials might be required.

For descriptions and evaluations of specific habitat monitoring protocols, refer to Johnson, et al.[1]

CONCLUSION

There may be significant consequence, productive or destructive, to any treatment that may be applied to rivers and streams. Determining those consequences, weighing them against risks to habitat and safety of people and property is crucial in selecting a treatment that is most effective. In Chapter 5, we'll explore how to identify and select the most appropriate treatment(s) to meet the particular circumstances present.

REFERENCES

1 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

2 Limiting factors analyses cited as having been published by the Washington State Conservation Commission are available from that agency online at www.scc.wa.gov/resources/library or by mail at the Washington State Conservation Commission, P. O. Box 47721, Olympia, WA 98504-7721.

3 Federal Register, July 10, 2000. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, 50 CFR Part 223. Endangered and Threatened Species; Salmon and Steelhead; Final Rules.

4 Publications cited as having been published by the Northwest Indian Fisheries Commission are available from that agency online at www.nwifc.wa.gov/TFW or by mail at Northwest Indian Fisheries Commission, 6730 Martin Way E. Olympia, WA 98512.

5 Publications cited as having been published by the Washington Department of Fish and Wildlife are available online at www.wa.gov/wdfw or by mail at Washington Department of Fish and Wildlife, 600 Capitol Way N., Olympia, WA 98501-1091.

Chapter 5

Identify and Select Solutions

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Chapter 5

Identify and Select Solutions

This chapter integrates the information provided in previous chapters to identify and select preferred treatment alternatives. The key points made in the previous chapters are reinforced in this chapter, including identifying the mechanisms and causes of failure, defining design criteria, considering mitigation, and evaluating "no action" alternatives. Additionally, this chapter will help the reader:

- become familiar with the concept of integrating the results from the site and reach assessments into the selection of streambank-protection treatments,
- make use of a series of matrices for identifying and selecting appropriate bank-protection techniques,
- review three case studies that demonstrate how to use the screening matrices,
- explore further techniques that may be appropriate for resolving common site- and reach-based erosion problems, and
- incorporate design considerations to guide the selection of a treatment solution.

PRESELECTION CONSIDERATIONS

Identifying the Mechanisms and Causes of Failure

Identifying suitable bank-protection alternatives begins with understanding the specific mechanisms of failure at a project site (Chapter 2, *Site Assessment*), as well as the reach-based causes of bank instability (Chapter 3, *Reach Assessment*). These site- and reach-based causes of bank erosion may be simple and discreet, or they may be highly interdependent and difficult to separate. Nonetheless, it is only through the process of identifying mechanisms and causes of failure that appropriate solutions can be developed.

It's important to consider a number of reach-wide factors when designing streambank-protection measures, including whether a project reach is in short-term or long-term disequilibrium. Where instability is caused by problems that extend throughout the watershed, then the selection of bank-stabilization measures needs to account for these conditions. For example, where a reach is degrading, bank protection must either account for the effects of scour (if the channel bed continues to drop), or it must prevent further degradation by some means (such as an at-grade bed control).

Objectives and Design Criteria

In order to identify and select appropriate bank-protection techniques, it is necessary to develop a series of design criteria that quantify the general project objectives (Chapter 4, *Considerations for a Solution*). These criteria, which take into consideration risk and cost and line up according to relative priority, are intended to outline the objectives of the project and provide the foundation for making design decisions about the specific sizes and components of bank-protection techniques.

Mitigation

Every bank-protection project should be evaluated with respect to potential mitigation requirements. Avoiding impacts completely should be the first consideration before designing a project. If impacts are unavoidable, they should be minimized, and compensatory mitigation will be necessary. The preferred approach is as follows:

- First - avoid impact,
- Second - minimize and compensate for impacts, and
- Third - compensate for the impacts.

Chapter 4 addresses mitigation requirements in more detail.

No Action

When identifying an appropriate bank-protection technique, keep in mind that the best course of action for a stream might be to take no action at all (Chapter 4). After considering the forces causing streambank erosion, it may become apparent that this natural process is too difficult or costly to arrest or change, or that the system-wide disequilibrium is too extensive to control locally. It might be more cost-effective to reduce or eliminate the need for bank protection at all. For example, if a migrating river channel threatens a structure, it might require less expense, effort and impact to move the structure a safe distance from the river than to apply bank protection.

It might be more cost-effective to reduce or eliminate the need for bank protection at all.

SELECTION PROCESS

A series of matrices are provided in this chapter to assist in identifying and selecting bank-protection and habitat-mitigation techniques. What matters most in selecting treatments is the specific site- and reach-based aspects of each individual project, so special care should be taken in evaluating these aspects before selecting treatments. Be sure to review Chapters 1 through 4 to learn how to assess site and reach conditions and other design considerations before selecting a bank-protection technique for a specific site. Doing so will help determine the most appropriate and successful course of action. You'll find more detailed information about the bank-protection techniques identified in this section in Chapter 6, *Techniques*. It is not at all unusual to find that combining two or more streambank-protection techniques produces more successful results, depending upon the goal to be achieved, different functions at play or different effects on habitat. Given the opportunities to combine these treatments, it is important to encourage creativity in designing bank protection, as long as design criteria are met.

Be sure to take the time to review the three case studies that follow the discussion on the screening matrices. They will help demonstrate the selection process using the matrices.

BANK-PROTECTION TECHNIQUES

The various bank-protection techniques described in these guidelines have been divided into functional groups, making it easier to determine the applicability of particular bank-protection techniques for differing site and reach conditions. *Table 5-1* lists each of the techniques, which are described in detail and by category in Chapter 6, *Techniques*. These groups include:

- no action,
- instream flow-redirection techniques,
- structural bank-protection techniques,
- biotechnical bank-protection techniques,
- internal bank-drainage techniques,
- avulsion-prevention techniques, and
- other techniques.

Flow-Redirection Techniques influence the flow patterns and hydraulics of a stream in order to reduce the erosive forces acting on a bank or bed. The changes in hydraulics involve shifts in flow distribution across the channel, average velocity in the cross section, or distribution of energy. Instream flow-redirection techniques involve placing materials within a channel, rather than strictly along a bank. These techniques directly and/or indirectly affect channel cross-sectional shape, erosion and deposition patterns, channel roughness, and hydraulic slope and capacity. The risks of these changes to adjacent property must be fully understood and appropriately managed before attempting such projects. If proper care is not taken to fully understand potential impacts, unintended damage to property can be severe.

Structural Techniques directly affect the structure of the bank to shield it from scour, strengthen it or structurally support it. For bank protection, structural techniques include rock and log toes and revetments. For bank strengthening and support, log cribwalls can be used. Structural support and strengthening are often combined with biotechnical bank-protection techniques to provide a stable foundation that allows installed vegetation to survive.

Biotechnical Techniques use vegetation and wood to reproduce the natural system and to provide structural and surface erosion protection. For the purposes of this document, biotechnical techniques are defined as consisting of entirely biodegradable components (for example, natural-material erosion-control fabrics, willow cuttings and large woody debris). One major benefit of biotechnical techniques over structural techniques is that vegetative methods are self-healing. That is, vegetation continues to grow, and large, woody material continues to be contributed as it falls into the stream. In an ecologically diverse and productive river system, its banks and channel will contain many pieces of large woody debris, and vegetation will be densely distributed along the banks.

No Action	Flow-Redirection Techniques	Structural Techniques	Biotechnical Techniques	Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques	Other Techniques
Allow bank erosion to continue Move structures at risk	Groins Buried groins Barbs Engineered log jams Drop structures Porous weirs	Anchor points Roughness trees Riprap Log toes Rock toes Log cribwalls Manufactured retention systems	Woody plantings Herbaceous cover Soil reinforcement Coir logs Bank reshaping	Subsurface drainage systems	Floodplain roughness Floodplain grade control Floodplain flow spreader	Channel modifications Riparian-buffer management Spawning-habitat restoration Off-channel spawning and rearing habitat

Table 5-1. Bank-protection techniques organized by functional group.

Biotechnical techniques mimic this condition. Vegetation and wood provide shade for temperature control as well as serve a food source and cover for fish and wildlife. They also cause pools to scour, resulting in improved fish habitat. A combination of biotechnical, flow redirection and structural techniques are typically used in bank-protection projects.

Internal Bank-Drainage Techniques are methods that provide for water to drain from within a streambank, whether caused by rapid drawdown or seepage from groundwater. These techniques are typically integrated with structural and biotechnical techniques and are seldom used independently.

Avulsion-Prevention Techniques reduce the potential for an avulsion, rather than providing a remedy once one has occurred. Avulsion-prevention techniques distribute and dissipate flood flows and prevent headcut development across a vulnerable floodplain area.

Channel Modification Techniques are used to change the channel geometry and/or planform to provide for more natural and stable conditions. Channel modifications can be designed to account for changing watershed conditions, such as sediment and flows, and to improve aquatic habitat in reaches of the channel that have been impacted. Channel modifications require an understanding of site- and reach-based conditions, and a thorough design approach. An abbreviated discussion of channel modifications can be found in Chapter 6.

Riparian-Buffer Management Techniques provide cover and shade, a source of fine or coarse woody material, nutrients, and organic and inorganic debris - all of which are essential for river and stream ecosystems function. Riparian buffers also provide habitat for wildlife, especially migrating and breeding birds. Examples of riparian-buffer management techniques include: conservation easements, fencing livestock out of the riparian zone and plantings.

SELECTING BANK-PROTECTION METHODS USING SCREENING MATRICES

One of the most difficult but important aspects of the design process involves moving from identifying the mechanism and causes of failure to the selection of an appropriate solution. To provide a tool for people with varying levels of experience, three screening matrices are presented. The matrices are configured to assist in selecting treatments that:

- perform adequately to meet bank-protection objectives;
- are appropriate with respect to site-based and reach-based processes;
- are properly weighed against their potential impacts to habitat; and
- are selected in an order of priority that first avoids, second minimizes, and third compensates for habitat impacts.

The three matrices act as progressively selective screens, or filters, of bank-protection techniques. Within each matrix, the techniques have been arranged according to their functional groups (no action, instream flow-redirection, structural, biotechnical, internal bank drainage, avulsion- and chute-cutoff prevention, and other). With each subsequent matrix, inappropriate techniques are progressively "screened out" by process of elimination, leaving an assortment of feasible treatment options.

One of the most difficult but important aspects of the design process involves moving from identifying the mechanism and causes of failure to the selection of an appropriate solution.

Screening Treatments Based on Site Conditions

Matrix 1 (*see Figures 5-1a and 5-1b on pages 5-9 and 5-10*) identifies several bank-protection techniques that should be considered in resolving the mechanisms of failure occurring at your site. It also identifies whether the no-action option should be considered. Start by identifying the mechanisms of failure that apply to your site. (In Matrix 1, see the columns "Is This Occurring at My Site?" and "Mechanism of Failure.")

In the first column, check ("√") each mechanism of failure that is occurring at your site. If you are not sure about a particular mechanism of failure, read Chapter 2.

Matrix 1 identifies several bank-protection techniques that should be considered in resolving the mechanisms of failure occurring at your site. It also identifies whether the no-action option should be considered.

Next, look across the row for each identified mechanism of failure, and circle all the techniques that are rated as "Good" at resolving this failure. (If there are no techniques rated as "Good," then select those rated as "Fair.") These are techniques that may be good options for your site. Do this for each type of failure you have identified. At the bottom of the matrix, sort through the techniques you've circled, identifying those that appear to best meet your site-based needs. Where there is more than one mechanism of failure, select the dominant mechanism and identify techniques repeatedly circled as "Good" (or those marked "Fair" if no "Good" options apply) that apply to it. Place greater weight on these techniques in the selection process.

To indicate which techniques are suitable and which are not, mark each technique that best meets your site-based needs in the bottom row with a "S" for suitable; mark those that are unsuitable with a "U." These unsuitable techniques may need to be revisited if the remainder of the screening process does not result in an acceptable choice.

Screening Treatments Based on Reach Conditions

Matrix 2 (*see Figures 5-2a and 5-2b on pages 5-11 and 5-12*) is used to identify bank-protection techniques that apply to the reach-wide conditions of the stream at your site (see Chapter 3). Begin by transferring the bottom row of Ss in Matrix 1 (in the row called "Suitability of Each Technique") to the first row in Matrix 2 (in the row also called "Suitability of Each Technique"). Take care to ensure that the Ss correspond to the same technique in each matrix. Check ("√") the first column adjacent to the reach-based conditions that describe your site. If you are not sure which may apply, read Chapter 3. Now, based on the screening thus far, only those rows where you placed a "√" and those columns where you placed an S should relate to your site. Read across the checked rows, circling all the techniques rated "Good" that you marked with an S (circle those rated as "Fair" if there are not any "Good" options available). Here, consider only those techniques that apply to both conditions at your site.

Matrix 2 is used to identify bank-protection techniques that apply to the reach-wide conditions of the stream at your site.

At the bottom of Matrix 2, sort through the techniques, identifying those that appear to best meet your needs. Where there are multiple reach-based conditions at work, focus on the dominant condition and identify those techniques that are repeatedly circled as "Good" (or those marked "Fair" if no "Good" options apply). Place greater weight on these techniques in the selection process. For those techniques that rank as suitable, mark them in the bottom row with an S. Those that are not suitable should be marked with a U. Here again, those techniques marked as unsuitable for now might need to be revisited if the screening process does not result in an acceptable choice.

Selecting Treatments Based on Habitat Impacts

The suitable techniques carried over from Matrices 1 and 2 are acceptable for your project based on specific site and reach conditions. Matrix 3 (*see Figures 5-3a and 5-3b on pages 5-13 and 5-14*) identifies the potential habitat impacts that these techniques might cause. It also identifies compensatory mitigation techniques for these impacts. The objective is to combine, or integrate, two or more techniques in order to achieve site-stability objectives, while avoiding or minimizing impacts to habitat. For a discussion of habitat and mitigation policies, objectives and targets, read Chapter 4. For the protection of fish habitat, mitigation sequencing must be used in the selection of the bank-protection technique. The sequence of mitigation activities is first to avoid the impact and, second, to minimize and compensate for any impacts that are unavoidable.

Matrix 3 identifies options that will avoid and/or minimize impacts and those that will compensate for losses. The matrix lists bank-protection and compensatory mitigation techniques in the top row. Habitat functions are listed in the left column: riparian function, cover, spawning, complexity and diversity, lost opportunity, construction and flood refuge. These functions are described in Chapter 4.

Matrix 3 identifies the potential habitat impacts that these techniques might cause. It also identifies compensatory mitigation techniques for these impacts.

Matrix 3 is constructed to reflect the mitigation sequence. The letter "A" (avoid) is shown in each cell for the techniques that generally avoid impacts to the habitat function of that row. Choices that impact habitats are marked as: "L" for low-impact, "M" for medium-impact and "H" for high-impact. Realize that there will be many situations that are exceptions from the matrix, due to specific habitat requirements or unique site conditions. If this is the case for the site under consideration, then describe the unique or special conditions and how they are accommodated.

To begin using Matrix 3, transfer the treatments marked with an S on bottom row of Matrix 2 to the first row of Matrix 3. If there are no suitable techniques that avoid impacts, look for techniques that minimize impacts, first considering techniques that have low, then medium and then high impacts, in that order. For every low-, medium- or high-impacting technique, you must provide a technique that compensates for the impact. Techniques that compensate for a particular habitat function are identified with a "C" in the rows under "Mitigated By."

Many specific techniques have a mix of C's, L's, M's, H's and A's in the rows associated with "Impacts To." Where this is the case, consideration and weight must be given to those functions that achieve the mitigation target. Mitigation targets are described in Chapter 4. The target may favor improvement of factors within the watershed that limit fish production, restore properly functioning habitat, and replicate natural the techniques.

Refer to Chapter 6 for further details on application, design and effects of each of the techniques.

MATRIX 1: SCREENING TREATMENTS BASED ON SITE CONDITIONS
Refer to Chapter 2 for Site-Based Assessment Information

		Potential Suitability of Bank-Protection Techniques: No Action	Other Techniques		Flow-Redirection Techniques							Structural Techniques							Biotechical Techniques					Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques		
Is This Occurring at My Site? (**Y**es or **N**o)	**Mechanism of Failure**		Channel Modifications	Riparian-Buffer Management	Groins	Buried Groins	Barbs	Engineered Log Jams	Drop Structures	Porous Weirs	Remove or Reduce Feature	Anchor Points	Roughness Trees	Riprap	Log Toes	Roughened Rock Toes	Log Cribwalls	Manufactured Retention Systems	Woody Plantings	Herbaceous Cover	Soil Reinforcement	Coir Logs	Bank Reshaping	Subsurface Drainage Systems	Floodplain Roughness	Floodplain Grade Control	Floodplain Flow Spreader
	TOE EROSION																										
	Reduced Vegetative Structure	F	I	G	G	G	G	G	F	F	-	D*	G	F	G2	G2	F	F	G	G2	G	G	G2	-	-	-	-
	In a Smoothed Channel	F	G	G2	G	G	F*	G	G2	G2	-	I	G	F	G2	G2	F	F	G2	F2	F	G2	G2	-	-	-	-
	Along a Bend	G	D	G2	G	G	G	G	F	F	-	D*	G	G	G	G	G*	G	G2	G2	G	G2	G2	-	-	-	-
	SCOUR																										
	Local Scour																										
	At a Tailout or Backwater Bar	G	I	G2	F*	F	F	D	F	F	G	G	G	G	G	G	G	D*	G2	G2	G2	G2	F2*	I	I	I	I
	Associated with an Obstruction	G	I	G2	F*	F	F	D	F	F	G	G	G	G	G	G	G	D*	G2	G2	G2	G2	F2*	I	I	I	I
	Constriction Scour																										
	Associated with Large Woody Debris Jam	G	F	G2	F*	F	F*	G*	P*	P*	G	G*	F*	F	G*	F*	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Bridge Crossing	F	I	I	D*	I	D*	D*	D*	P*	G	I	I	G	P	G	I	G*	I	I	I	I	G2	I	I	I	I
	At Existing Bank Feature	G*	G	G2	D*	G	D*	D*	P*	P*	D*	G*	F*	F	G	F	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	Drop/Weir Scour	G	D	G2	D	I	I	D	F*	P*	D	F	G*	F	G	F	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	Jet Scour																										
	At a Lateral Bar	G	D	G2	D	F	D	D	F	F	F2	G	G	P*	G*	F*	G	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Side Channel or Tributary	G	D	G2	G*	G	I	D	I	I	D*	G	G	F	G2	G2	G	D*	G2	G2	G2	G2	F2	I	I	I	I
	Subchannels in a Braided Channel	G	D	G2	P	P	P	P	I	I	I	P*	F	F*	F2*	F2*	F*	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Channel Bend (Energy Sink)	G	D	G2	D	I	I	D	F2*	F2*	I	G	G	F	G2	G2	G	F*	F2	F2	G	F2	F2	I	I	I	I
	SUBSURFACE ENTRAINMENT																										
	Groundwater Seepage	G	D	I	F	F	F	F	P	P	F	I	F	G2	G	G	G2	G2	G2	G2	G2	G2	G2	G	I	I	I
	Rapid Drawdown	G	D	I	F	F	F	F	P	P	F	I	F	G2	G	G	G2	G2	F2	F2	F2	F2	F2	G	I	I	I
	MASS FAILURE																										
	Saturated Soils	G	D	I	F*	I	F*	F*	P	P	-	I	F2	F*	G2*	G2*	F	G*	D*	I	P	I	G2	G	I	I	I
	Increased Surcharge	F	S	I	P*	I	P*	P*	P*	P*	G	I	P*	F*	P*	P*	F	G*	P*	P*	F	I	G2*	I	I	I	I
	Lack of Root Structure	F	D	G2	I	I	I	I	I	I	I	I	I	F*	G2	G2	F	F	G2	P	F	F2	G2	I	I	I	I
	Undercutting/Removal of Lateral/Underlying Support	D	D	I	I	I	I	I	I	I	I	I	I	F*	G	G	F	F	F2	P	F	F2	G2	I	I	I	I
	AVULSION POTENTIAL																										
	In Mature Floodplain	G	D	G	I	I	I	I	I	I	-	I	I	I	I	I	I	I	I	I	I	I	I	-	F	P	F
	In Channel Floodplain	I	D	G	I	I	I	I	I	I	-	I	I	I	I	I	I	I	I	I	I	I	I	-	G	G	G
	CHUTE-CUTOFF POTENTIAL																										
	In Mature Floodplain	G	D	G	G	G	G	G	F	F	-	I	G	G	G	G	G	G	G2	G2	G	G2	F	-	F	I	I*
	In Channel Floodplain	I	D	G2	G	G	G	G	F	F	-	I	G	G	G	G	G	G	G2	G2	G	G2	F	-	G	G	G
	Suitability of Each Technique **S**uitable/**U**nsuitable																										

Level of Suitability
* = See Figure 5-1 (b) for additional explanation
G = Good. Directly addresses human-caused mechanism of failure, site-based, or reach-based cause, or allows mechanism of failure to correct itself, or allows mechanism of failure to continue when appropriate, or directly the addresses (corrects) hydraulic condition created by the reach-based cause.
G2 = Good in combination with a technique rated G or in low to moderate risk situation.
F = Fair. Does not address mechanism of failure, site-based, or reach-based cause. Is not as good a bank protection solution as "good."
F2 = Fair in Combination with a Technique Rated for G.
P = Poor. Does not address mechanism of failure, site-based, or reach based cause. Not as good a bank protection solution as "fair."
I = Inappropriate. Does not work., and does not address mechanism of failure, site-based, or reach-based cause.
D = Dependent upon Site Conditions. Too varied to generalize in this matrix.
- = Not Applicable.

Notes:

1. The matrix ratings are general.; there will be situations that are exceptions to the matrix ratings. Each should stimulate further discussion. The ratings don't compare feasability, cost or risk.

2. The tables following each of the matrices include explanations of some of the ratings in the matrices. Explanations are given for those ratings that are not obvious or are incomplete without some explanation.

3. See Chapter 5 for instructions on how to use this matrix.

Figure 5-1(a). Matrix 1: Screening techniques based on site conditions.

MATRIX 1: SCREENING TREATMENTS BASED ON SITE CONDITIONS
Explanation of Matrix 1 Ratings

MECHANISM OF FAILURE		TECHNIQUE	RATING	EXPLANATION OF RATING
All		No action	G, F, I, D	"No action" is always an option. It does not rate "good" if mechanism of failure is human-caused. "No action" may involve the decision to simply take not action. "No action" may also involve solving the problem by undertaking "out-of-channel activities" (such as moving a building or structure) rather than implementing bank protection.
General bank erosion	Smoothed channel	Barbs	F	Not enough roughness.
	Smoothed channel	Log cribwalls	F	Assumes cribwall is roughened.
	Reduced vegetation, Along a bend	Anchor points	D	Depends on scale of channel and erosion. Anchor points are intended for local scour.
Scour		Manufactured retention systems	G, F, P, D	Might apply if the bank is also slide-prone; refer to mass failure.
Local scour	Scour at tailout, backwater, or obstruction	Groins	F	Structures placed upstream of scour to improve flow alignment.
Local scour	Scour at tailout, backwater, or obstruction	Bank reshaping	F2	Does not solve scour; bank reshaping is done to support planting.
Constriction scour		Various techniques	G,F	Often inappropriate since constriction scour is defined here as in the bed only. Some techniques apply where they would support a bank that could otherwise be undermined by the scour. That condition does not occur where a channel is confined (bridges).
	Associated with debris	Drop structures, porous weir	P	Used to backwater the constriction. Poor because debris jam is transient, structures are not.
		Flow-redirection techniques	G	Engineered log jam is transient and flexiblle, other flow redirection techniques are not.
		Groins, barbs	F	Debris is transient, rock is hard and permanent.
		Log toe	G	Allows bed scour if log toe is supported by bank.
		Rock toe	F	Fails with continued bed scour unless adequate roughness is added. Roughness will exacerbate constriction.
	Associated with debris, at existing bank feature	Anchor point	G	Assumes feature is natural and can be reinforced to form anchor point.
		Roughness trees	F	Allows bed scour to continue; trees can span scour hole and support bank, but assumes roughness exaerbates constriction.
	Bridge	No action	F	Assumes the mechanisms of failure are human caused. Other causes are G. See the definition of "G" rating.
		Manufactured retention system	G	For example, sheet pile at toe of footing.
		Bank reshaping	G2	Remove sloping fill under bridge in conjunction with other retention system.
		Flow-redirection techniques	G, F, P, D	Place upstream to align the channel more efficiently to the constriction.
	At existing bank feature	No action	G	Assumes feature is natural.
		Remove or reduce feature	D	An existing groin or other artificial constriction might be modified.
Drop/weir scour		Groins	D	Groins are downstream to roughen channel and create backwater.
		Drop structures	F	Cannot redirect flow effectively to a drop. May be used to backwater drop.
		Porous weir	P	Cannot redirect flow effectively to a drop. Less effective backwater than drop structure.
		Roughness trees	G	Allows bed scour to continue. Trees can span scour hole and support bank.
Jet scour	At lateral bar	Riprap	P	Lateral bar may be transient.
		Log toe	G	Assumes scour occurs at a moderate flow when toe protection is more effective.
		Rock toe	F	Assumes scour occurs at a moderate flow when toe protection is more effective. Rock toe is permanent; lateral bar may be transient.
	At tributary	Groins	G	Groins intended to scour tributary bar.
		Remove or reduce feature	D	Gravel removal might be appropriate if it is a one-time event.
	Braided subchannel	Anchor points	P	Channels are transient and may impact between anchor points.
		Structural techniques	F	Subchannel is transient in location and time.
	At abrupt channel bend (energy sink)	Drop structures, porous weir	F2	Located upstream to dissipate and direct flow, or located downstream to backwater. Use with anchor point.
		Riprap	F	Tends to fills energy sink and lose energy-dissipation volume; fails if scour hole deepens.
	Groundwater seepage	Riprap	G2	Needs drainage to make riprap secure.
	Rapid drawdown	Biotechnical techniques	F2	Drawdown implies a "no-grow zone" where vegetation is less effective.
	Groundwater seepage, Rapid drawdown	Groins, barbs, engineered log jam	D	Does not address problem. but could fix channel in place away from problem or let bank recline.
Mass failure	All	Riprap	F	Assumes riprap is a buttress.
	Saturated soils	Log toe, Rock toe	G2	Assumes bank can be reshaped and planted to a stable slope.
		Groins, barbs, engineered log jam	F	Does not address cause, but could fix channel in place away from problem or let bank recline. Seepage continues until bank is in equilibrium.
		Manufactured retention system	G	Assumes it contains appropriate drainage.
		Woody Plantiings	D	Depends on depth of failure.
	Increased surcharge	Various flow-redirection, structural, and biotechnical techniques	P	Assumes there is a structure on the bank (surcharge) that will fail unless the entire bank is stabilized.
		Reshape bank	G2	Assumes that the surcharge is moved.
	Increase surcharge, lack of root structure	No action	F	Assumes the mechanisms of failure are human caused. See the definition of "G" rating.
Chute cutoff	Mature floodplain	Flow spreader	I	Assumes disturbance of mature forest in floodplain.

Figure 5-1(b). Matrix 1: Explanations of ratings in Matrix 1.

MATRIX 2: SCREENING TREATMENTS BASED ON REACH CONDITIONS
Refer to Chapter 3 for Reached-Based Assessment Information

Is This Occurring at My Site? (Yes or No)	How Does This Technique Perform → Under This Condition ↓	Potential Suitability of Bank-Protection Technique: No Action	Other Techniques		Flow-Redirection Techniques							Structural Bank-Protection Techniques							Biotechical Techniques					Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques		
			Channel Modifications	Riparian-Buffer Management	Groins	Buried Groins	Barbs	Engineered Log Jams	Drop Structures	Porous Weirs	Remove or Reduce Feature	Anchor Points	Roughness Trees	Riprap	Log Toes	Roughened Rock Toes	Log Cribwalls	Manufactured Retention Systems	Woody Plantings	Herbaceous Cover	Soil Reinforcement	Coir Logs	Bank Reshaping	Subsurface Drainage Systems	Floodplain Roughness	Floodplain Grade Control	Floodplain Flow Spreader
	Suitability of Each Technique From Matrix 1:																										
	REACH IN EQUILIBRIUM																										
	Meander Migration																										
	Within Channel-Migration Zone	G	I	G	P	G	P	F	P	P	-	D*	G	P	G	P	F	P	G	G2	G	G	G2	-	-	-	-
	At Edge of Channel-Migration Zone	G	I	G	G	G	G	G	F	F	-	D*	G	G	G2	G2	G	G	G	G2	G	G	G2	-	-	-	-
	REACH IN DISEQUILIBRIUM																										
	Large-Scale Flood Events	D*	D	G	D	D	D	D	D	D	-	D*	D	D	D	D	D	D	G	G2	G	G	G2	-	-	-	-
	Aggrading Reach																										
	Reduced Hydrology/ Increased Sediment Supply	D*	D*	G	G*	F	P	G	I	I	G2*	D*	G	G	F2*	F2*	G	G	G	G2	G	G2*	G2	-	-	-	-
	Downstream Constriction	P	F	G	F*	F	P	F	F*	I	G	D*	F	F	F2*	F2*	F	F	G	G2	G	G2*	G2	-	-	-	-
	Reduced Slope or Downstream from Confined Reach	D*	D*	G	F*	P	I	P	F*	I	-	D*	D	F	F2*	F2*	F	F	G	G2	G	G2*	G2	-	-	-	-
	Confined Channel (with Dikes/Berms)	P	G	G	I	I*	P	I	I	I	G	D*	D	F	F2*	F2*	F	F	G	G2	G	G2*	G2	-	-	-	-
	Degrading Reach																										
	Increased Hydrology/ Reduced Sediment Supply	D*	G	F2*	F*	F	P	G*	G	G	G*	D*	G	P	F	F	P*	P*	F2	P	F*	P	F2	-	-	-	-
	Shortened Channel	P	G	F2*	G	G	P	G	G	G	-	D*	F	F	F	F	I	I	F2	P	F	P	F2	-	-	-	-
	Natural Channel Evolution (Headwater Streams)	G	G	F2*	P	P	P	G	F*	F*	-	D*	P	P	F	F	I	I	F2	P	F*	P	F2	-	-	-	-
	AVULSION POTENTIAL																										
	Aggrading Reach	D	I	G	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	G	F	G
	Localized Downstream Constriction	P	G	G	I	I	I	I	I	I	G	I	I	I	I	I	I	I	I	I	I	I	I	I	G	G	G
	Previously Relocated Channel	P	G	G	I	I	I	I	I	I	G	I	I	I	I	I	I	I	I	I	I	I	I	I	G	G	G
	Braided Channel	D	I	G	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	G	F	F
	Large Storm Event	D	I	G	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	G	G	G
	Suitability of Each Technique From Matrix 2: **S**uitable/**U**nsuitable																										

Level of Suitability
* = See Figure 5-2 (b) for additional explanation.
G = Good. Directly addresses human-caused mechanism of failure, site-based, or reach-based cause, or allows mechanism of failure to correct itself, or allows mechanism of failure to continue when appropriate, or directly the addresses (corrects) hydraulic condition created by the reach-based cause.
G2 = Good in combination with a technique rated G or in low to moderate risk situation.
F = Fair. Does not address mechanism of failure, site-based, or reach-based cause. Is not as good a bank protection solution as "good."
F2 = Fair in Combination with a Technique Rated for G.
P = Poor. Does not address mechanism of failure, site-based, or reach based cause. Not as good a bank protection solution as "fair."
I = Inappropriate. Does not work., and does not address mechanism of failure, site-based, or reach-based cause.
D = Dependent upon Site Conditions. Too varied to generalize in this matrix.
— = Not Applicable.

Notes:

1. The matrix ratings are general; there will be situations that are exceptions to the matrix ratings. Each should stimulate further discussion. The ratings don't compare feasability, cost, or risk.

2. The tables following each of the matrices include explanations of some of the ratings in the matrices. Explanations are given for those ratings that are not obvious or are incomplete without some explanation.

3. See Chapter 5 for instructions on how to use this matrix.

Figure 5-2(a). Matrix 2: Screening techniques based on reach conditions.

MATRIX 2: SCREENING TREATMENTS BASED ON REACH CONDITIONS
Explanation of Matrix 2 Ratings

REACH-BASED CAUSE		TECHNIQUE	RATING	EXPLANATION OF RATING
EQUILIBRIUM, DISEQUILIBRIUM				
All	All	Anchor points	D	Anchor points may be appropriate wherever local scour is occurring regardless of the reach condition, except for avulsions.
	Large flood event	All	D	Action depends upon probability of flood recurrence and whether it left the reach vulnerable to increased erosion.
REACH IN DISEQUILIBRIUM				
All		No action	D	Reach conditions should be addressed if a bank-protection project is built. This is not meant to say that the project should be built for the purpose of correcting reach conditions.
Aggrading reach	All	Woody plantings	G	Woody plantings in floodplain provide roughness and enforce banks.
		Log toe, rock toe	F2	Toe treatments may get buried. Need complementary bank treatments.
		Coir logs	G2	Toe treatments may get buried. Assumes coir logs can cover bank or includes complementary bank treatment.
	Reduced hydrology/increased sediment, Downstream constriction, Reduced slope	Groins, roughness trees	G, F, P	Roughness techniques can be appropriate when overall roughness is small compared to scale of channel so thalweg is moved away from bank but overall backwater is not increased.
	Downstream constriction, Reduced slope	Drop structures	F	Use to concentrate flow into single channel.
	Reduced hydrology / Increased sediment supply	Channel modificatiion	D	Sediment sump or dredging might be reasonable if increased sediment is temporary and not likely to recur. Levees usually increase flood hazard risk in this situation.
		Remove or reduce feature	G2	"Remove or Reduce feature" means removal or reduction (remedy) of source of excess sediment. Protection is not immediate so a complementary measure is needed.
	Reduced slope	Roughness trees	D	Can be good bank protection if roughness is small scale compared to channel so it does not affect conveyance by roughness or constriction.
	Confined channel	Buried groins	I	Assumes groins cannot be set far enough from the channel, therefore the channel cannot expand to its natural width.
Degrading reach	All	Riparian-buffer management	F2	Does not resolve degradation. Riparian zone may become perched on terrace.
	Increased hydrology / Reduced sediment supply	No action	D	"No action" may be appropriate if channel is approaching equilibrium.
		Groins	F	Roughness generally good for degrading channel. Rigid structures may be undermined and fail.
		Engineered log jam	G	Better than groin since log jam is more resilient.
		Cribwalls, manufactured retention systems	P	Assumes structures constrict the channel, without maximizing roughness. Structures may be undermined and fail.
		Soil reinforcement	F	Same as cribwalls but more flexible.
		Remove or reduce feature	G	"Remove or Reduce Feature" means restoration of natural sediment load. Protection is not immediate, so complementary measure is likely needed.
	Natural channel evolution	Drop structures, porous weirs	F	Bed structures create nick points in bed as channel continues to degrade. They will break down into the channel if they are erodible rather than hard, fixed structures.
		Soil reinforcement	F	Assumes soil reinforcement does not constrict the channel. Reinforced soil is flexible enough to accomodate degrading channel but does not allow floodplain evolution.

Figure 5-2(b). Matrix 2: Explanations of ratings in Matrix 2.

MATRIX 3: SCREENING TREATMENTS BASED ON POTENTIAL, LONG-TERM HABITAT IMPACTS
Refer to Chapter 4 for Habitat Considerations

Suitability of Mitigation and Bank-Protection Techniques with Respect to Habitat

This Technique → Impacts and/or Mitigates This Habitat Function ↓		No Action	Other Techniques			Riparian-Buffer Management	Flow-Redirection Techniques							Structural Techniques							Biotechnical Techniques					Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques		
			Spawning-Habitat Restoration	Off-Channel Spawning and Rearing Habitat	Channel Modifications		Groins	Buried Groins	Barbs	Engineered Log Jams	Drop Structures	Porous Weirs	Remove or Reduce Feature	Anchor Points	Roughness Trees	Riprap	Log Toes	Roughened Rock Toes	Log Cribwalls	Manufactured Retention Systems	Woody Plantings	Herbaceous Cover	Soil Reinforcement	Coir Logs	Bank Reshaping	Subsurface Drainage Systems	Floodplain Roughness	Floodplain Grade Control	Floodplain Flow Spreader
Suitability of Each Technique from Matrix 2:																													
Riparian Function:	Impacts To	A	A	A	D*	A	L	A	L	A	A	A	D	L	A	H	L	L	M	H	A	A	L	A	L	M	A	A	A
	Compensated By	-	-	-	D*	C	-	-	-	-	-	-	D	-	-	-	-	-	-	-	C	C	-	-	-	-	-	-	-
Cover:	Impacts To	A	A	A	A*	A	L	A	L	A	A	A	D	A	A	H	L	M	M	H	A	A	L	A	L	A	A	A	A
	Compensated By	-	-	-	C*	C	D	-	D	C	C	C	D	-	C	-	C	-	-	-	C	C	-	-	-	-	-	-	-
Spawning:	Impacts To	A	A	A	A*	A	L*	L*	L*	L*	L*	L*	D	A	A	H	M	M	H	H	A	A	A	A	A	A	A	A	A
	Compensated By	-	C	C	C*	-	D*	D*	D*	D*	D*	D*	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Complexity and Diversity:	Impacts To	A	A	A	A*	A	A	A	A	A	A	A	D	A	A	H	L	M	H	H	A	A	L	A	L	A	A	A	A
	Compensated By	-	-	C	C*	-	C	-	C	C	C	C	D	-	C	-	C	-	-	-	C	-	-	-	-	-	-	-	-
Lost Opportunity:	Impacts To	A	A	A	A*	A	H*	D*	H*	L	M	M	D	L	L	H	L*	H	H	H	A	A	A	A	A	A	A	M	M
	Compensated By	-	-	C	C*	-	-	-	-	C	-	-	D	-	-	-	-	-	-	-	C	-	-	-	-	-	-	-	-
Flood Refuge:	Impacts To	A	A	A	A*	A	A	A	A	A	A	A	D	A	A	H	A	A	M	H	A	A	A	A	A	A	A	A	A
	Compensated By	-	-	C	C*	C	C	-	-	C	-	-	D	-	C	-	-	-	-	-	C	-	-	-	-	-	-	-	-
Suitability of Each Technique From Matrix 3: **S**uitable/**U**nsuitable																													

Level of Impact
* = See Figure 5-3 (b) for additional explanation.
D = Site Dependent. Depends upon site - too varied to generalize in this matrix.
The ratings for the "Impacts Caused By" are:
A = Avoids Impact. Impacts to the habitat function are generally avoided.
L = Low Impact. Potential low levels of impacts.
M = Medium Impact. Potential medium-levels of impacts.
H= High Impact. Potential high levels of impacts.
The ratings within the "compensated by" rows are:
- = Not Applicable.
Additional options in the matrix are:
D = Site Dependent. Depends upon site conditions - too varied to generalize in the table.
C = Technique Compensates for habitat Impact.

NOTES
1. The ratings assume long-term impacts as opposed to short-term impacts. The ratings may vary if short-term impacts are under consideration. Each rating is subjective and may vary given site-specific conditions.

2. Construction may cause temporary impacts. Refer to Chapter 4 for information on how to mitigate for construction.

3. "No Action" may involve the decision to simply take no action. It may also involve solving the problem by undertaking "out-of-channel activities" (such as moving a building or structure) rather than implementing bank protection.

4. Matrix 3 is provided to assist in identifying options that will avoid or minimize impacts or will compensate for losses. Realize that this matrix is general; there will be situations that are exceptions to the matrix. The exceptions might be due to specific habitat requirements or unique site conditions. The matrices are a first effort to relate techniques and impacts; each cell should stimulate further discussion.

5. Any habitat impact listed on the matrix assumes that the habitat function is currently present. The standard of impacts to be mitigated is a regulatory issue. Possible standards include impacts to habitat currently present, or impacts to habitat that would be present in an unaltered site. Mitigating for habitat that would occur in an unaltered state is different than lost opportunity, which depends on erosion to be created.

6. The preferred bank-protection technique is the one that, in addition to solving the causes of scour, avoids the habitat impacts. Look for techniques with an "A" in the rows labeled "impacts caused by." If there are no techniques that avoid impacts, minimize impacts by looking for techniques that have low, medium and then high impacts, in that order. For every low, medium or high impact there must be provided a technique that compensates. Appropriate techniques for compensatory mitigation depends upon the mitigation target as described in Chapter 4. Compensating techniques for a particular habitat function are identified with a "C" in the rows "impacts mitigated by." Many specific techniques have a mix of C, L, M, H and A's in rows associated with "impacts caused by". In that case, consideration and weight must be given to what functions are critical or limiting, what functions cannot otherwise be mitigated and what functions might be most impacted by the projects. These conditions are also described in Chapter 4. See Chapter 5 for additional instructions on how to use this matrix.

Figure 5-3(a). Matrix 3: Screening techniques based on habitat impacts.

MATRIX 3: SCREENING TREATMENTS BASED ON LONG-TERM POTENTIAL HABITAT IMPACTS
Explanation of Matrix 3 Ratings

HABITAT FUNCTION	IMPACT CAUSED BY OR COMPENSATED BY	TECHNIQUE	RATING	EXPLANATION OF RATING
All	Impacts To, Compensated By	Channel modifications	A, C	Assumes that a full complement of habitat features is included in the channel modification project.
Riparian Function	Impacts To Compensated By	Channel modifications	D	May depend on riparian function at site (e.g., E. Wa vs W. Wa and emergent vs mature conifer forest)
Cover	Impacts To, Compensated By	Groins	F	Assumes groins are a wood-catching structure. Cover habitat depends greatly upon species and age class.
	Compensated By	Barbs	P	Barbs are too low to catch debris. Cover habitat depends upon species and age class.
Spawning	Impacts To, Compensated By	Flow-redirection techniques	L, D	Flow-redirection techniques create hydraulics suitable for spawning habitat though the habitat may vary from the habitat that is impacted.
Lost Opportunity	Impacts To	Groins, barbs	H	Assuming they are permanent rock groins rather than deformable woody groins.
		Buried groins	D	Depends upon the distance buried groins are from channel. Impact is much less if they are located at the edge of the channel-migration zone.
		Log toes	L	Log toes are considered deformable.

Figure 5-3(b). Matrix 3: Explanation of ratings in Matrix 3.

CASE STUDIES

To demonstrate the selection process, three case studies in Washington State are provided. The case-study sites vary from one another based on geography, geomorphology and level of risk. Case-study site # 1 is a rural reach of the Nooksack River, a braided river in Whatcom County. Case-study site # 2 is an urban reach of Salmon Creek in Vancouver. Case-study site #3 is an arid, rural reach of the Tucannon River in southeastern Washington.

Case Study #1: Nooksack River

Project Background

The Nooksack River Fish Habitat Enhancement and Erosion Control Pilot Project involved the remediation of severe erosion problems at two sites on the Nooksack River, using nontraditional methods. The project sites included 3,100 feet of streambank that had been progressively and severely eroding at a rapid rate for several years (*see Figures 5-4 and 5-5*). Many acres of farmland and low-lying forest had been lost, and there was concern that the erosion would facilitate floodwater access to a swale that carries water to the Everson Overflow and, ultimately, into the Fraser River watershed in Canada.

Concern about the Everson Overflow played a significant role in project initiation and funding. When the Nooksack River reaches a discharge of approximately 25,000 cubic feet per second, floodwaters overtop the Nooksack Watershed Divide and enter a tributary basin of the Fraser River. Over the past century, this overflow has led to flooding in several towns in Washington and British Columbia. By the summer of 1997, bank erosion at both project sites had cut headward into overbank swales that contribute to the Everson Overflow. Concern was raised that continued erosion would allow floodwaters to enter the swales at progressively lower water surface elevations (smaller floods). Thus, it appeared that continued bank erosion at both sites threatened to exacerbate the Everson Overflow problem.

Figure 5-4. Plan view of erosion on the Nooksack River.

Figure 5-5. Ground view of erosion on the Nooksack River.

This pilot stabilization project, designed and constructed in 1997, was carried out to test the ability of several non-riprap bank treatments to control bank erosion and associated sediment inputs, as well as to create needed fish habitat.

Site-based Assessment

The primary mechanism of failure for erosion at the two Nooksack River sites was toe erosion. There were two site-based causes for toe erosion: bend scour and a reduced vegetative bank structure associated with land clearing for agriculture. Bend scour was the dominant cause, which occurs when the erosive force shifts from the bed of the channel to the outer corner of the channel as it encounters a bend. A secondary mechanism of failure was the potential for an avulsion caused by natural aggradation in this river reach.

Reach-based Assessment

A geomorphic analysis conducted for the project indicated that channel migration was occurring in the project reach and that erosion in the project reach had extended beyond the historical limits of the meander belt. According to data from 1996 to 1997, the channel was migrating laterally, with bankline migration rates between 310 and 350 feet per year near the project sites. Lateral channel migration is a typical reach-based cause of toe erosion. In the case of the Nooksack River, meander migration was occurring at the edge of the channel-migration zone.

The Nooksack River is a wandering, gravel-bed river, typical of the western Washington region. Rivers in this region are characterized by depositional zones that form laterally unstable, braided channel segments and by transport zones that are single-thread, laterally stable reaches between the sedimentation zones. In the vicinity of the project sites, the river flows through a depositional reach that is characterized by multiple channels, extensive bar surfaces and lateral instability. Thus, the project reach of the Nooksack River is naturally aggrading and is probably in equilibrium over the long term.

Selection Process

Using Matrix 1, a number of bank-protection techniques were found to have a good level of suitability when toe erosion along a bend is the cause of erosion. Using Matrix 2, a number of bank treatments were found to have a good level of suitability when an equilibrium reach is experiencing meander migration at the edge of the channel-migration zone. When the matrices were combined, nine bank treatments were deemed acceptable. Three of the nine techniques were instream flow-redirection techniques, and the remaining six techniques were structural bank-protection techniques (several of the biotechnical techniques were also considered acceptable when used in combination with the other methods).

Several design considerations were important for determining the final bank-protection treatments used. First, the client and resource agencies would not allow the use of riprap, a structural technique that had been used unsuccessfully at these sites in the past. Second, the project budget precluded the use of expensive techniques such as log toes. And, finally, fish habitat was of primary concern. Thus, the treatment options were further screened using the first four categories of Matrix 3 (all of which pertain to fish habitat). Only four treatments were found to be acceptable at low-to-medium levels of impact on fish habitat: groins, buried groins, barbs and roughness trees.

Based on this process, bank treatments were selected that were relatively low cost, conducive to habitat formation and able to stand up to the dynamic behavior of a high-volume river (design discharge of 42,000 cubic feet per second). Because of the pilot-project nature of this work, several treatments were needed for effective comparisons to be made. With these conditions in mind, two types of treatment were selected: rock groins and log groins, with cabled, woody debris to enhance fish habitat. Bank reshaping, woody plantings and herbaceous cover were also selected for additional bank stability and habitat enhancement.

Design

Bank treatments used in this project included groins constructed of logs that were cabled to wooden piles (*see Figure 5-6, next page*); groins consisting of a rock key and foundation with an upper surface of concrete doloes (*see Figure 5-7, next page*); and groins built entirely of rock. The all-wood, log-and-pile groins were used where hydraulic analyses indicated they were durable enough for site conditions. The other site had higher-flow energy and received the dolo groins. Designs for both sites included cut-back trenches to prevent flanking of the groins, which could result in excavation of the barb keys by erosion. Both site designs also incorporated woody debris anchored to (or built into) the groins and banks. To promote bank stability, all banks were groomed back to a 2:1 slope. To protect the upper banks and to facilitate the rapid establishment of native riparian species, both designs also included detailed revegetation plans.

Figure 5-6. Log groins on the Nooksack River.

Figure 5-7. Concrete doloes with woody-material recruitment on the Nooksack River.

Mitigation

Matrix 3 identifies habitat impacts from various bank-protection techniques. Groins may cause a low impact to cover and a medium impact to riparian function, spawning and construction. To mitigate for these potential impacts, special provisions were made in order to maximize fish habitat in and around the groins. The woody and dolo groins were designed to be quite porous, thus creating "chutes" of flow as well as quiescent zones within and downstream of the groins. In addition, the porosity of the groins was designed to facilitate natural recruitment of woody debris. Furthermore, woody debris was cabled along the downstream edges of the rock and dolo groins and along the banks between groins to provide additional cover for fish. Finally, the particular arrangement of the groins would encourage development of deep scour holes near the tips of the groins, which would offer pool habitat at lower flows. The steep banks were reshaped and vegetated to mitigate for impacts to riparian function.

Monitoring

A three-year monitoring plan was developed for the two Nooksack River sites. Attributes monitored and associated monitoring techniques are shown in *Table 5-2*.

For more information on this project, contact Whatcom County Public Works Department, Division of Engineering, Whatcom County, WA, or Inter-Fluve, Inc., Bozeman, MT.

Project Attribute	Monitoring Technique
Barb and bank configuration	Yearly topographic survey and aerial photos, observations, photographs and video tape.
Erosion and deposition	Yearly topographic survey and aerial photos, observations, photographs and video tape.
Fish-habitat availability and usage	Habitat surveys, snorkel surveys.
Revegetation success	Vegetation surveys.
High-flow hydraulics	Observations, video tape of high flow events.
General site geomorphology	Yearly topographic survey and aerial photos, observations, photographs and video tape.

Table 5-2. Attributes and monitoring techniques associated with the Nooksack River site.

Case Study #2: Salmon Creek

Project Background

The Salmon Creek Bioengineered Bank-Stabilization Project was part of a multi-year effort by the Clark Public Utilities in Clark County to implement bank protection at approximately 30 sites within the Salmon Creek drainage area that had experienced recent bank erosion. The Salmon Creek watershed, located near Vancouver, is typical of basins in expanding urban areas of the Pacific Northwest that have been transformed from forest to agriculture to mostly urban land use. These watershed changes have included concurrent declines in salmon and steelhead populations, as well as increased channel erosion.

Clark Public Utilities, using money for fish-habitat restoration, identified several bank-protection project sites. The project objectives were to use innovative bank-protection technology that addresses long-term bank stability and is sensitive to fish and wildlife habitat. Early project sites (1996) typically included eroded vertical banks from three to 12 feet in height, composed mostly of fine sediments (silt) that, once eroded into the channel, threatened habitat quality within Salmon Creek. The design solution for these sites incorporated a stable rock foundation, with native-soil reinforcements, woody plantings and herbaceous cover above. Later project sites (1997) were targeted for a less-intensive bank-stabilization approach, such as the use of woody debris, coir fabrics and vegetation. At one particular site, channel modifications were used in conjunction with woody debris and woody plantings to promote bank stability and enhance habitat.

This case-study description focuses on one particular site, about 650 feet in length, where the streambank was severely eroding into adjacent properties. An expansive gravel bar was directing the channel thalweg toward a steep slope with fine sediments, and single-family residences located at the top of the slope were at risk (*see Figure 5-8*).

Figure 5-8. Eroding bank on Salmon Creek.

Site-based Assessment

The mechanism of failure at this site was toe erosion. The toe erosion had two site-based causes: bend scour and reduced vegetative structure associated with human development. The primary cause was reduced vegetative structure, a condition that occurs when woody vegetation is disturbed along the bank and riparian area, subsequently making the bank more susceptible to erosion.

Reach-based Assessment

This Salmon Creek site was located in a depositional reach with a lower gradient than upstream or downstream reaches and extensive gravel bars that occluded previous channel alignments. A bridge at the downstream end of the site, constricts the channel and causes the reach to backwater at high flows. As a result, the channel in this reach had realigned several times in the last thirty years, each occurring after a large flood event. The potential for avulsion was also a mechanism of failure as evidenced by aggradation, previous channel relocations and the presence of a downstream constriction.

Selection Process

Using Matrix 1, treatments were screened for the project site with a mechanism of failure of toe erosion due to erosion along a bend and/or reduced vegetative structure. Using Matrix 2, treatments were further screened using the reach-based considerations for an aggrading reach with a localized, downstream constriction and reduced slope. This resulted in 11 acceptable treatments, ranging from channel modifications to structural bank-protection techniques, to biotechnical treatments.

Several design considerations were important in determining the final bank-protection treatment used for this site. Since low-cost alternatives were desirable, several expensive techniques were eliminated from consideration. In addition, a combined approach was desirable in order to satisfy the client's preference for innovative treatments that benefited habitat. Most importantly, techniques were needed that would remedy the tendency for the aggrading channel to realign. Based on these considerations, channel modifications and woody plantings were selected as the most useful approach to restoring channel and bank stability.

Since fish habitat was emphasized for this project, Matrix 3 was used to identify habitat impacts of the various bank-protection techniques. The treatments used at this site generally avoid impacts to fish habitat. However, several design elements were included to ensure that habitat elements were enhanced. A backwater channel at the left channel margin adjacent to the gravel bar was excavated (lengthened, widened and deepened), and woody debris was added to provide escape and cover habitat for fish. Woody debris was also placed in the high-flow channel to enhance rearing habitat. In addition, the bank plantings were designed as a long-term benefit to fish by fostering a riparian area, which will eventually provide shade and cover for the stream channel at each site.

Design

The bank-protection techniques used at the project site included channel realignment, high-flow channel creation, and vegetative plantings (*see Figure 5-9*). The six-foot-high, vertical right bank was protected by relocating gravel bar material and realigning the channel toward the left bank. Photographic records of channel changes within the reach were used to select the most stable channel configuration. Next, material was excavated to form a high-flow channel upstream to increase conveyance and to provide some relief during flooding. It also decreased erosive potential along the newly created right-channel boundary. Finally, the slope of the eroding bank was reduced, and the roughness of the bank was promoted by planting willow clumps salvaged from the high-flow channel excavation. These treatments were combined with woody-debris placement in off-channel areas and woody plantings to promote bank stability and habitat.

Figure 5-9. Channel realignment, vegetation plantings and bank reshaping on Salmon Creek.

Monitoring

Unfortunately, monitoring was not done on this project. For follow-up information, contact Clark Public Utilities, Vancouver or Inter-Fluve, Inc., Hood River, OR.

Case Study #3: Tucannon River

Project Background

This project is located on the Tucannon River in Columbia County, on property owned by the Washington Department of Fish and Wildlife. This reach of the Tucannon River has been straightened, cleaned and diked, resulting in isolation of the riparian zone and loss of pool habitat. Most recently, the property had been managed for cattle grazing, and the left-bank riparian zone was in very poor condition. The main damage to the site occurred during February 1996, when a flow of 5,500 cubic feet per second was recorded at the USGS gauge at Starbuck, WA. The recurrence interval for this magnitude of flood is between 10 and 25 years. As shown in *Figure 5-10*, the flood scoured the left bank, formed numerous gravel bars at the site and created a braided section of channel with high width-to-depth ratios.

Figure 5-10. Left-bank erosion on the Tucannon River.

Researchers have documented a lack of spring chinook salmon spawning in the reach relative to upstream and downstream reaches. This is attributed to lack of deep pools with large woody debris cover and high water temperatures. These conditions are due to channel straightening, cleaning and diking activities following the 1964 and 1970 floods and subsequent loss of riparian-zone function.

The goal of the project was to provide a demonstration project that would address fish-habitat needs, channel stability issues and floodplain function. The habitat needs include deep pools, large-woody-debris cover, reduced summer water temperatures and over-wintering habitat for juvenile salmon. The project objective was to form a single channel with appropriate width, depth and curvature for stability.

Site-based Assessment

The primary mechanism of failure was toe erosion. There were two site-based causes for toe erosion: 1) reduced vegetative bank structure associated with grazing activities, and 2) bend scour. Reduced vegetative bank structure was the dominant cause. It occurs when the woody vegetation in the riparian area is disturbed or removed. Loss of the vegetation root structure reduces the shear-resisting strength of the bank and the ability of the bank to resist erosion.

Reach-based Assessment

This reach of the Tucannon River has been impacted by channel diking (upstream and downstream), large woody debris removal and straightening. However there were no dikes in the immediate vicinity of the site, and it is uncertain if the channel had been straightened at the site. The primary reach-based cause of erosion was large floods experienced throughout the watershed in February 1996. Many of the bridges in the Tucannon watershed were damaged or destroyed during the floods. These floods caused a rapid change in the channel form and short-term disequilibrium. The rapid change in form resulted in several braided channels at the site. The lateral erosion was within the channel-migration zone.

Selection Process

According to Matrix 1, a number of bank-protection techniques are rated as "Good" when the mechanism of failure is toe erosion caused by reduced vegetative bank structure. Using Matrix 2, a number of bank treatments are again rated "Good" when a reach is in disequilibrium caused by a large-scale flood event. When the matrices are combined, there were suitable bank-protection treatments for this particular project, ranging from channel modifications to structural bank protection to biotechnical treatments.

In Matrix 1, engineered log jams are rated G2 (meaning they are considered Good when used in combination with other techniques rated as Good) for a reduced vegetative structure bank. Since there was no immediate threat to infrastructure, the engineered log jams were accepted over other instream flow-redirection and structural bank-protection techniques, given the habitat value provided by engineered log jams.

Using Matrix 2, engineered log jams were further screened for reach conditions that are in short-term disequilibrium primarily caused by large-scale flood events, though meander migration within the migration zone could be considered as secondary. The rating for use of engineered log jams is "Site Dependent" for large-scale flood events. Jams are rated "Fair" to "Good" for addressing meander migration. Because of the low risk of impact at the site, the technique was considered acceptable.

Since this was a demonstration project, one of the design considerations included using a composite treatment, with emphasis on restoration of fish habitat. Using Matrix 1 and Matrix 2, biotechnical techniques and woody and herbaceous plantings in combination with bank reshaping were selected to increase bank stability and eventually decrease summer water temperatures.

Matrix 3 was used to identify habitat impacts of the various bank-protection techniques. Engineered log jams both avoid and compensate for all habitat impacts except construction impacts. The use of large woody debris in the jams would provide fish habitat and prevent erosion of the new bank line. The jams would collect additional woody debris and form deep pools with excellent cover. The bank between jams was not armored or diked, so the floodplain would function during floods. The jams were designed to maintain the thalweg in the new alignment, and the bankline in the "shadow" of the jams would be a deposition zone where vegetation could be re-established. The floodplain area would also be revegetated to speed the establishment of a riparian zone. Woody and herbaceous plantings are rated in Matrix 3 as "Avoiding All Impacts." Bank reshaping is rated as having a low impact on cover and riparian function and a medium impact for construction. Planting vegetation would compensate for impacts from bank reshaping and would be designed as a long-term benefit to fish by fostering a riparian area to provide shade and cover for the stream channel.

Design

Figure 5-11 and *Figure 5-12* show the project two years after construction. The engineered log jams were modeled after a technique developed by T. B. Abbe and D. R. Montgomery.[1] Key pieces were made by cabling several trees together and cabling four, three- to four-foot-diameter boulders to each piece. The boles of key pieces were buried in gravel-bar sediments up to the rootwad, against which smaller logs were racked. As a factor of safety, several four-foot-diameter boulders were placed on the rack for additional ballast.

Figure 5-11. Engineered log jams on the Tucannon River.

Figure 5-12. Engineered log jams on the Tucannon River.

Channel geometry was based on a preliminary analysis and included bankfull width (40 feet) and depth (3.5 to 4.0 feet), and meander radius (330 feet). The channel cross section shape was triangular, with a 2:1 slope on the outside of the bend and 8:1 slope on the inside of the bend. The five engineered log jams were spaced at 90-foot intervals along the meander. The stepwise progression of engineered log jams is intended to maintain the thalweg of the channel along the desired alignment. This will not prevent portions of flood flows from leaving the channel between jams, nor will it prevent the floodplain from functioning. A riprap cutoff trench extends into the bank at the upstream jam to reduce the risk of the channel cutting behind the first structure of the series.

Beyond the boundaries of the bankfull channel the soils were graded to blend into the local topography. Both banks were planted with native vegetation, including cottonwood, willow, Ponderosa pine and wild rose. Willow and cottonwood live stakes were planted in August, following the engineered-log-jam construction, but nearly all died. A second planting of live stakes, plus rooted pine and rose, was completed the following spring. These survived.

Monitoring

The preproject conditions were documented by oblique aerial photos taken in 1998. Photos were also taken from a nearby hillside in 1998 and 1999. Photographs will be taken repeatedly as significant flows bring about changes at the site. Following project completion, an as-built survey recorded the location of the new channel, thalweg, engineered-log-jam locations and widths, and the location of the edge of the 1996 eroded bankline behind the jams. The survey may be repeated if deemed necessary. There have not been any significant run-off events since the construction and consequently little change to the project.

Biologists with the Washington Department of Fish and Wildlife have conducted several snorkel surveys of the site since construction. They have verified significant use of the engineered log jams by juvenile chinook salmon and steelhead, and resident rainbow trout. There have also been several sightings of adult salmon resting at the engineered log jams. Additional surveys may occur but are not currently scheduled.

CONCEPTUAL STREAMBANK PROTECTION

The selection matrices are based on a numerical rating approach to identify possible treatment techniques that address a particular erosion problem. To aid further in the selection process, this section supplements the matrices with a qualitative description of those techniques that are consistently rated as "Good" or "Fair." For the sake of brevity, only the most common erosion problems are described here. This section also provides treatment alternatives to consider during and/or immediately following an emergency.

Before settling on any one or combination of treatments, it's important to determine whether a permanent treatment is required or if a deformable bank treatment would work better.

To stabilize an eroding bank in an area that poses a high risk to adjacent buildings or infrastructure, a permanent treatment is generally used. Such techniques typically use rocks and logs at the toe of the slope (and some distance up the slope), with the inclusion of soil or other appropriate growing media to support plants. These measures halt bank erosion at the site, while providing the physical template for the creation of aquatic habitat and establishment of riparian vegetation.

A deformable bank treatment should be considered where a small amount of continued bank erosion each year is acceptable or even preferable, but the current rate of erosion is excessive. Deformable bank treatments provide for immediate bank stabilization, using native and biodegradable materials, in order to allow healthy riparian vegetation to become established. Unlike permanent treatment materials, however, deformable bank treatments allow the bank to shift and change somewhat over time at a natural, acceptable pace. In this scenario, long-term bank erosion is minimal, and stabilization relies on maintaining good streamside vegetation.

Treatments for Scour

Scour is caused by features in the channel that disrupt the natural flow patterns and increase the turbulence in the vicinity of those features. This turbulence creates scour holes where energy is dissipated. Roughness elements placed in a scour hole are not the best solution, since their scale often eliminates the energy dissipation volume of the scour hole. Rather, adequate volume in the scour hole should be provided to assist in energy dissipation.

Before settling on any one or combination of treatments, it's important to determine whether a permanent treatment is required or if a deformable bank treatment would work better.

An effective scour hole does not transfer any carry-over energy downstream. It therefore offers some protection to downstream banks and channel. The importance of scour holes cannot be downplayed; destroying them by straightening the bankline can lead to more complex and destructive dynamics downstream. If the scour hole is just beginning to evolve, you can expect lateral and bed scour until the hole has matured and stabilized.

Balancing the need to preserve a scour hole while preventing further erosion requires the use of anchor points. Anchor points are either natural (e.g., tree, rock outcropping) or artificial hard structures (e.g., rock trench) at the upstream and downstream end of an energy sink. They fix the upstream and downstream points of the scour hole so volume cannot be gained by erosion in the upstream or downstream directions. By fixing these points, volume is gained by forcing erosion either laterally, or (even better) vertically, by eroding the channel bed and creating a deep pool.

Treatments for Toe Erosion

Toe erosion is the most common mechanism of failure in Washington State. Toe erosion results as material is entrained from the toe and/or surface of the bank by flowing water. Toe erosion may be caused by reach- and site-based causes. Common site-based causes include reduced vegetative bank structure, smoothed channel and bend scour. Common reach-based causes include meander migration, aggradation and degradation.

Treatments to consider for toe erosion caused by reduced vegetative bank structure include restoring a hospitable environment for vegetation by applying toe protection and reshaping and planting the bank. Toe protection can either be permanent or deformable depending upon the level of risk and the location of the streambank in the migration corridor. Fencing out livestock and establishing a riparian buffer are very effective solutions. Techniques to redirect erosive flows away from the bank and to provide roughness can be used in combination with the above techniques. Groins should not be used since they create strong eddies along the bankline.

Toe erosion along a bend (bend scour) can result from either natural or human activities. A channel that is in equilibrium and migrating will create bend scour. Likewise, a channel that is in disequilibrium will also create bend scour. It is important to recognize whether bend scour is occurring in an equilibrium or disequilibrium channel. Applying structural bank treatments to bend scour in an equilibrium channel can have profound impacts on upstream and downstream channel dynamics as discussed in Chapter 3, *Reach Assessment*. These techniques disrupt the natural meander migration and patterns of erosion, often resulting in the need for even more bank protection. Deformable treatments are the most appropriate since they allow for gradual meander migration. These are discussed in more detail in the following section. Applying structural bank treatments in a disequilibrium channel experiencing bend scour can also have profound impacts upstream and downstream. For these reasons, deformable techniques should also be considered first. If the level of risk to infrastructure is such that any further erosion is not tolerable, then flow redirection and structural techniques may be necessary.

Toe erosion is also caused in a channel that has been smoothed. The best solution is to add what was originally lost; that is, *add roughness elements*. Roughness elements, such as woody debris, woody vegetation and randomly placed boulders can be incorporated into the stabilized bank to enhance the hydraulics and habitat of the reach. Other appropriate techniques include grade control, such as a drop structure or porous weir.

Treatments for an Aggrading Channel

A reach aggrades when more sediment is transported into the reach than can be transported out of the reach. Aggradation occurs either naturally or is induced or accelerated by human activities. The reach-based causes for aggradation are reduced hydrology, increased sediment supply, downstream constriction, reduced slope, or channel confinement. Refer to Chapter 3 for more information on the reach-based causes of aggradation.

If aggradation is caused by an increased sediment supply, reducing the excess supply of sediment from upstream sources is the most effective solution. Sediment transport to the riverine system originates from different hill-slope and valley morphologies and is dominated by either fluvial or mass wasting processes.[2] Other sources originate from the channel itself due to excessive bank erosion. One way of reducing the excess sediment supply is to increase the capacity for sediment transport within a reach by modifying the channel to an appropriate pattern, profile and cross section. The feasibility and design of this concept requires a detailed analysis of sediment transport characteristics and hydrology. Identifying and selecting a migration corridor that extends beyond the current active channel should also be considered. Broadening the channel's migration corridor will allow aggradation and recovery to occur naturally.

Debris jams play an important role in bedload transport by providing storage of bedload and metering the rate of downstream transport. Many river channels have experienced a decline in woody-debris input. Constructing a debris jam upstream from an aggrading reach may reduce the rate of bedload supply transported downstream. Alternatively, constructing a midchannel debris jam in an aggrading reach will create a stable island immediately downstream. This has a stabilizing effect on the total channel cross section. However, if the cause of aggradation is a confined channel or a downstream constriction, then engineered log jams are not recommended, since they can further confine or constrict the channel.

Removing or reducing a constriction that is causing aggradation is another way of treating an aggrading channel. If the constriction is a bridge, consider removing or redesigning the bridge. A bridge can be redesigned to reduce the constriction by increasing the channel area under the bridge (e.g., increase span and/or vertical clearance) or streamlining the bridge approach (e.g., use channel modifications and/or wing walls). The decision to remove or redesign a structure, such as a bridge, can be costly, and it must be balanced with economics and the level of risk to property that is threatened by erosion. If the constriction is a culvert, consider removing or redesigning the culvert. If the constriction is due to a debris pile, consider partially dismantling the debris pile. However, debris that is removed must be placed back in the channel as habitat-restoration elements, used in other bank-protection projects, or stockpiled for future habitat-restoration efforts. The decision to remove a debris pile must be carefully considered with respect to habitat functions that may be impacted.

If the floodway has been confined by a levee or road, *setting back the confinement or removing it* will allow the channel to regain its natural channel length and slope. The minimum outer limit of the setback should be at the edge of the channel's natural meander belt. Optimally, the setback should be far enough beyond the channel's meander belt to provide floodplain function and an appropriate level of flood management to adjacent properties.

Removal of sand and gravel to alleviate aggradation problems should only be considered after analyzing and exhausting more preferable techniques. This technique requires a detailed analysis and understanding of the channel hydraulics, hydrology, sediment budget and biological effects of removing materials. Locating appropriate sites for removal is crucial. The most common site for gravel removal is where the channel is aggrading. However, this is most often a short-term solution; it may have significant impacts on habitat, and it requires ongoing maintenance. Other sites to consider for removal are upstream from the aggrading reach where the material is stored, including the initial upstream source of sediment, such as an upland mass slide. Optimally, the location for removal should be identified as part of local watershed planning studies.

Treatments for a Degrading Channel

A common cause of degradation is an increase in hydrology. The optimum long-term solution is to identify and *remedy the cause of the increase in hydrology* rather than focusing only on the eroding bank. In other words, don't just treat the symptom; treat the cause. Under the best of circumstances, this would involve local-government planning efforts in the development of basin or watershed studies and the implementation of a *storm-water management ordinance*. The next-best solution is to redefine the channel to accommodate the anticipated long-term inputs of sediment and flows, consisting of a modification of the channel's pattern, profile and dimensions to fit the new hydrologic regime. Examples include lengthening, roughening, widening and/or sloping the banks of the channel. However, if only a short-term solution is available, appropriate techniques include grade stabilization and use of bank protection to increase roughness along the channel bank.

The primary concern to be aware of if applying bank-protection treatments in a degrading channel is the potential for the river to undermine the treatment by lowering its channel bed. Consequently, the design of a bank-protection technique applied at the toe of a bank must be sufficient to withstand down-cutting. This resistance is critical to project performance (in addition to depth of scour calculations based on existing conditions).

To minimize or prevent further channel lowering, consider stabilizing the bed using *grade-control structures,* such as porous weirs or drop structures. Construction of grade-control structures will prevent degradation upstream from the structure. Degradation downstream from the structures will continue if the cause of degradation is not controlled. *Bank and/or bed stabilization* placed on a channel that is actively incising has a strong potential for failure due to undercutting of those treatments; consequently, an actively incising channel requires aggressive bed stabilization.

Raising the channel to reconnect the old floodplain surface is another option. This technique requires selecting appropriate locations to tie into the old channel, but it may prove difficult if tie-in points are similarly incised.

Where a channel is shortened, *lengthening the channel* and adding roughness elements are possibilities. This will require a comprehensive study of undisturbed reaches or reaches in a geomorphically similar river to understand the river's natural channel pattern, profile and dimensions. Based on this information, the straightened reach can be rechannelized to mimic its natural pattern, profile and dimensions. Roughness elements, such as woody debris, woody vegetation and randomly placed boulders, can be incorporated in the rechannelized reach to enhance the hydraulics and habitat of the reach.

Relocating the channel to reconnect the old floodplain surface around an incised reach can be highly effective. However, for this treatment, the abandoned channel must still be treated so as not to recapture the main flow at a lower elevation.

Another alternative for treating a degrading channel is to *enhance the natural, incised-channel evolution process* by widening the incised channel. This will facilitate the formation of a new, inset floodplain surface at a lower elevation than the pre-incision surface.

Treatments to Prevent Avulsion or Chute Cutoff

Where a potential for channel avulsion or chute cutoff due to aggradation is recognized, it is important to determine the cause for that aggradation. Techniques that prevent avulsion or chute cutoff will require long-term maintenance if the causes of aggradation are not addressed.

Where overland flow is concentrated and creating a potential for avulsion or chute cutoff, *floodplain roughness and flow spreaders* can help reduce this potential. *Trees and/or large woody debris* can be placed in a series of rows perpendicular to the direction of overland flow to form small dams that are porous and collect debris. They dissipate flow energy and distribute the flow across the floodplain.

Another means of controlling overland flow is to *construct a floodplain flow channel* to convey overland flows back to the river. A floodplain berm may be used in conjunction to direct flows to the floodplain channel, especially if the cause of overland flow is the presence of floodplain mining pits. The channel must be armored to prevent scour, and egress must be provided to prevent fish stranding. An abandoned channel may be used as a floodplain flow channel.

Grade control involves creation of a thick pad of heavy rock or large woody debris placed below grade in the floodplain. The purpose for grade control is to prevent surface erosion or nickpoint migration caused by overland flow. Soil can be placed on top of the grade control and planted with vegetation. Grade-control measures can be used in conjunction with a floodplain flow channel. They do not prevent overland flow during flood events. This treatment does not eliminate a flood hazard, though erosion will be minimized or even prevented.

The least-appropriate technique for dealing with an avulsion is constructing a levee. Ironically, this has been the historic technique of choice. Because the cause of an avulsion is floodplain surface erosion and not direct bank erosion, a revetment is not the most appropriate technical or economical solution. The only situation in which a setback levee is recommended is if there is a high level of risk to property or life and all other techniques have been thoroughly investigated and eliminated.

The least-appropriate technique for dealing with an avulsion is constructing a levee. Ironically, this has been the historic technique of choice.

Flow spreaders are also used in combination with other other bank-protection techniques where there is a potential for a chute cutoff. Chute cutoffs differ from an avulsion in that a chute cutoff is a type of meander cutoff that changes channel alignment on a smaller scale than an avulsion. Chute cutoffs occur when a bend in the stream becomes so tight that it causes sediment and debris to deposit and creates backwatered flow conditions in the upstream limb of the bend. The backwatered conditions increase the frequency of over-bank flows. As the flow shortcuts across the bar and re-enters the channel on the downstream limb of the bend, erosion and the development of a new channel or "chute" results. For these reasons, it is critical to consider both streambank-protection techniques that address meander migration and floodplain erosion-control techniques, such as floodplain roughness and flow spreaders.

If a channel is fully avulsed or a chute cutoff has occurred and the new channel is in an acceptable location, it may be appropriate to enhance the new channel rather than return the channel to its original course. Treating a newly avulsed channel is similar to treating an incised channel. Defining an appropriate channel width and shape promotes geomorphic equilibrium on the new channel segment. Erosion control is necessary if downstream sediment loading is excessive. Where livestock use is high, avulsed channel segments should be provided with a protected riparian buffer zone to allow natural recovery of the new segment, including obtaining easements, planting and fencing the buffer.

Treatments for Emergency Conditions

As described in Chapter 4, emergency treatments may be implemented during a flood event, or when conditions remain unstable. Where floodwaters are high and access to the channel is limited due to physical and safety constraints, treatments involving dumping or placement of rock along the bank from the top of the bank may be considered. Since visibility of the bank and toe area are usually limited by high water, the orientation of installed rock materials is difficult to evaluate until floodwaters have receded. Another treatment involves placing rock at the top of the bank, so that, as the channel migrates, the rock is launched, eventually preventing further bank retreat. Other treatments include exposed and buried groins, anchor points and avulsion-prevention techniques in the floodplain, such as placement of large woody material or roughness. An emergency treatment will likely require further construction after the recession of flood waters to ensure it is has an adequate key and to incorporate habitat measures as mitigation. An emergency treatment may also need to be replaced by a more appropriate treatment measure that addresses the site and reach conditions, as well as risk, habitat and design considerations.

An emergency treatment may need to be replaced by a more appropriate treatment measure that addresses the mechanism and causes of bank erosion.

DESIGN CONSIDERATIONS

Streambank-protection designs must consider many components and variables. Often, these are aspects of design that need to be incorporated into a solution; others are fundamental considerations that guide selection of a particular treatment. All of these require consideration within the context of mitigation needs (see Chapter 4). The design process requires an iterative approach of "solving" for these various components; that is, providing a solution for one aspect and then adjusting it as another aspect is considered.

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The following subsections address important components of the design process for each of the functional protection techniques described previously. The design processes have been organized in a chronological sequence as a designer would address them. For example, the erosive energies at a site (shear and scour) are considered first, while the effects on channel geometry and the type of revegetation are secondary. However, the importance of these design considerations varies both from site to site and according to the type of technique employed. For some locations or technique groups, a component may be less important (or not important at all), while in others it may be the most significant aspect of the project.

Bank Resistance to Shear Stress

In Chapter 2, the effects of shear were examined to identify the mechanisms of bank failure. It is also imperative to calculate a value of shear stress to determine an appropriate bank-treatment design.

Recognize that, once a bank is stabilized, it is altered from pre-existing conditions; the shear stress at the site after construction may be different from preconstruction conditions. Thus, if a channel cross section is changed substantially, one must use proposed conditions to calculate a new shear stress.

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Shear stress is calculated by:

- measuring the dimensions of a channel cross section (see Appendix F, *Fluvial Geomorphology*),
- determining the water depth at the river stage at the proposed design discharge (see Appendix D, *Hydrology*),
- determining the slope of the water at this same river stage, and
- using these parameters to calculate shear (see Appendix E, *Hydraulics* for appropriate equations).

Shear stress is vertically distributed within a channel cross section (see Chapter 2); therefore, the bank treatment can be designed to account for these vertical differences. Where bank shear is greater near the toe of slope, rock or woody material might be used to provide stability. Midslope bank stabilization might consist of biodegradable, erosion-control fabrics that will provide protection until vegetation is established. The top of the slope might require minimal stabilization (e.g., simple seeding and mulching).

Shear is also greater on the outside of bends, up to 2.5 times greater than the inside of a bend (see Chapter 2). Thus, bank-treatment design needs to account for the lateral position within a bendway. The amount of shear that a site might be exposed to thus depends upon the channel slope, the depth of the water at a particular design flow, the location up the bank and the position in the channel (in a straight reach or bend).

Toe Protection to Resist Scour

In order to protect against continued scour, it's important to identify the type of scour so that maximum scour depth can be calculated for the bank-treatment design (Chapter 2). Anticipating maximum depth of scour helps identify the type and depth of toe foundation needed to provide a firm base for a stabilized bank.

Determining the maximum depth of scour is accomplished by:

- identifying the type(s) of scour to be concerned with at a site;
- calculating the depth for each type of scour;
- accounting for the cumulative effects of each type of scour occurring at the site (if more than one is present); and
- reviewing the calculated scour depth for suitability based on experience from similar streams, conditions noted during the field visit and an understanding of the calculations.

Equations are available to calculate the maximum depth of each type of scour (Appendix E). These equations are type-specific (e.g., a bend scour equation will give you an erroneous value if the cause of erosion is actually constriction scour). The equations are also empirical; they are based on repetitious experiments or measurements in the field and, therefore, can be biased towards a specific type of stream where the data was collected. For example, some equations are based specifically on sand-bed streams or, in the west, granular beds, while other equations are based on eastern streambeds with cohesive soils.

In addition to calculating the scour forces on the bed, it is also important to know the composition of the existing bed materials when designing a bank-protection project. It is likely that the existing materials are insufficient to resist scour and must be augmented or reinforced with additional materials. Where existing bed materials are substantially smaller than placed materials, some form of protection against entrainment or piping must be used. A gravel filter layer or a synthetic construction fabric is typically used in such situations as a barrier between native and placed materials.

Appropriate Channel Geometry and Roughness

Considerations of channel geometry and roughness should include:

- evaluating the effects of encroachment,
- maintaining sediment continuity, and
- providing an appropriate planform.

These aspects are described in Chapter 3 and highlighted in this section.

Encroachment involves placing materials or configuring a stabilized bank to extend into the channel or narrow the channel. In some situations, bank-stabilization measures do not encroach on a river and, thus, have no impact on channel geometry and associated flow conveyance. For example, in a river with a width of over 100 feet, placing a bank treatment that extends into the channel a few feet will generally have no effect on conveyance or flow characteristics. However, in smaller channels where *any* encroachment will have an effect, or in larger channels where encroachment may be substantial (for example, with groins or barbs), the effect of encroachment should be evaluated in design.

The effects of encroachment include:

- creating localized flow turbulence (which may be desirable for habitat creation, or undesirable because of increased shear or scour forces);
- shifting the deepest part of the channel cross section (thalweg), which may affect downstream erosion and deposition patterns;
- reducing conveyance, thereby increasing the frequency of overbank flows (flooding); and
- adversely affecting aquatic habitat that exists along the channel margin.

Roughness can have a substantial effect on the amount of encroachment. Grasses generally do not encroach on a channel conveyance, whereas a stand of dense trees along the banks and floodplain restricts conveyance. Channel roughness is important to channel function and health. Roughness dissipates energy away from the soil surface, thereby reducing surface erosion (for example, willow branches absorb energy that would otherwise be expended on a streambank). Roughness promotes the deposition and storage of sediment. From a habitat perspective, roughness can be very important, as it usually provides habitat for fish in the form of cover and refuge.

Channel roughness is important to channel function and health.

Maintaining sediment continuity through a project reach is also an important consideration of channel geometry and roughness. As a bank-stabilization project is designed, the width, depth, slope and roughness of the channel should be maintained or improved to provide for the desired sediment-transport regime. For further discussion of sediment continuity, see Chapter 3.

Lastly, the shape of the stabilized bank in planview should be considered to ensure that the orientation of the bank relative to a bend is appropriate (i.e., not too tight). Again, refer to Chapter 3 for a discussion of this consideration.

Gradual Bank Deformability

As discussed earlier in this chapter and also in Chapters 3 and 4, bank-protection measures can be designed to be permanent (fixed in place) or to gradually change over time. During the design process, the question should be posed whether or not bank protection needs to remain in place permanently, for example, to protect a building or a bridge or some other infrastructure with a long life expectancy. Conversely, if the erosion problem is in a setting where the rate of erosion needs to be greatly reduced, but not altogether stopped, then a deformable bank might be designed. Deformable banks can be used where there is a riparian corridor, agricultural land use and where minor erosion will not threaten infrastructure.

Deformable bank-protection measures do not impinge on natural, long-term, meander-migration processes (described in Chapter 3); and, thus, do not exacerbate upstream and down-bank instability as do permanent stabilization measures. Deformable protection measures have the added advantage of having less impact on channel stability and aquatic and terrestrial habitat, providing for long-term planform deformability without adversely impacting the migration patterns of streams and rivers.

Deformable bank protection includes a biotechnical bank-protection treatment for the portion of bank above the water surface. In some situations, this level of protection is sufficient. Where below-water protection is required against shear forces (where the native bed and bank materials are readily eroded), deformable bank toes might include those made from small wood and gravel, or from gravel wrapped in biodegradable erosion control fabric as shown in *Figure 5-13*.[3] In these applications, the gravel or cobble approximates the size of the largest gravel or cobble in the stream. Once the wood or fabric decays, the gravel or cobble can be gradually eroded. By that time, the above-water portion of the bank will be vegetated, resisting erosion.

Deformable bank-protection measures do not impinge on natural, long-term, meander-migration processes and, thus, do not exacerbate upstream and down-bank instability as do permanent stabilization measures.

Figure 5-13. Gravel wrapped in biodegradable fabric serves as a deformable bank.

Soils and Subsurface Materials

Another design consideration is bank material, which may be cohesive (with a high silt/clay content) or noncohesive (largely sands and gravels), have a large percentage of rock or no rock, be stratified (layers of differing materials), nonhomogeneous (differing from one point on the bank from another nearby) or consistently the same. Topsoils can be thick, thin or nonexistent.

Although bank treatments may be placed over these materials, it is still important to identify their composition for revegetation design and technique selection. Subsurface materials may need to be separated from placed materials (to prevent piping or particle-by-particle transport of fines through the soils by flowing groundwater). Subsurface materials and topsoils may also be used in constructing a stabilization technique (for example, by using large rock found in the bank or using topsoil as a growing medium for fascine installation).

Limits of Vegetation Establishment

Design of bank-stabilization measures that involve native-planting restoration will need to account for the lower limit of vegetation in a channel. Within each stream segment, the lower bank limit where herbaceous species (grasses and forbes) and woody species (shrubs and trees) survive is largely dictated by hydrologic conditions. (see Appendix H, *Planting Considerations and Erosion-Control Fabrics*). Plant species are adapted to tolerate varying levels of inundation for different periods of time (i.e., the duration and frequency of flows). The lower limit of vegetation is exhibited in stable stream reaches by the lowest elevation where older or mature plants are found.

Bank-stabilization measures using plants that rely on vegetation for long-term stability must account for this lower vegetated limit. In the long-term, plants cannot be expected to survive below this elevation. Thus, this elevation often dictates the height of hardened toe features (rock or logs), with the recognition that the placed materials, not plants, will have to provide stability below this point. It is important to consider the rooting depth and type of plants when determining the lower vegetated limit. Grasses, for example, have a relatively shallow rooting depth and may not provide much stabilization below the lower vegetated limit. Larger trees, however, have extensive root systems, providing stabilization a significant depth below the limit.

It is important to consider the rooting depth and type of plants when determining the lower vegetated limit.

The lower vegetated limit is generally not determined by a flow of a given hydrologic probability (see Appendix D). It is best determined by measuring the base level of existing, mature vegetation within a noneroding portion of channel. Where no examples exist near a project site, collect the information further upstream or downstream and extrapolate to the project site using stage-discharge relationships for the channel cross sections in question.

Plant Ecology and Riparian Habitat

Successful bank-protection projects depend upon an understanding of the plants available for use. In selecting appropriate plants, consider the objective of revegetation. Plants may be used to:

- provide surface-erosion protection (where grasses may be preferable),
- buttress unstable slopes (where extensive or deep-rooting trees may be desirable),
- create shade to moderate the stream-water temperature (where fast-growing trees or those with leafy canopies might be appropriate), and/or
- reduce surface-water velocities across a floodplain by distributing flow (by increasing surface roughness and by collecting woody debris) or by preventing particle entrainment (by providing root and shoot protection).

In addition to choosing appropriate species for appropriate locations, other considerations include:

- physical status of plants to be used (e.g., whole transplant, seed, cutting, bare-root stock, containerized, or ball and burlap);
- time limitations for planting (e.g., dormant cuttings);
- initial maintenance required (e.g., irrigation, weed control, or beaver and other animal control);
- succession of plants over time (assuming contributions of plant materials from upstream); and
- time scale within which vegetation must be structurally effective.

It is also important to consider the effects of these plants on channel conveyance. As shrubs and trees mature, they have the potential of encroaching into the channel cross section and increasing the frictional roughness of the channel margins. Roughness can be estimated for intermittent and full grow-out conditions (when shrubs may be excessively brushy or when trees mature). Roughness can be used in hydraulic calculations to estimate changes in shear stress or channel conveyance (see Appendix E).

Aquatic and Fish Habitat

Aquatic- and fish-habitat considerations should include existing site and reach habitat, and potential site and reach habitat. First, alterations or impacts to existing habitat should be avoided, minimized or mitigated as part of selection and design (see Chapter 4). When selecting and designing a project, recognize that an eroding channel is not static; in the process of erosion, habitats are formed. Likewise, any mitigation should be designed to evolve as the channel evolves. The most elegant bank-protection solution mitigates by avoiding habitat impacts and, in fact, restores habitat.

The most elegant bank-protection solution mitigates by avoiding habitat impacts and, in fact, restores habitat.

Second, biological capacity and habitat potential should be incorporated into a bank-protection project and should not affect the full habitat potential of the site and reach. An understanding of the biological needs and the effects of a bank-protection project are essential in order to assess the habitat impacts and habitat potential of a site and reach. A detailed discussion of these needs for various species of fish and wildlife and at various life stages is provided in Appendix G, *Biological Considerations*. An annotated bibliography, prepared by the Army Corps of Engineers, is included in Appendix K, *Literature Review of Revetments*; it describes biological effects due to stream channelization and bank stabilization.

Composite Treatments

Bank-protection techniques might consist of a single type of treatment from the toe to the top of the streambank. More commonly, a treatment varies from toe to top, depending upon the amount of scour and the vertical distribution of shear up a bank. In these settings, a combination of treatments might be employed. Rock or logs may be used as a roughened toe, and vegetative techniques might be used up a bank slope.

More commonly, a treatment varies from toe to top, depending upon the amount of scour and the vertical distribution of shear up a bank.

The use of composite treatments includes conditions where internal drainage influences bank stability. In settings where rapid draw-down occurs (see Chapter 2), especially in a flashy stream with streambank soils composed of silts and clays or in inter-tidal zones, designs should provide for internal drainage. Drainage reduces the potential for mass failure and toe erosion (caused by differential hydrostatic pressures) by using a buried chimney drain, a layer of rock within the bank, or a synthetic sheet drain.

Bank treatments also include internal slope reinforcement in conditions where mass failure is a mechanism of failure. Surface-level bank-protection techniques have little influence on failures caused by more deep-seated geotechnical instability. In some settings, techniques can be incorporated to improve internal stability. For example, incorporating layers of geogrid within a reconstructed bank provides internal stability.

Upstream and Downstream Transitions

Bank-protection design focuses on the section of eroding bank. It is also necessary to design transitions from the bank treatment (along the eroding bank) into the existing stable bank (that is, upstream and downstream from the eroding bank). Successful transitions prevent erosion from extending beyond a treated site. Transitions are important, since failure of the transition might threaten the entire treatment. Transitions include tying bank protection into existing stable features (such as mature trees or a bridge abutment). Where stable endpoints do not clearly exist, transitions might involve modifying the treatment to create an abrupt, diagonal angle into the bank, preventing the flow from "end-running" around the bank protection.

Designing Around Existing Bank Protection

Bank protection is commonly installed in proximity to already existing bank protection. Designing bank stabilization near existing bank protection requires combining habitat and geomorphic effects of the existing and proposed bank treatments. Refer to Chapter 3 for a discussion of the possible response of channel meanders to bank stabilization and Appendix F. Where the existing bank protection is not adequate, remove and/or replace the existing protection. Removal and/or replacement allows more flexibility to protect or create aquatic habitat.

Floodplain Considerations

It's important to identify the location(s) where avulsion can occur by inspecting the floodplain and overbank areas and by determining those locations where topography is lower or vegetation is reduced (or both). For an accurate assessment of a large-scale problem, undertake a topographic survey of a site, in conjunction with field mapping of vegetation, zones of erosion, high-water marks and photos. This information can be used for determining floodwater patterns and erosive energies on the floodplain at various flows (see Chapter 2).

Hydraulic modeling can be used with measured topography to identify water surface elevations associated with various floods. Most low-effort, hydraulic models (such as the U.S Army Corps of Engineers River Analysis System-HEC-RAS[4]) do not deal with depicting split flows across a floodplain (for example, over an uneven floodplain surface or at the initial stages of floodplain overtopping). Nonetheless, with careful attention to stage/discharge relationships, one can predict which areas of the floodplain will be more susceptible to erosion than others.

Using floodplain topography and hydraulic models, the average anticipated shear stress on the floodplain surface is calculated (Chapter 2). The amount of shear that a floodplain site is exposed to will depend upon the depth of the water at a particular design flow. It is important to calculate an average value of shear stress first, then, to determine an appropriate treatment design for the floodplain surface. However, the actual site-specific shear stress may be dictated by topographic or vegetative variability as flows recede. Flows tend to concentrate in one or more locations across the floodplain as floodwaters recede, forming single channels of overbank flow across the floodplain. Where overbank flow returns back into the main channel, headcuts may form. These headcuts can migrate upstream across a floodplain and are the primary cause of an avulsion (see Chapter 3 and Appendix F).

Material Placement in the Floodplain

Placement of nongrowing medium on the floodplain surface, such as small- to medium-sized woody material, helps to distribute flows and increases surface roughness (thereby reducing the potential for avulsion). Placement of such materials requires attention to size, location, distribution and measures for securing (if necessary). Water levels (from stage/discharge relationships) and erosive energies (from hydraulic models) are used to guide selection and placement of materials. Some design considerations include buoyancy, accumulation of material in undesirable locations and making use of a combination of materials (such as plants and small, woody materials).

Other Mechanisms of Failure

While not covered in detail in these guidelines, other site-specific mechanisms of failure might need to be considered to successfully select and design a bank-protection project. Additional failure mechanisms include: wave action on large rivers caused by wind or boat traffic, large-scale woody debris movement or collection in jams, the effects of ice (sheet ice, anchor ice and ice jamming), earthquakes and the impacts from how the land is used (such as with high recreational traffic or where vandalism might be prevalent). More information will be provided about these failure mechanisms as these guidelines are updated.

Physical Site Limitations and Project Constructability

During the design process, one must consider how a particular bank-protection technique would need to be installed. Site limitations dictate whether (or at least how) a technique is built, including site access, dewatering, and sediment and erosion control. How to best access a site during construction depends on the type of heavy equipment needed (if any) and the limitations imposed by this equipment. For example, a rubber-tired backhoe may not be able to drive up a steep slope; a small excavator may have limited reach, or a standard dump truck may have inadequate clearance or traction in a wet, unstable streamside setting. See Appendix M, *Construction Considerations* for more information about project construction.

Also note the type and amount of materials required and how to best transport materials to the site. Dumping rock from the top of the bank damages riparian vegetation, and large quantities may require a staging area. Access directly up the channel may have the least impact (or most impact) of all methods. Construction can cause undesirable impacts to a site but can be minimized with careful and creative approaches to site access (see Chapter 4 regarding mitigation for construction impacts).

One must consider during the design phase whether and how a site will need to be dewatered. Water may be entirely diverted around a project (with pump and pipe, a coffer dam, or a diversion tube). In other locations, the site may be isolated from flowing water so that work can occur in standing water (using barriers, sediment fences, or coffer dams). For emergency projects, work may occur directly in flowing water during a receding limb of a flood, when turbidity is already high. Diverting flow and dewatering a site is difficult if not adequately planned; and, if poorly implemented, it can prevent a project from being constructed.

Consider during the design phase how to control erosion and minimize sediment inputs to the stream. Erosion control typically involves containing surface flow with berms, silt fencing or other measures. With streambank-protection projects, erosion-control measures may be placed a number of times sequentially in order to contain a site during different project phases. For example, a silt fence might be placed at the toe of a slope as access is created, then moved upslope as a log toe is installed. The silt fence may be removed altogether once a project is completed and the site is protected with erosion-control fabric.

CONCLUSION

There are a tremendous number of considerations to take into account before designing and installing streambank-protection treatments. Assessing site and reach conditions, defining project objectives and design criteria, and identifying risk, mitigation and design considerations are integrated to determine the best possible bank-protection treatments. Either taking no action or selecting the treatment or combination of treatments that meets all of these needs is the most desirable direction to pursue. The concepts and techniques discussed thus far in these guidelines are illustrated in Chapter 6.

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CREDITS

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Figure 5-5. Source: Inter-Fluve, Inc.
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Chapter 6

Techniques

This chapter provides information on specific techniques used in integrated streambank protection.

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Groins

Flow-Redirection Techniques

DESCRIPTION

Groins, also called spur dikes, are large roughness elements that project into the channel from the bank and extend above the high-flow, water-surface elevation. They are usually constructed in a series and act together hydraulically to provide continuous bankline roughness. Though commonly constructed of rock, groins can be built with large woody debris or pilings that collect debris. *Figure 6-1* (at the end of this technique discussion) shows various applications of groins throughout Washington State.

The main functions of groins are to redirect flow away from a streambank and to reduce flow velocities near the bank, which, in turn, encourages sediment deposition. As more sediment is deposited behind the groins, banks are further protected. Groins tend to induce scour near their tips, and scour holes are likely to form in those locations. Depending upon factors such as the angle of attack of flood flows and depositional patterns, eddies may form between groins, which may lead to scour along the bases of groins or adjacent streambanks. In general, however, deposition can be expected between groins that are properly designed and installed in an appropriate location.

Barbs and groins are often mistaken for one another because they look similar, and both function to redirect flow. The primary difference between groins and barbs is that groins are higher-profile structures that tend to deepen the thalweg and narrow the stream, while barbs have less of an effect on the cross-sectional shape of the stream.

APPLICATION

Groins are used to realign a channel or redirect flow away from a streambank to protect it from erosional forces. They are also used to increase channel roughness at locations that lack roughness elements. Groins are best applied as bank protection in long, uniform bends where the upstream flow approach remains relatively constant over time. Frequently, groins are applied to reduce flow velocities and shear stress along eroding banks. In certain cases, groins can be used to narrow the channel in low-gradient, aggrading reaches causing flow velocities and sediment transport rates to increase.

Prior to applying groins as a bank-protection technique, it is important to understand the existing physical characteristics and geomorphic processes present in a potential project reach (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Groins work best in wide-radius bends where they can even out the hydraulic effect along the bank. In tight-radius bends or other constricted reaches, groins may not be very effective, and their application can further exacerbate existing erosion problems or move them upstream. Care in sizing and spacing the groins is crucial to avoid creating a constriction. Use of groins within a channel migration zone is also not recommended because it interrupts the natural riverine channel-migration process and may cause future erosion problems upstream and downstream. Refer to the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of groins based on the mechanism of failure and causes of streambank erosion.

Groins are often installed as a combination of habitat enhancement and bank protection. However, recent work has called into question the use of rock structures for habitat enhancement and, therefore, as mitigation. Density at rock groins were less than those found at adjacent, untreated banks.[1]

Variations

Groins can be set back from the active channel as an eventual line of bank protection. This type of groin is referred to as a *buried groin*. Buried groins are discussed as a separate technique in this chapter.

Groins can be constructed to be permeable or impermeable. An impermeable groin (e.g., solid-rock groin) allows minimal flow-through, whereas a permeable groin (e.g., log groin) allows flow to pass through it easily. A permeable groin acts as sieve and tends to collected a greater amount of woody material than an impermeable groin. As material is collected at the permeable groin, it eventually functions more like an impermeable groin. Impermeable groins tend to be more effective at redirecting the flow than permeable groins with no accumulated debris.

Tight-Radius Scour Holes

As mentioned earlier, groins are not particularly effective in tight-radius bends. Indeed, they can do more harm than good. A tight-radius bend with a deep scour pool acts as an energy sink, significantly dissipating stream energy. Partially filling the bend and pool with groins and/or shortening the flow path through the bend will increase the energy leaving the site, possibly increasing erosive forces where they were minimal before. For this reason, it is best to avoid using groins in tight-radius bends and pools. Again, groins work best in wide-radius bends where they can even out the hydraulic effect along the bank.

High-Gradient Channels

In higher-gradient channels, groins tend to act more like jetties. Under these conditions, they are more effective at diverting or redirecting flow than at increasing roughness.

Emergency

Groins have been used successfully during emergency situations for bank protection. Groins are constructed by dumping or placing rock from the top of the bank. This type of emergency installation can be carried out during flood events or immediately after flood waters have receded. Groins constructed under flood conditions will necessarily be short, only extending from the bank as far as can be reached by equipment on the bank. Typically, groins installed under emergency conditions will require further construction after floodwaters recede to ensure they are adequately keyed into the bank and constructed to the proper dimensions for their intended, long-term function. Once the crisis has passed, groins constructed during an emergency may need to be replaced with a bank-protection technique that better addresses the mechanism and causes of erosion.

EFFECTS

Groins constrict the channel by creating roughness and by blocking a portion of the channel. The constriction can increase erosive shear stress on the opposite bank. Caution is advised when designing groins that are more than 10 percent of the bankfull channel width, particularly in channels that are already constricted. A constriction creates a backwater effect (increases the water depth) upstream, decreasing flow velocities and increasing sediment deposition. A tailout bar often forms downstream of a constriction as the channel expands and loses transport capacity. Once a tailout bar is formed, moderate flows may pass around the bar and along channel banks, causing toe erosion.

The intended effect of groins is to shift the thalweg away from the bank. The new thalweg alignment may affect the downstream channel or banks. Appropriate spacing and sizing of groins to dissipate flood-flow energy can minimize this effect. Energy dissipation at a groin typically creates a scour hole in the channel bed near the tip of the groin. Rock or other materials used to construct a groin can be placed below the estimated scour depth at the groin tip to prevent undermining. Excess rock can also be placed on the channel bed such that, as scour occurs, it launches into the scour hole. Scour holes provide important cover and holding habitat for fish. See Appendix E, *Hydraulics* to learn about methods used to calculate scour depth. Sources of additional information regarding the effects of groins can be found at the end of this technique discussion.[2,3]

DESIGN

The design of groins for bank protection requires balancing the effects of creating a constriction, providing channel roughness, generating habitat benefits and controlling costs. If groins must be used at sites where they will not be as effective as they could be, their impacts can be at least partially mitigated by building them shorter and closer together than typically applied.

The Federal Highway Administration has developed a well-established design process for traditional, impervious rock groins, which can be found in FHWA Publications HEC-20 and HEC-23.[4,5] Conceptual design drawings are shown in *Figure 6-2* and *Figure 6-3*.

Orientation

Groins may be aligned perpendicular (standard) or angled upstream or downstream to the flow. Regardless of orientation, groins should always be oriented relative to the high-flow streamline in order to function correctly. The high-flow streamline may not correspond with the low-flow channel alignment, particularly in braided channels.

An upstream-orientation bank angle generally creates the greatest roughness and flow disturbance and results in the greatest scour depth at the groin tip. Should the groins be overtopped, an upstream orientation may result in less bank erosion than a downstream one.

Downstream, angled groins tend to create less roughness and are recommended for use in high-gradient channels or degrading reaches where flow redirection is more important than increasing channel roughness. With less roughness, scour-hole development is minimized along the channel bank between the groins. This orientation may cause more flow to impinge on the opposite bank. If downstream angled groins are overtopped, the cresting flow will impinge directly on the adjacent, downstream bank. Downstream-oriented groins are often used for navigation channels because less turbulence is created, and flow patterns are more uniform.

Length

Groin length is defined as the projected length of the groin perpendicular to the flow direction. The optimal design length of a groin depends upon the location and objectives of the project and varies according to channel width and spacing among groins. The longer the groin, the greater length of bank it will protect. Length is usually limited by the degree the channel is confined and the opposite bank's susceptibility to erosion. As a groin is lengthened, the channel becomes more constricted. This produces upstream backwater, a deepened and narrowed channel off the tip of the groin, an increase in the flow directed across the channel and increased stream energy downstream. Flume tests indicate that diminishing returns are gained from groin lengths greater than 20 percent of bankfull channel width.[4] Impermeable groins are typically limited to 15 percent of the bankfull channel width.[3] Depending upon site-specific hydraulics and upstream and downstream effects of roughening and constricting the channel, groins may need to be more closely spaced and shorter in length than normal to reduce off-site impacts.

Spacing

Spacing between groins depends upon project objectives and is a function of groin length, angle, permeability and the channel radius of curvature. Although not specifically determined for groins, the spacing of experimental baffles (which function hydraulically similar to groins) was found to have an influence on roughness in flume studies. Groins that are spaced too close to each other or too far from each other create less roughness than optimally spaced groins. Groins that are spaced too close to each other tend to mimic a riprap bank; there is minimal space between groins for turbulence and energy dissipation to occur. When groins are unnecessarily close to each other, they are more costly, and they require greater bank disturbance during construction. For increased habitat and diversity, wider spacing is desired. Groins installed in tight-radius curves must be positioned closer to each other than normal; all the more reason to avoid placement of groins in such circumstances.

Spacing between groins is influenced by the length of the groin and the ratios of groin length to channel width and channel radius of curvature to channel width.[6] Maximum spacing is determined by the intersection of the tangent flow line with the bankline, assuming a simple curve. This maximum-spacing approach is not recommended, but can be used as a reference for designers. In situations where some erosion between groins can be tolerated, the spacing can be set somewhere between the recommended distance and the maximum. Longer groins can be placed further apart from each other than shorter ones.

Flume studies show that stream flow expands out of the channel constriction created by a groin at an angle of about 17 degrees (this value is for impermeable groins; the angle varies for permeable groins and they should be specifically designed depending on their permeability).[4] The next downstream groin is placed at the point where the flow line would intersect the bank if there were not a downstream groin. This is roughly 3.3 times (tan 73 degrees) the length of the groin from the point of contact with the bank and its tip. Groins have been successfully placed at distances of about two to five times their length, which adds a range to the previous result and allows some flexibility in locating them. By using a tangent to the high-flow line, one can project a line off the tip of a groin and identify on the bank the approximate location of the next groin.

Height

The height of groins should not exceed the bank height because erosion in the overbank area could increase the probability of out flanking at high stream stages. If flood flows are below the top of the bank, the groins can be lower. The groin crest should slope down and away from the bank. This is usually preferred since it creates less channel confinement at high flows. Additionally, because bank shear generally decreases with elevation, groin elevation may not need to extend the full height of the bank.

Key

To ensure that groins are not flanked by high flows, they must be properly keyed into the bank. The length of this key varies with the installation. A minimum key of eight feet or $4(D_{100})$, whichever is greater, has been proposed by The Natural Resources Conservation Service.[7] On large rivers, this is insufficient. Exactly how much is enough will depend upon the erodibility of the soils and other site-specific details. The upstream groin should be keyed in at least 50 percent of its exposed length. This groin acts as the keystone to the rest of the group. If it fails, others may fail. In a large group of groins, perhaps every fifth should be keyed in at a greater depth than the others, in case there are failures within the group. The length of key should be equal to or greater than 1.5 times the bank height.[5] Equations have been developed for estimating key length based on the expansion angle and radius of curvature[6]:

When the radius of curvature is large (R > 5(W)) and the spacing is greater than L/tan(Ø), then:

$$LK = S \tan(Ø) - L$$

When the radius of curvature is small (R<5W) and the spacing is less than tan(Ø), then:

$$LK = L/2(W/L)^{0.3}(S/R)^{0.5}$$

Where:

R = radius of curvature
W = channel width
S = spacing between groins
L = length of groin measured from the groin tip to the bankline
Ø = angle of expansion = 20°
LK = length of key

Groins should also be keyed into the channel bed or constructed with a launchable toe to protect against scour. The key should extend into the streambed to the predicted scour depth at a minimum. Alternatively, rock added to the tip of the groin can protect against scour by gradually launching and falling into the scour hole as it develops. This eliminates the need to dig in the bed of the channel, and it places the toe at the correct depth of scour. Estimates for the required amount of extra rock can be based on scour-depth calculations.[3] Launching is most often used on channels with fine-grained beds. It has been used inappropriately on beds that do not scour, resulting in excess rock in the channel. This extra, launchable rock narrows the channel and reduces habitat value.

Wooden groins are generally supported by piles driven into the river bed. The depth of pile penetration required should be determined by a geotechnical engineer. Piles should be driven to a depth adequate to resist hydraulic forces, floating-debris impacts and buoyant forces at the design discharge, assuming maximum scour is attained. This depth will vary according to site hydraulics, expected impact from floating debris and subsurface materials. Stone can be placed along the base of a wooden groin to counter scour that might otherwise destabilize the structure.

Permeability

The effective application of permeable groins depends upon stream characteristics, the desired reduction in flow velocity and the radius of curvature. Permeable groins can be used successfully in mild bends and where only small reductions in velocity are desired. In stream systems where woody materials exist, permeable groins collect and retain floating, woody material and, over time, become less permeable. Impermeable rock groins are by far the most commonly used in Washington streams. Suitable rock size can be determined by a number of methods.

Permeable groins can be made from a variety of materials. Wood pilings, large woody debris, a combination of rocks and logs, and/or concrete doloes have all been successfully used. The greater the stream energy, the more robust the materials and their anchoring must be.

Material Sizing

If a hydraulic analysis of the site has been performed, the velocity will be known, and the Isbash relationship can be used to size the rock.[3] This equation was derived for bridge abutments and has been used successfully for some time. The Natural Resources Conservation Service and the U. S. Army Corps of Engineers both have developed riprap sizing methods. The conservation service recommends using a D_{50} equal to 1.5 to two times the size determined from riprap design for bankfull flow.

Rock should be angular, and not more than 30 percent should have a length exceeding 2.5 times its thickness. Rock should be well-graded, with only a limited amount of material less than half the median rock size. The size of rock can be determined by available riprap design procedures. Rock sized for typical bank revetment riprap is too small for groins. The NRCS recommends using a D_{50} rock size that is two times the D_{50} rock diameter determined using standard riprap design procedures for continuous riprap at bankfull conditions. Large woody debris installed in groins should be at partially submerged for habitat value and longevity. Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for guidance.

Log groins are typically constructed using wooden or steel piles, wood cross-logs and rootwads. Steel piles have the advantage of being stronger, allowing better (deeper) penetration through gravel or cobble subsurface materials; and they are free of buoyant forces. The obvious disadvantage to steel piles is their longevity - they are likely to far outlive the other components of the groin. Cross-logs are typically branchless logs cabled across the piles to form a fence-like structure. Rootwads can be included in the structure to add complexity. See Appendix I for additional information.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Groins redirect flow away from an eroding bank and prevent further, lateral, channel migration. Periodic inputs of gravel and woody debris, resulting from bank erosion, will be reduced, representing a lost opportunity for future development of habitat complexity. Woody debris can be incorporated into the construction of groins as one means of mitigating for habitat loss. Groins may also capture floating wood debris, especially if the surface is left jagged rather than smooth.

Thalweg alignment is often affected by placement of groins. A relocated thalweg will dictate new erosional and depositional patterns in the channel, which may impact existing spawning areas. The use of groins to provide bank stabilization along an eroding channel bend will reduce near-bank pool habitat. Relocation of the thalweg away from the bank results in reduced riparian function and overhead cover from existing vegetation on the bank. Live, woody plant cuttings can be incorporated into groin construction as mitigation for loss of bank vegetation. Segments of bank located between groins can also be revegetated, with both woody and herbaceous species to replace lost riparian function.

Refer to Chapter 4, *Considerations for a Solution* for further discussion of mitigation requirements and to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

A groin will provide some fish habitat at all flows. Cover habitat can be provided in the surface turbulence created by a groin. At lower flows, slack-water habitat may be formed on the downstream side of the groin. A back eddy often forms off the tip of each groin, a good feeding station for fish in the slower water. At higher flows, the back eddies can become fairly strong and have high energy. A groin may provide some refuge from flood flows, or the swirling eddies may become too great for fish to hold in. If the rock used to construct the groin is large enough, it may provide interstitial cover for fish, unless the rocks have been over compacted to interlock.

Groins may accrete gravel and other sediment, either at a single groin or, more likely, between groins in a series. This accretion may raise the riverbed and provide shallow, slack-water habitat along the accreted shoreline. The upstream accretion may sort gravels and create a spawning area where none existed before. Accretion may increase to the point where a beach forms that remains unsubmerged during all but high-water events. Slack-water habitat at extreme flows may provide refuge for both adults and juveniles.

Refer to Matrix 3 in Chapter 5 for more detail on mitigation benefits provided by this bank treatment.

RISK

Habitat

Spawning areas can be impacted by the construction of groins, particularly if the habitat is located on the margin of a point bar, in the tailout of a bank scour pool or on the riverside of the thalweg on a straight river stretch. As discussed in the section on general fish-habitat needs, scour can kill eggs or alevins that are still in the gravel. Over the long term, the bed and bars should stabilize, and these scour impacts should become minor.

In a situation where the existing unarmored bank may be sustaining a deep, lateral, scour pool with overhanging vegetative cover and woody debris, the placement of groins will likely eliminate this habitat. The habitat-generating value of the groins will likely not compensate for elimination of the better habitat. In these cases, the best habitat decision is to leave the eroding bank alone and build no groins.

A survey of over 600 bank-stabilization projects in western Washington assessed five different types of bank treatments for their impacts/benefits to fish.[1] Rock groins alone and with large woody debris were two of the treatments evaluated. Stabilized sites were compared with untreated control sites in the same river that were naturally stable and as similar to the stabilized site as possible. Bank treatments that incorporated large woody debris were the only types that consistently had greater fish densities than their corresponding control areas during spring, summer and winter. Fish densities were generally lower at groins than their controls during the spring and summer, but greater during the winter.

In general, the study results suggest that fish densities are generally lower at banks stabilized with groins except those with a large woody debris component. Fish densities were positively correlated with total surface area of large woody debris at all sites. Based on these results, such debris should be incorporated into groins whenever practical. Most large woody debris used in surveyed groin projects was found between the groins (a depositional area). These areas often lacked sufficient depth for rearing habitat. Additionally, large woody debris incorporated directly into the groins was often placed too high with respect to summer water depths. Care should be exercised when incorporating large woody debris into groins to make sure that it is placed at the correct elevation within the groin.

Infrastructure

Avoid existing vegetation as much as possible, positioning the groin between trees rather than removing trees and brush. Minimize bank sloping and armoring between the groins. If the bank between groins is unvegetated or newly armored, revegetation should be initiated on both the slope and on the top of bank.

Reliability/Uncertainty of Technique

The use of groins is a well-established and reliable method of realigning a channel thalweg when standard design and construction approaches are applied.

Recent studies have questioned the use of rock structures as habitat. Fish appear to prefer pool habitat along untreated banks over that provided by rock groins. Therefore, rock groins should not be used strictly as habitat features.

CONSTRUCTION CONSIDERATIONS

Materials Required

Groins may be constructed with a variety of materials. Angular rock is the most common type of material used; however, large woody debris and concrete doloes have also been used.

Woody vegetation should be planted in all groin surfaces that have the proper hydrologic zones and growing medium. Generally, live cuttings are the most suitable. Refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for more information.

Timing Considerations

Groins are best constructed during low flow, when dewatering is possible and when critical life stages of resident and anadromous fish are less likely to be impacted by construction activities. In order to install rock or logs to the depth of scour, excavation within the channel bed will be necessary and, consequently, will require temporary dewatering systems. Keying into the streambed by constructing a launched toe may also require dewatering. Dewatering allows for ease of installation and limits siltation of the stream during construction. This can be accomplished with a coffer dam during low water.

Critical periods in salmonid life cycles, such as spawning or migration, should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

COST

The main function of groins is to redirect flow away from the bank, thus modifying flow patterns in the near-bank region, encouraging sediment deposition and reducing bank erosion. Corresponding decreases in velocities and shear stresses along the bank allow less-intensive and less-expensive bank treatments to be applied between groins. In other words, groins, in combination with other bank treatments, may not only protect a streambank more effectively than traditional bank-revetment measures, they may cost less as well.

The major cost components of groin construction include access, materials, dewatering and installation. For further information on the costs of these components and specific construction materials, refer to Appendix L, *Cost of Techniques*. Cost of individual groins may vary from $2,000 to $5,000 depending upon their size and site-specific factors.

MAINTENANCE

Maintenance of groins may include replacement of construction materials (e.g., rock, logs) that shift or are removed by high flows. This may include replacement of nonsurviving plant material. Groin materials lost to high flows should be replaced before damage occurs to the bank or structures located between the groins.

Erosion along the perimeter of the groin, as well as along the streambank between groins, should be closely monitored and evaluated for need of repair. Rock should be placed along the bank for a short distance upstream and downstream of the groin tie-in point to the bank. Placement of this material will help to prevent erosion at this critical location, which could result in flanking of the groin at high flows.

MONITORING

Because groins involve impacts to the channel and banks, they will require comprehensive monitoring of the integrity of the structures, channel and bank features and in-channel habitat. Monitoring of groin projects should be initiated prior to construction, with baseline-conditions surveys of the physical channel, its banks and its habitat value. This should include five cross sections at intervals equal to the channel width upstream, five downstream and one through each groin at a minimum. This will allow comparison of modified conditions to preproject conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation from fixed photo points of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring*.

Monitoring of groin structures should include preproject and subsequent annual surveys of key members, as well as visual assessments of groin configuration, dimensions and hydraulic function. The general integrity of the structures should be evaluated, including the identification of any significant settling of header or footer rocks as determined from survey and comparison of photos.

Impacts to the channel and to habitat must be carefully monitored. Channel changes occurring following installation can be documented by reviewing an annual survey of cross sections surveyed prior to installation and at the time of completion. Patterns of sediment deposition or scour should be noted. Similarly, changes to available habitat should be documented on a schedule dictated by fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[8] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

Monitoring should be conducted annually at a minimum and following all flows having a return period of two years or greater. Monitoring should be conducted for at least five years after groin installation. Mitigation components of groins must be monitored for the life of the mitigation requirement.

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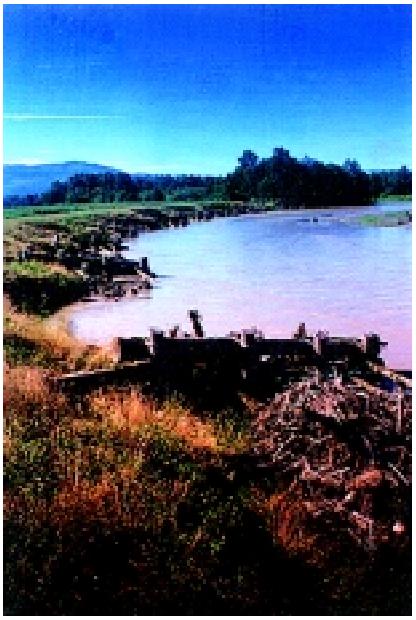
a. Wood Groins with bank reshaping and plantings. During Construction. Wind River. 1999.

d. Wood Groins. Wind River. One year after construction. Note wood accumulation. 2000.

b. Wood Groins. Klahowya Creek, Tributary to E. Fork. Nookachamps River. 2001.

e. Dolo Groins. Nooksack River. 1998.
Source: Inter-Fluve, Inc.

c. Rock Groin with woody debris accumulation. Big Quilcene River. 1998.



f. Wood Groins. Nooksack River. 1998.

Figure 6-1. Various applications of groins throughout Washington State.

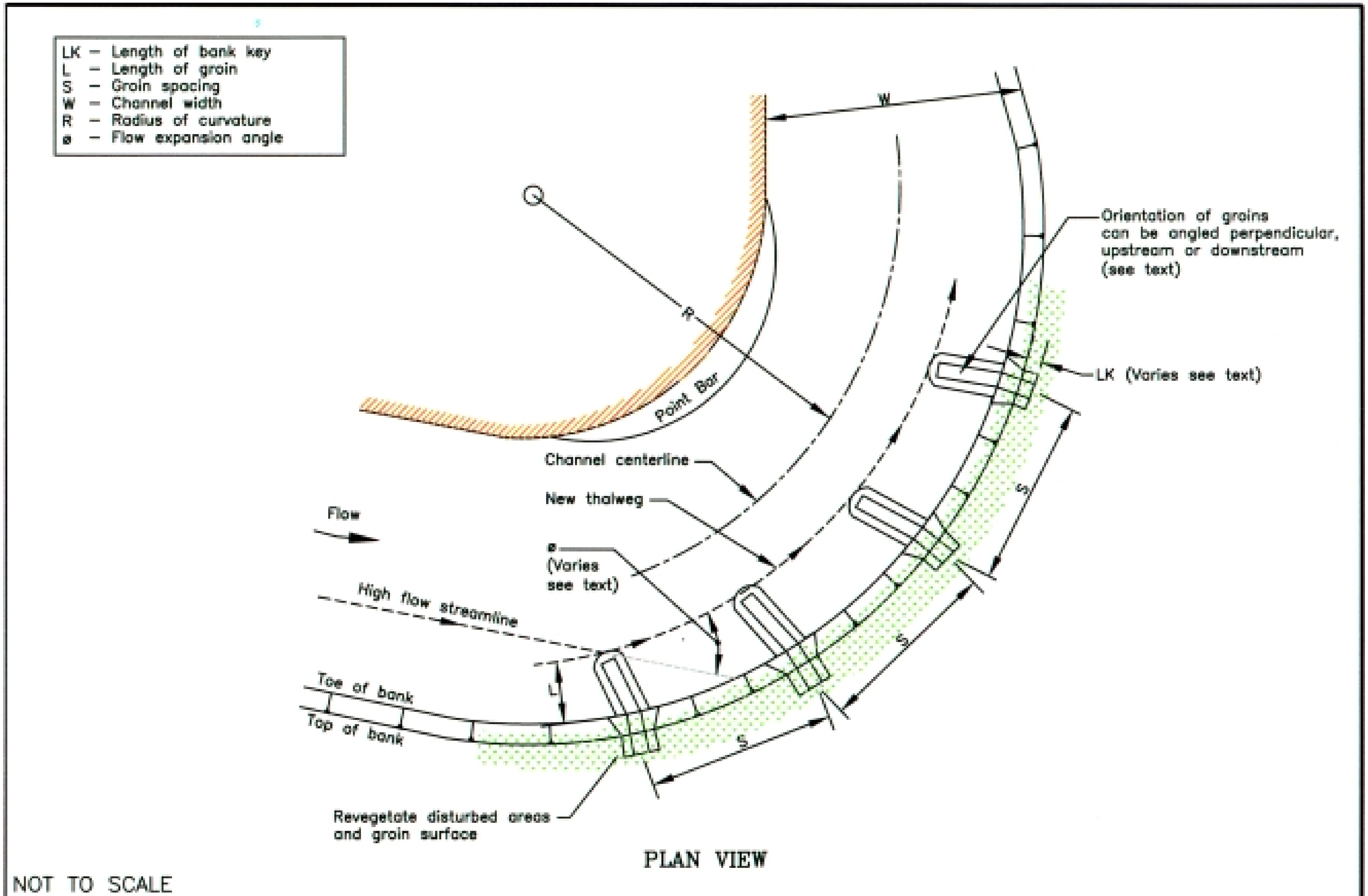


FIGURE 6–2

GROINS CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES
www.wa.gov/wdfw/hab/ahg/ispgdoc.htm

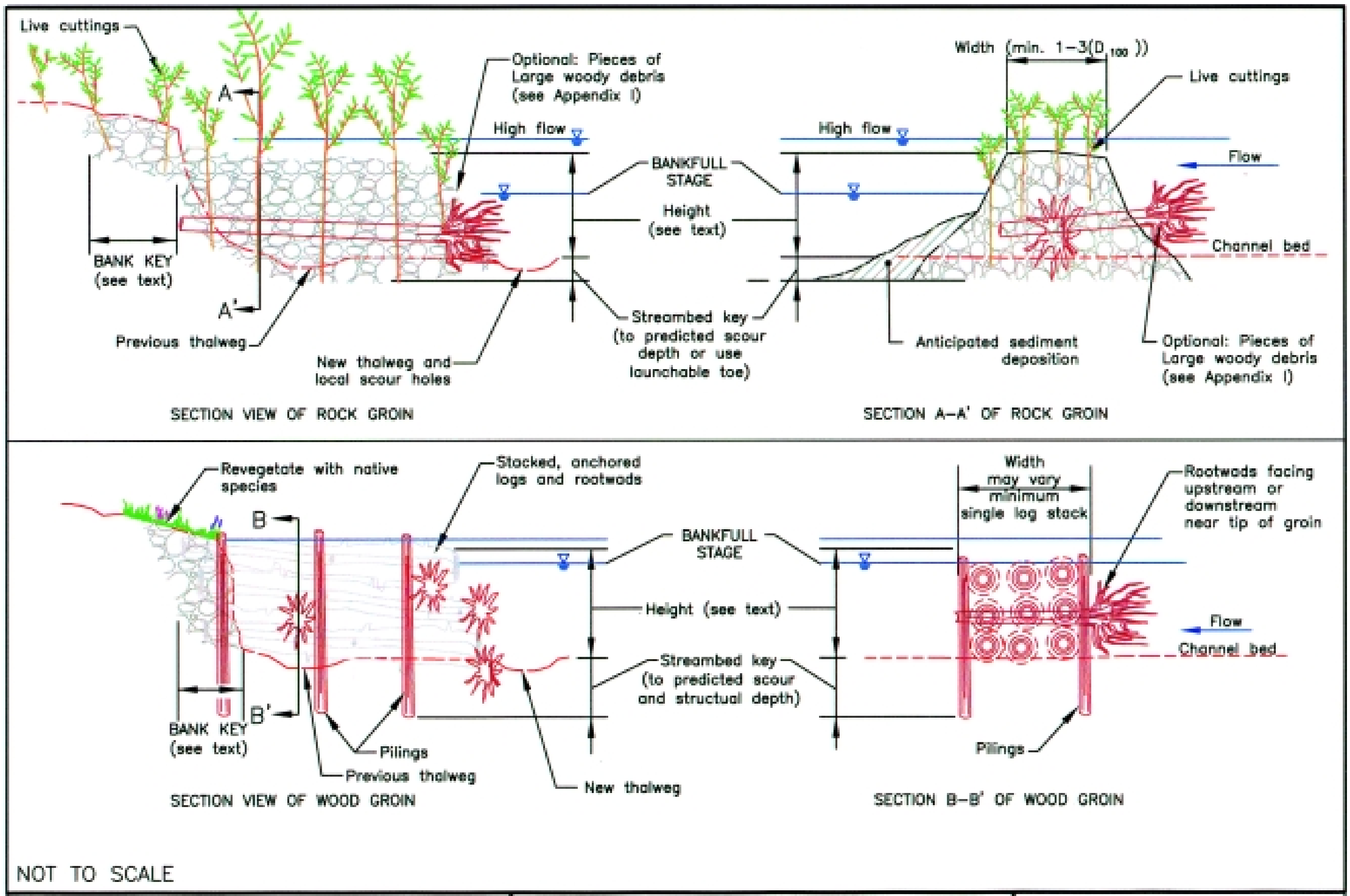


FIGURE 6-3

GROINS CONCEPTUAL DESIGN

Buried Groins

Flow-Redirection Techniques

DESCRIPTION

There are situations where property and structures are not immediately in danger from streambank erosion but are likely to become so in the near future. In such cases, setback alignments can be constructed to protect them. One type of setback alignment is called a buried groin (also called buried rock trenches, transverse dikes or sills). Buried groins are structures embedded in the ground, inland from the eroding bank. If channel erosion reaches the buried groin, the groin will stop or reduce the rate of erosion from progressing farther toward the property or structure to be protected. Once exposed, buried groins redirect flow away from a streambank and reduce flow velocities near the bank to protect it from erosional forces. Buried groins become groins once they are exposed (see the discussion in this chapter addressing *Groins* for additional information). Buried groins can also provide the benefit of a wider channel-migration corridor for continued, natural channel evolution.

APPLICATION

Buried groins are installed between the eroding bank and the structure or property at risk, and they are most effective when positioned as close to the stream's migration corridor boundary as possible. These structures can be used where natural stream- and/or floodplain-corridor function is a priority, and some channel migration is allowable. Buried groins can be used as an integrated, medium- to long-range planning tool. Buried groins can also be used in concert with exposed groins placed along the bank of an active channel. If erosion is likely to extend downstream or upstream from the groins, buried groins can be extended along the predicted future location of the streambank for added protection.

Buried groins can be integrated with deformable, biotechnical or experimental treatments at eroding banks to promote natural, channel-migration processes through gradual, controlled erosion. Buried groins can be placed inland from these other bank treatments at a location beyond which continued erosion and channel migration is not desirable.

Specific site and reach limitations will help determine whether or not buried groins are a suitable solution (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for further guidance). Buried groins are appropriate for sites where the mechanism of failure is toe erosion. They can be used to establish or define a migration corridor, and they can be used in combination with grade-control structures (e.g., a porous weir or drop structure) in a degrading channel. Refer to the screening matrices in Chapter 5, *Identify and Select Solutions* for further guidance on the applicability of buried groins.

Variations

Buried groins are typically constructed from large rock. However, they can also be constructed with large woody debris (see Appendix I, *Anchoring and Placement of Large Woody Debris*). Buried groins can be constructed to be either impermeable or permeable. The permeability of a buried groin depends upon stream characteristics, the desired reduction in flow velocity and the radius of curvature. Impermeable groins are typically constructed using riprap, whereas permeable groins are constructed from a variety of materials such as wood pilings, large woody debris and concrete doloes.

Emergency

Buried groins can be used during emergency situations since they are set back from the affected channel bank, allowing for construction to occur away from flood flows. However, they typically require heavy equipment for installation and substantial amounts of excavation and construction materials.

EFFECTS

The effects of buried groins on the channel and floodplain are essentially negligible until the channel erodes and exposes them. Once this occurs, buried groins function and cause similar effects as exposed groins that are constructed in an active channel (refer to the technique described in this chapter called *Groins* for additional information). Once the buried groins are exposed, they create roughness along the new bank and maintain the thalweg alignment along their tips. Scour holes will also form off the tips of the groins.

DESIGN

Conceptual design drawings of groins are shown in *Figure 6-4* and *Figure 6-5* at the end of this technique discussion.

The design of buried groins is like that of standard groins, with a few important differences. The primary difference between standard groins and buried groins is the location within the channel corridor where they are placed. Standard groins are constructed along an active bank, whereas buried groins are positioned at a location inland from the active bank. Due to their setback location, designing buried groins is more difficult than standard groins because you cannot determine in advance precisely what the channel's physical characteristics (dimensions, alignment, flow velocity and patterns, etc.) will be when the groins are eventually exposed. Given the uncertainty of future channel characteristics, scour depth is also difficult to predict. To compensate for this uncertainty, buried groins can be constructed with a launchable toe to protect against scour rather than trying to predict how deep the scour will go and then installing the groins to that depth. Estimates for the required amount of extra rock for the launchable toe can be made on the basis of conservative scour-depth calculations for the existing channel.[1] Because it is difficult to anticipate future conditions, buried-groin design needs to be somewhat conservative in order to address as many potential conditions as possible. The section in this chapter that discusses *Groins* provides further details on exposed-groin design, including depth and height of installation.

The orientation, length and spacing of buried groins are determined in a similar manner to that used for exposed groins that are installed along an active channel. However, because the orientation, curvature and location of the channel when it eventually intersects the buried groins cannot be known with certainty, designs will have to compensate for this uncertainty. The recommended design process is similar to that for traditional, impervious rock groins.[2,3]

Location

Careful analysis is required to determine appropriate locations for installation of buried groins. The intended function of the buried groins will influence the placement location. For instance, if the buried groins are intended to protect property or structures from an eroding channel bank, it's easy to see that the buried groin needs to be located somewhere between the property to be saved and the eroding bank. It's not as easy to determine correct positioning when buried groins are to be used to define a meander migration corridor or to provide back-up protection for deformable, biotechnical, or other experimental bank treatments. Under both circumstances, placement will require an understanding of the geomorphic processes within the reach and adjacent reaches (see Chapter 3 and Appendix F, *Fluvial Geomorphology*). A reach assessment can help establish realistic meander-corridor limits. Once the limits of a migration corridor are determined, buried groins can be placed at the boundary to prevent erosion outside the corridor.

Material Sizing

Determining the most suitable size of rock for an impermeable-rock buried groin can be accomplished using a variety of methods. Rock sized for typical bank-revetment riprap is too small for groins. If a hydraulic analysis of the site has been performed, flow velocity will be known and the Isbash relationship can be used to size the rock.[1] The Isbash relationship is a time-tested equation used for designing bridge abutments. Since groins have the same effect as bridge abutments in that they constrict a channel, the Isbash-relationship calculation can be applied to determining rock size for groins. Another way of calculating the correct size of rock to be used in the groin is to use a method developed by the Natural Resources Conservation Service and the U.S. Army Corps of Engineers. The conservation service recommends using a D_{50} equal to 1.5 to two times the size determined from riprap design for bankfull flow.

Rock should be angular, and not more than 30 percent should have a length exceeding 2.5 times its thickness. Rock should be well graded with only a limited amount of material less than half the median rock size. Large woody debris installed in groins should be submerged for habitat value and to reduce the rate of decay. Refer to Appendix I for guidance.

Permeable buried groins can be constructed from logs, a combination of logs and rock, or concrete doloes. Log groins are typically constructed using wooden or steel piles, wood cross-logs and rootwads. Steel piles have the advantage of being stronger, allowing better (deeper) penetration through gravel or cobble subsurface materials, and being free of buoyant forces. The obvious disadvantage to steel piles is their longevity - they are likely to far outlive the other components of the groin. Cross-logs are typically branchless logs cabled across the piles to form a fence-like structure. Rootwads can be included in the structure to add complexity. See Appendix I and the discussion in this chapter addressing *Engineered Log Jams*.

Orientation

The orientation of flow as a channel migrates into buried groins cannot ordinarily be determined in advance with any degree of certainty. Because of the uncertainty of future channel dimensions, buried groins should be aligned perpendicular to the existing migration corridor margin. In situations where there is a high degree of certainty, then buried groins can be angled downstream or upstream. Refer to the technique described in this chapter called *Groins* for additional information.

Length

Groin length is defined as the projected length of the groin perpendicular to the flow direction. The length of impermeable groins typically does not exceed 15 percent of the bankfull channel width.[1] In the absence of accurate information about future channel dimensions, the length of buried groins can be based instead on the existing bankfull-channel width.

Spacing

Spacing between buried groins depends upon project objectives and should be determined as a function of groin length and permeability. Maximum spacing is determined by the intersection of the tangent flow line with the bank, assuming a simple curve; however, the future channel curvature cannot be predicted with great certainty. The maximum spacing is not recommended, but is a reference for designers. Flume studies show that stream flow expands at an angle of about 17 degrees out of a channel constriction created by impermeable groins.[2] The next downstream groin is placed at the point where the thalweg would intersect the bank if there were not a downstream groin. This is roughly 3.3 times (tan 73°) the length of the groin from the point of contact with the bank and its tip. Groins have been successfully placed at about two to five times their length, which adds a range to the previous result and allows some flexibility in locating them.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Placement of buried groins impacts riparian function and eventually affects dynamic river processes, including channel migration. Sediment and woody-debris inputs will be reduced once the buried groins are exposed, representing a lost opportunity for development of habitat complexity and diversity. Mitigation of these impacts can include the incorporation of large woody debris into the construction of buried groins. Live, woody, plant cuttings can be planted into the buried groins once they are exposed as a means of enhancing riparian function. Segments of bank located between groins can also be revegetated with both woody and herbaceous species to replace lost riparian function. Placement of large woody debris between groins is not recommended because this is typically a depositional area that lacks sufficient depth for habitat development. Locating buried groins such that the greatest migration corridor width is attained, within geomorphic or infrastructure limitations, will maximize mitigation for lost opportunity impacts. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Buried groins do not provide any immediate mitigation benefit. By installing groins at a location that is setback from the active channel, allowance can be made for natural channel and flood-plain function until the groins are exposed. The channel can migrate naturally to the limits defined by the buried groins. Buried groins can also serve as a back-up structure that enables application of a less structural type of treatment, such as biotechnical techniques, at the eroding bank face. If the treatment along the bank face begins to fail, the buried groins will provide needed stabilization until repairs can be initiated.

Buried groins should be combined with biotechnical or deformable bank-stabilization techniques and riparian-buffer management. They provide a mechanism for protecting a riparian buffer against erosive forces that could result from rapid channel migration until vegetation in the buffer has become mature. Buried groins constructed with large woody debris will provide habitat complexity and diversity along the active bank once the groins are exposed. Buried groins implemented in association with a riparian buffer are a good example of an integrated streambank-protection strategy that provides for natural channel and floodplain evolution.

RISK

Habitat

Buried groins represent a risk of lost opportunity for development of habitat diversity. Once the channel has migrated into the groins and exposed them, gravel and woody debris recruitment will be reduced. Depending upon their location within the channel migration zone, buried groins may reduce or prevent development of diverse, off-channel habitat, including side channels and swales, wetlands or ponds.

Risks to in-channel habitat are the same for buried groins as they are for exposed groins once the buried groins have been exposed. If there is a spawning area on the margin of a point bar, in the tailout of a bank scour pool or on the river side of the thalweg on a more straight river stretch, the spawning area is at risk of becoming scoured. This can be a severe problem for fish, because scour can kill eggs and alevins that are still in the gravel; however, as the bed and bars stabilize over time, these scour impacts should become minor.

A survey of over 600 bank-stabilization projects in western Washington assessed five different types of bank treatments for their impacts and/or benefits to fish.[4] Rock groins and rock groins with large woody debris were two of the treatments evaluated. Stabilized sites were compared with similar, naturally stable, untreated control sites in the same river. Bank treatments that incorporated large woody debris were the only ones that consistently had greater fish densities than their corresponding control areas during spring, summer and winter. Fish densities were lower at groins than their controls during the spring and summer, but they were greater during the winter.

Study results found that fish densities were lower at stabilized banks except those with a large-woody-debris component. Fish densities were positively correlated with total surface area of large woody debris at all sites. Based on these results, such debris should be incorporated into buried groins whenever practical. On the other hand, most large woody debris used in surveyed groin projects was found between the groins. The area between groins is a depositional area that typically becomes more shallow over time. For this reason, these areas often lacked sufficient depth for rearing habitat. Additionally, large woody debris incorporated directly into the groins was often placed too high with respect to summer water depths. Since bed elevations and corresponding water depths cannot be accurately predicted for the point at which the channel exposes the buried groins, it is recommended that large woody debris be incorporated at a variety of elevations. This will improve the chances that at least some beneficial habitat will be developed.

Infrastructure

Buried groins offer minimal risk to infrastructure because the typical placement of buried groins is away from the active channel. However, their location must anticipate meander-migration patterns. For instance, if the channel migrates in a different pattern than expected, the buried groins may not intercept the channel, leading to a continued threat to infrastructure from channel migration.

Once they are exposed, buried groins can be undermined if scour depth is not accounted for in the design process. Buried groins should be adequately keyed into the bank and bed. Positioning keys for buried groins may be more difficult than positioning the groins themselves, because there is typically no active channel margin to help define placement depths and distances for the key.

Reliability/Uncertainty of Technique

There is little available research on the long-term performance of buried groins. They are a relatively new technique for streambank protection. Furthermore, because groin design is typically dependent on existing channel shape and buried groins are intended to be effective for some eventual and unknown channel alignment, their design assumes a high degree of uncertainty. Design processes will likely become more refined as more research is accomplished. Monitoring and performance reporting should be encouraged to aid the further development of this technique by future practitioners. Refer to Appendix J, *Monitoring* for a further discussion of monitoring.

CONSTRUCTION CONSIDERATIONS

Materials Required

Buried groins can be constructed using a variety of materials. Rock is the most common type of material used in Washington; however, large woody debris and concrete doloes have also been applied.

Timing Considerations

Buried groins can be constructed during virtually any flows, as they are separate from the active channel. However, they are best constructed during low groundwater periods, particularly if wood is used, in which case buoyancy will need to be addressed. Critical periods in resident and anadromous fish life cycles such as spawning or migration should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Cost

Because buried groins are not constructed within the active channel, there are no costs associated with dewatering or sediment control for this technique. Therefore, the total cost is less than for a conventional riprap or groin design. However, the cost of installation per structure may be greater than its counterparts because more excavation is required, and disposal of excavated material is also required.

The major cost elements of buried-groin construction include access, materials, installation and disposal. For further information on the costs of these components and specific construction materials, refer to Appendix L, *Cost of Techniques*. Cost of individual buried groins may vary from $2,000 to $5,000 depending upon their size and site-specific factors.

MAINTENANCE

Maintenance of buried groins should be minimal until they are exposed by channel flows. Once exposed, maintenance activities include replacement of construction materials (e.g., rock, logs) that shift or are removed by high flows. Erosion along the perimeter of the groin, as well as along the streambank between groins, should be closely monitored and evaluated for need of repair. Buried groins installed as launchable material may require considerable maintenance and adjustment, including addition of rock, once exposed.

Buried groins will require reclamation and revegetation efforts in areas disturbed by their installation.

MONITORING

Monitoring of buried groins should begin with accurate documentation of their placement location, configuration and dimensions. All surveys should be tied to a monument or benchmark situated outside the risk area. Measurements can also be taken from their placement location to the active channel in order to evaluate rates of bank erosion. Prior to being exposed, buried groins should be inspected annually and following all flows greater than a two-year return period to determine whether they have become exposed. Once exposed, monitoring should be conducted as detailed in this chapter under the technique, *Groins*. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[5] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

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2 Lagassse, P. F. et al. 1995. Stream Stability at Highway Structures. Hydraulic Engineering Circular No. 20. U. S. Department of Transportation, Federal Highway Administration.

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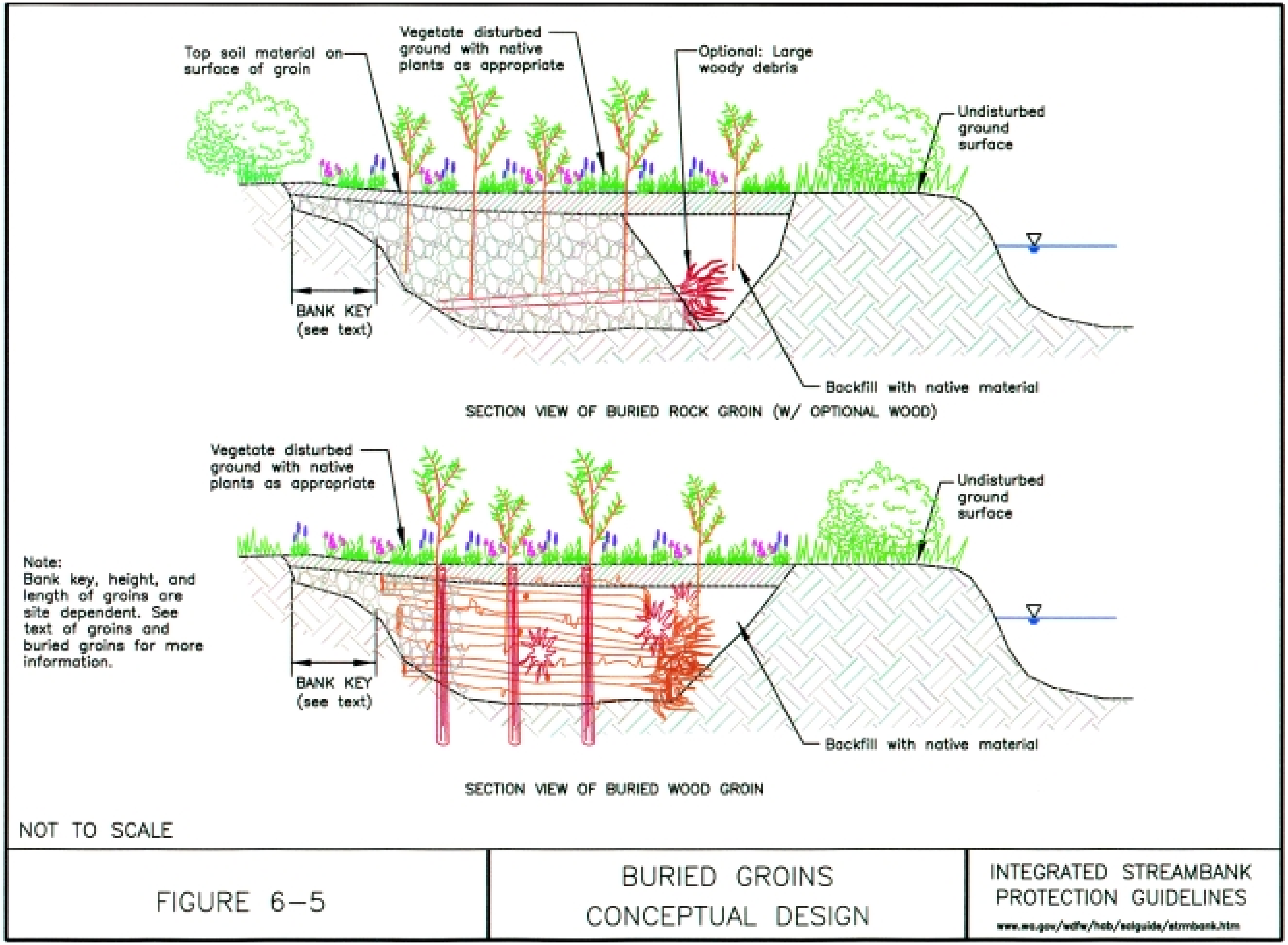
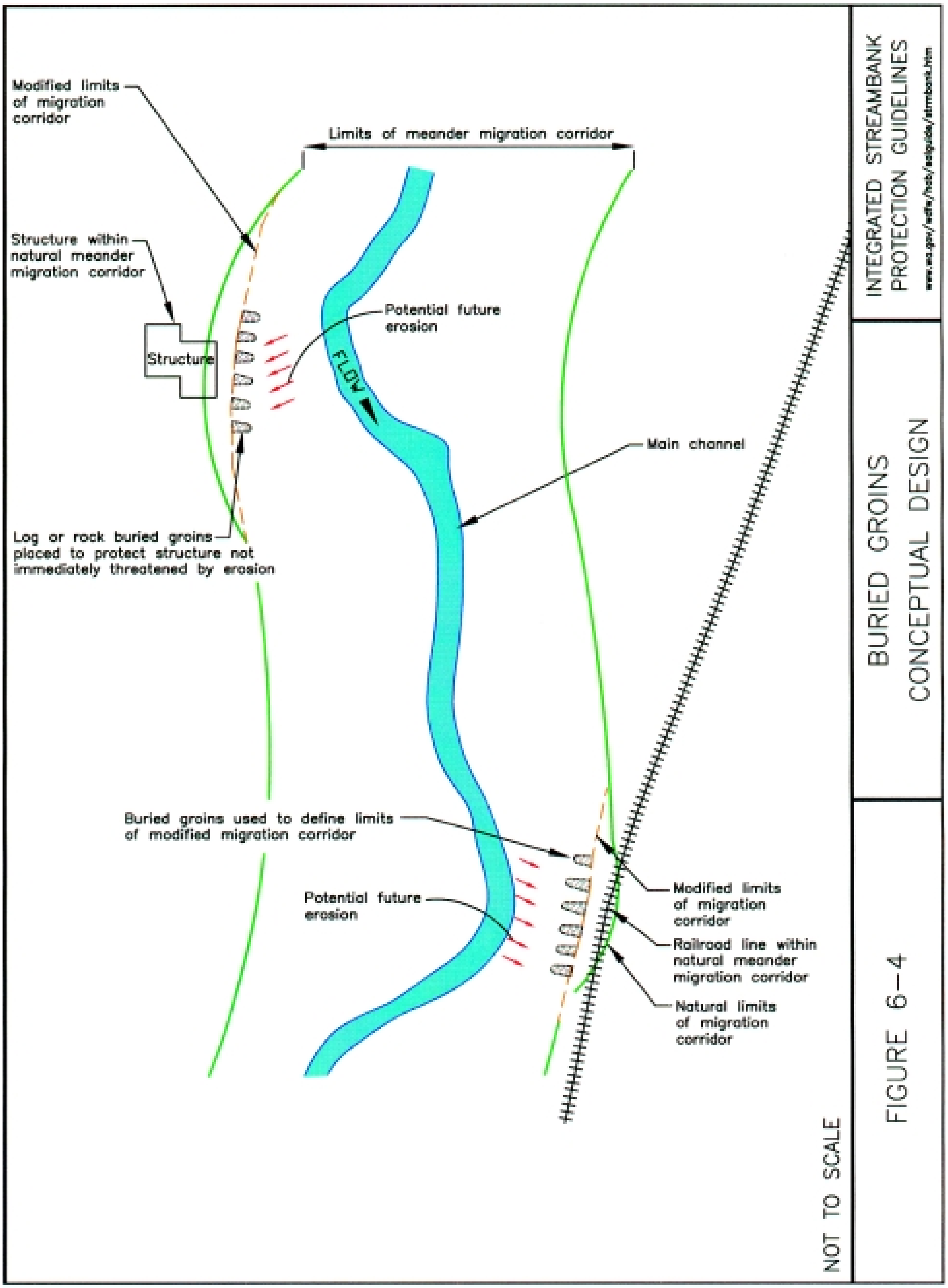


Top soil material on surface of groin
Vegetate disturbed ground with native plants as appropriate
Optional: Large woody debris
Undisturbed ground surface
BANK KEY (see text)
Backfill with native material
SECTION VIEW OF BURIED ROCK GROIN (W/ OPTIONAL WOOD)
Vegetate disturbed ground with native plants as appropriate
Undisturbed ground surface
Note:
Bank key, height, and length of groins are site dependent. See text of groins and buried groins for more information.
BANK KEY (see text)
Backfill with native material
SECTION VIEW OF BURIED WOOD GROIN
NOT TO SCALE
BURIED GROINS CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES
www.wa.gov/wdfw/hab/ahg/strmbank.htm

FIGURE 6–5


Modified limits of migration corridor
Limits of meander migration corridor
Structure within natural meander migration corridor
Structure
Potential future erosion
FLOW
Main channel
Log or rock buried groins placed to protect structure not immediately threatened by erosion
Buried groins used to define limits of modified migration corridor
Potential future erosion
Modified limits of migration corridor
Railroad line within natural meander migration corridor
Natural limits of migration corridor
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
BURIED GROINS CONCEPTUAL DESIGN
FIGURE 6–4

DESCRIPTION

Barbs, also called vanes or bendway weirs, are low-elevation structures that are projected into the channel from a bank and angled upstream to redirect flow away from the bank and to control erosion.[1] Barbs function similarly to weirs in that flow spills over the barb toward the center of the channel, reducing the water velocity near the bank. Barbs also increase channel roughness, which dissipates energy, reduces channel-bed shear stress and interrupts sediment transport. Barbs are typically constructed from rock, large woody debris or a combination of both. *Figure 6-6* (at the end of this technique discussion) shows various applications of barbs throughout Washington State.

Barbs and groins are often mistaken for one another because they look similar, and both function to redirect flow. The primary difference between groins and barbs is that groins are higher-profile structures that tend to deepen the thalweg and narrow the stream, while barbs have less of an effect on the cross-sectional shape of the stream. Groins also provide greater roughness and more channel constriction, which results in greater scour depths and increased flood stage. Similar to groins, barbs induce scour near their tips, and scour holes are likely to form in that location. Unlike groins (which are seldom completely submerged), barbs may experience scour along their downstream edge due to overtopping flows plunging over the barb crest. Depending upon factors such as the angle of attack of flood flows and depositional patterns, eddies may form between barbs in some circumstances, which may lead to scour (erosion) along the bases of barbs or adjacent streambanks. In general, however, deposition can be expected to occur between barbs that are properly designed and installed in an appropriate location.

APPLICATION

Barbs are used to redirect erosive flows away from a streambank or a bridge pier, or to direct water through a culvert or under a bridge. Barbs are often applied in combination with other types of bank-protection techniques. For example, the effect of barbs on near-bank hydraulics allows biotechnical techniques such as bank reshaping and planting to succeed. This allows an integrated bank treatment that provides greater habitat complexity and diversity. Barbs may also be used to complement downstream bank-protection techniques by directing the thalweg away from the banks. Barbs range in a continuum of size from short barbs to those that span the entire channel width (e.g., grade-control structures).[1]

Barbs are appropriate for sites where the mechanism of failure is toe erosion. To ensure long-term function, they are best applied on long, uniform stream bends where the upstream flow approach remains relatively constant over time. They are inappropriate in aggrading, degrading or high-gradient channels. Aggrading reaches may deposit sediment around and over the barbs, reducing or eliminating their hydraulic effect. In degrading reaches, barbs may be undermined, causing them to fail. Barbs are not recommended in streams with gradients over two percent; however, they may work in smaller, high-gradient streams and may not work in large rivers with a shallower slope.

Barbs should be avoided where the potential exists for an avulsion to occur. In addition, at some point, the radius of curvature may become too small for barbs to be a suitable technique to use. In tight-radius bends, localized hydraulics may preclude proper functioning of barbs. Refer to the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of barbs based on the mechanism of failure and causes of streambank erosion.

Emergency

Because barb materials must be positioned with precision, constructing barbs during flood conditions is not recommended. However, barbs can be installed immediately following a flood event if its application is appropriate.

EFFECTS

The intent of barbs is to protect a bank while keeping the effects of turbulence, scour and roughness to a minimum. Barbs use weir hydraulics of flow passing over the structure to disrupt the secondary currents across the stream bottom and redirect flow away from the bank.[2] Secondary currents result from the friction of viscous fluid flowing across the channel bed and banks. Secondary currents have a primary role in bank erosion, and barbs force these currents to flow perpendicular to their normal erosive course. In other words, barbs work hydraulically to reduce the erosive forces acting on a streambank.

DESIGN

Conceptual design drawings are shown in *Figure 6-7* and *Figure 6-8*.

Orientation

The angle of the barb to the upstream bankline tangent typically ranges from 50 to 85 degrees. Flow is redirected from the barb in a perpendicular direction to the barb axis or the downstream face if the sides are not parallel. Channel bends with smaller radii of curvature will require smaller barb angles to meet this criterion.

Length

The length of a barb should provide bank protection but not adversely confine the channel. In order for barbs to affect the dominant flow pattern, they must extend to the thalweg. The Natural Resources Conservation Service recommends that the effective length of a barb should not be greater than 25 percent of the bankfull channel width.[3] The effective length is defined as the projected length of the barb perpendicular to the flow direction. A length of 1.5 to two times the distance from the bank to the thalweg has proven satisfactory on some bank stabilization projects.[2] It should be noted that, as barb length increases, scour depth and flow concentration at the tip increase.

Spacing

Barbs are most commonly constructed in a series; however, individual barbs can be used for localized flow redirection. Barb spacing is affected by barb length, the ratios of barb length to channel width and the bend radius of curvature to channel width. Given that flow will be directed in a perpendicular direction from the downstream barb face, the subsequent barb should be placed such that it captures this flow near its center before the flow impinges on the bank. Spacing can be computed based on the following guidance formulas[4,5]:

$$Spacing = 1.5L(R/W)^{0.8}(L/W)^{0.3}$$
$$Spacing = (4 \text{ to } 5)L$$

L = Length
R = Bend Radius
W = Channel Width

Spacing affects the roughness through a bend. A large number of closely spaced barbs are hydraulically smoother than fewer barbs occupying the same distance. Placement of barbs should extend beyond the area of bank erosion. To train flow away from the bank, the barb field should begin upstream of the point where flow impinges on the bank. The first barb in the series typically receives the greatest pressure and should be built accordingly. Depending upon site-specific conditions, this may be well above where the actual erosion is occurring. At the downstream end of the field, the flow should be directed out into the channel.

Height

Barb height is determined by analyzing flow depths at the project site. The height of the barb should also be below the ordinary high water mark and should be equal to or above the mean low-water level (*Figure 6-8*).[2] Hydraulically, a barb needs to be of sufficient height to influence the secondary bed currents. Barbs are intended to function like weirs; therefore, the top of the barb should be flat, or nearly flat, with a maximum slope into the channel of 5:1. The flat weir section typically transitions into the bank on a slope of 1.5:1 to 2:1. Barbs constructed at or above the design high-water elevation are considered groins and should be designed as such.

Width

For rock barbs, the top width ranges from one to three times the D_{100} rock size. Barb width may need to be increased to accommodate equipment for constructing long barbs or for working in large rivers. Wider structures will result in a more uniform weir effect and should be used if a deep scour hole is anticipated downstream of the barb. Barb width for nonrock barbs is generally dictated by the construction materials.

Key

Barbs should be properly keyed into the bank to prevent flanking of the structure due to erosion in the near-bank region. Typically, the key length is about half the length of short barbs (10 to 20 feet in length) and one-fifth the length of longer barbs (greater than 50 feet) and should not be less than 1.5 times the bank height.[2] The Natural Resources Conservation Service guidelines recommend a minimum key length of eight feet or 4(D_{100}), whichever is greater.[5]

Barbs should also be keyed into the channel bed or constructed with a launchable toe. The key depth can be determined by calculating the expected scour depth around the tip of the barb (refer to Appendix E, *Hydraulics* for guidance on scour depth calculations). If a bed key is not incorporated or is too shallow, scour may erode the bed material downstream of the barb, causing barb materials to fall into the scour hole. Dewatering will likely be required during excavation of the bed key. A launchable toe counters scour effects by placing additional rock material along the base of the barb, which will launch into a scour hole if one develops. The launchable approach may preclude having to perform detailed scour calculations; however, caution should be applied because additional rock can be inappropriately placed on beds that do not scour, resulting in greater impact to the channel and unnecessary costs associated with the extra rock.

Wooden pile barbs also need to be keyed into the bank and the channel bed. Piles should be driven to a depth into the streambed adequate to resist hydraulic forces, the impact of floating debris and buoyant forces at the design discharge, assuming maximum scour is attained. This depth will vary according to site hydraulics, expected impact of floating debris and subsurface materials. Rock can be placed along the base of a wooden barb to counter scour that might otherwise destabilize the structure.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Barbs redirect flow away from an eroding bank and disrupt erosive secondary currents, which, in turn, affects sediment-transport patterns, especially in the near-bank region. Realignment of flow and redistribution of sediment will often impact existing spawning areas. A decrease in bank erosion will reduce periodic inputs of gravel and woody debris into the channel, which represents a lost opportunity for continued development of habitat complexity. Riparian function is also impacted by replacing riparian vegetation with a barb.

One way to partially mitigate for habitat loss is to incorporate large woody debris into the exposed portion of the barb at the bank and in the barb key. Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for additional information on how to position large woody debris. Live, woody plant cuttings can also be incorporated into this part of the barb. Segments of bank located between barbs can also be revegetated with both woody and herbaceous species to replace lost riparian function.

Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Barbs create channel roughness, a feature that has been lost in many rivers over the last 100 years through the removal of large woody debris. The added roughness dissipates energy and creates turbulence and scour holes, which provides cover for fish. Barbs produce a low-energy environment where fish can seek refuge at periods of high flow. They produce useful scour holes, providing micro-habitat at low flow, especially in rivers with high width-to-depth ratios.

Untreated banks may exist between barbs, providing soil for trees close to the stream and a shallow, low-velocity area with small woody debris and leaf litter. Barbs can include large woody debris in their structure and may eventually recruit floating large woody debris. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this bank treatment.

RISK

Habitat

If there is a spawning bed on the margin of a point bar or in the tailout of a bank-scour pool, the spawning bed may be scoured by the effects of a barb. The existing, unarmored bank may be sustaining a deep, lateral scour pool with overhanging vegetative cover and woody debris. This might be the only significant pool habitat for some distance. Placement of barbs may eliminate this habitat. The habitat-generating value of the barbs will likely not compensate for elimination of the pool habitat.

A survey of over 600 bank-stabilization projects in western Washington assessed five different types of bank treatments for their impacts/benefits to fish.[6] Rock barbs and rock barbs with large woody debris were two of the treatments evaluated. Stabilized sites were compared with untreated, control sites in the same river that were naturally stable and as similar to the stabilized site as possible. Bank treatments that incorporated large woody debris were the only types that consistently had greater fish densities than their corresponding control areas during spring, summer and winter. Fish densities were generally lower at barbs than their controls during the spring and summer, but greater during the winter.

Study results indicate that fish densities are lower at stabilized banks except those with a large-woody-debris component. Fish densities were positively correlated with total surface area of large woody debris at all sites. Based on these results, large woody debris should be incorporated into barbs whenever practical. Most large woody debris used in surveyed barb projects was found between the barbs in a depositional area with insufficient depth for rearing habitat. Care should be exercised when incorporating large woody debris to ensure that it is placed at a suitable elevation within the barb. Appendix I provides guidance on anchoring large woody debris into barbs.

Infrastructure

During construction, avoid disturbing existing vegetation. Position barbs between trees and shrubs, if possible, rather than removing the vegetation. Minimize bank sloping and armoring between barbs. If the bank between barbs is un-vegetated or newly armored, revegetation should be initiated on the slope and top of the bank.

Reliability/Uncertainty of Technique

The Natural Resources Conservation Service has design standards for stream barbs, and many of them have been constructed in Washington State. The U. S. Army Corps of Engineers has researched and built a bendway weir. The Corps' Waterways Experiment Station in Vicksburg, MI, has conducted several physical-model studies on the use of bendway weirs to improve navigation on large rivers, and research is providing valuable information on their use and effectiveness.

Barbs and bendway weirs are a little different, and no quantitative assessment of their performance has been done. The Federal Highway Administration is currently engaged in a survey of barbs. This is a developing field, and the limits of various design parameters have not been established.

CONSTRUCTION CONSIDERATIONS

Materials Required

Typical materials used in the construction of barbs are rocks and logs. Rock should be angular and the size of rock can be determined by appropriate riprap design procedures. Rock sized for typical bank revetment riprap is too small for barbs. The Natural Resources Conservation Service recommends using a D_{50} rock size that is two times the D_{50} rock diameter determined using standard riprap-design procedures for continuous riprap at bankfull conditions.

Log barbs have typically been constructed using wooden or steel piles, wood cross-logs and rootwads. Steel piles have the advantage of being stronger, allowing better (deeper) penetration through gravel or cobble subsurface materials, and they are free of buoyant forces. The obvious disadvantage to steel piles is their longevity - they are likely to far outlive the other components of the barb. Cross-logs are typically branchless logs cabled across the piles to form a fence-like structure. Rootwads can be included in the structure to add complexity. Large woody debris installed in barbs should be submerged below the ordinary high-water line for habitat value and longevity. Refer to Appendix I for guidance.

Woody vegetation should be planted in the barb at proper hydrologic zones and growing medium. Generally, live cuttings are the most suitable. Refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for more information.

Timing Considerations

Barbs are best constructed during low flow, when dewatering is possible and when resident and anadromous fish are less likely to be impacted by construction activities. In order to install rock or logs to the depth of scour, excavation within the channel bed will be necessary and, consequently, will require temporary dewatering systems. Keying into the streambed by constructing a launched toe may also require dewatering. Dewatering allows for ease of installation and limits siltation of the stream during construction. This can be accomplished with a coffer dam during low water.

Critical periods in salmonid life cycles, such as spawning or migration, should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

Cost

The main function of barbs is to direct flow away from the bank, thus modifying flow patterns in the near-bank region to encourage sediment deposition and reduce bank erosion. Corresponding decreases in velocities and shear stresses along the bank minimize the need for bank protection to be applied between barbs. Therefore, barbs, in combination with other bank treatments, may protect a streambank more effectively and at less cost than traditional bank-revetment measures. The cost is generally less than that for a conventional riprap or groin design.

The major cost components of barb construction include access, materials, dewatering and installation. For further information on the costs of these components and specific construction materials, refer to Appendix L, *Cost of Techniques*. Cost of individual rock barbs may vary from $2,000 to $5,000 depending upon their size and upon site-specific factors.

MAINTENANCE

Maintenance of barbs may include replacement of construction materials (e.g., rock, logs) that shift or are removed by high flows. This may include replacement of nonsurviving plant material. Barb materials lost to high flows should be replaced before damage occurs to the bank or structures located between the barbs.

Erosion along the perimeter of the barb and at the key should be closely monitored and evaluated for need of repair.

MONITORING

Because barbs involve impacts to the channel and banks, they will require comprehensive monitoring of the integrity of the structures, channel and bank features and in-channel habitat. Monitoring of barb projects should be initiated prior to construction, with baseline-conditions surveys of the physical channel, its banks and its habitat value. This should include five cross-sections at intervals equal to the channel width upstream, five downstream and one through each barb at a minimum. This will allow comparison of modified conditions to preproject conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation from fixed photo points of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring*.

Monitoring of barb structures should include preproject and subsequent annual surveys of key members and visual assessments of their configuration, dimensions and hydraulic function. The general integrity of the structures should be evaluated, including the identification of any significant settling of header or footer rocks as determined from survey and comparison of photos.

Impacts to the channel and to habitat must be carefully monitored. Channel changes occurring following installation can be documented by reviewing an annual survey of cross sections surveyed prior to installation and at the time of completion. Patterns of sediment deposition or scour should be noted. Similarly, changes to available habitat should be documented on a schedule dictated by fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[7] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

Monitoring should be conducted annually at a minimum and should be conducted following all flows having a return period of two years or greater. Monitoring should be conducted for at least five years after barb installation. Mitigation components of barbs must be monitored for the life of the mitigation requirement.

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a. Teanaway River, along Highway 970. 1996.

a. Clark Fork River, MT.
Source: Allan Potter, Geomax.

b. Cowlitz River, near Toledo, WA.

d. Upper Klickitat River. 2001.
Source: Allen Potter, Geomax.

Figure 6-6. Various applications of log or rock barbs throughout Washington State.

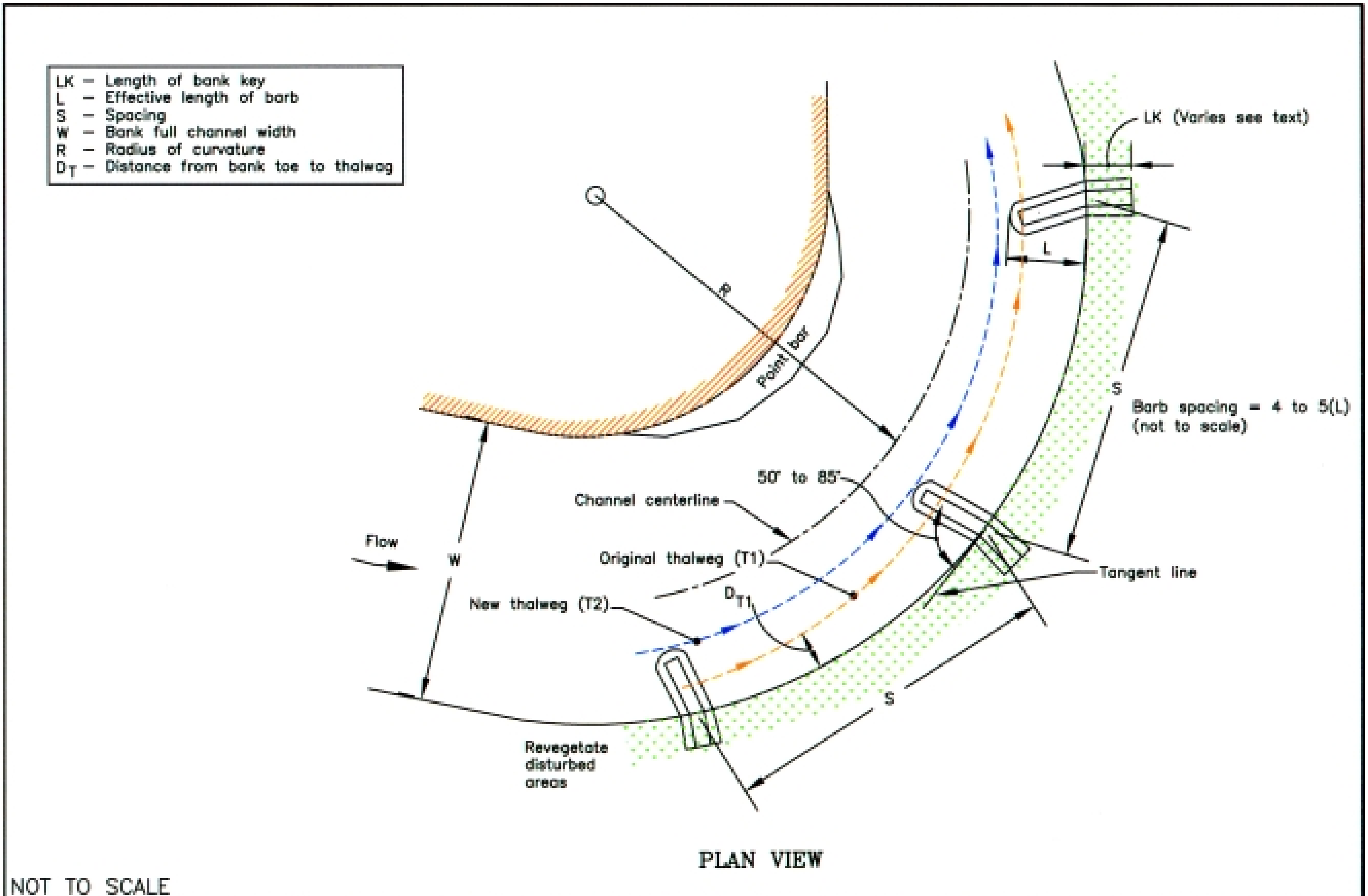

FIGURE 6–7

BARBS
CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES
www.wa.gov/wdfw/hab/ahg/strmbank.htm

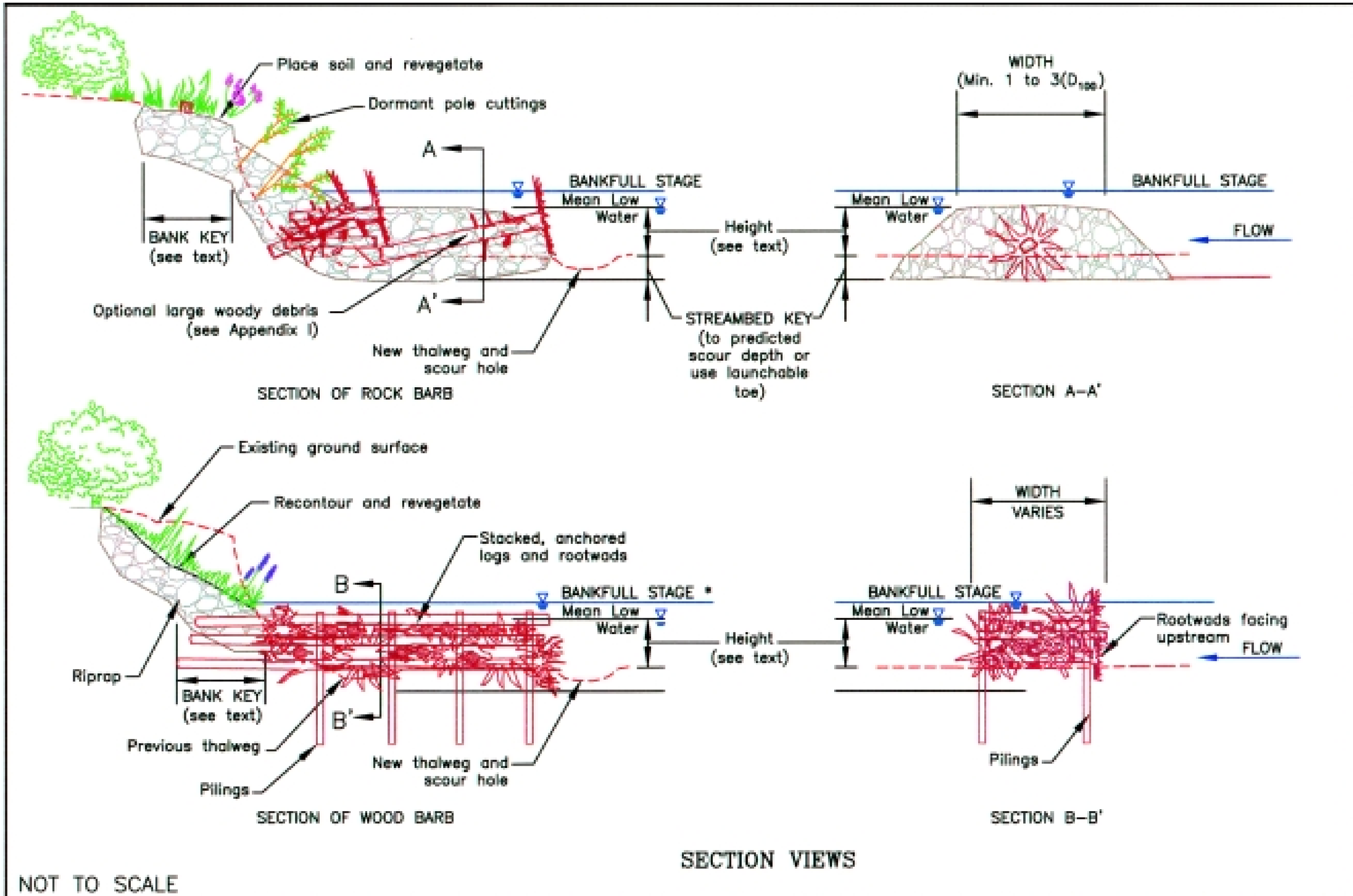

FIGURE 6–8

BARBS
CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES
www.wa.gov/wdfw/hab/ahg/strmbank.htm

Engineered Log Jams
Flow-Redirection Techniques

The following technique was developed for the Integrated Streambank Protection Guideline. Its focus is on streambank protection. While similarly titled techniques may appear in other Aquatic Habitat Guidelines, their contents may differ from the text presented here.

DESCRIPTION

Engineered log jams are collections of large woody debris that redirect flow and provide stability to a streambank or downstream gravel bar. Engineered-log-jam constructions are patterned after stable, natural log jams and can be either unanchored or anchored in place using man-made materials. Naturally occurring log jams in alluvial channels are usually formed by one or several key members, consisting of large trees with rootwads attached, that stabilize and anchor other debris that is "racked" against the key members.[1] Log jams extend above bankfull water surface and, when connected to a streambank, are hydraulically similar to groins. *Figure 6-9* (at the end of this technique) shows examples of engineered log jams throughout Washington State.

Naturally occurring log jams may start as a single, large tree, as a large number of trees drifting together or as an undercut, timbered bank giving way and the trees coming with it. Over the years, people have removed many of these naturally formed structures for navigation, firewood and flood-control purposes. However, log jams provide habitat for a wide variety of fish species during most of their life stages. Engineered log jams are also fundamental to the dynamics of a healthy, forested, river ecosystems.[2] Engineered log jams as a bank-protection treatment are still considered experimental, but they are becoming increasingly popular as bank protection because they integrate fish-habitat restoration with bank protection.

APPLICATION

Prior to extensive logging activities in the past century, log jams were common throughout many of our streams. These accumulations of woody material helped create stable stream channels and habitat for fish and wildlife. Only in recent years have engineers and scientists begun studying the role of log jams in stabilizing streambanks. Mimicking how these accumulations form and function is the basis for the concept and design of engineered log jams.

Engineered log jams are used to realign a channel or redirect flow away from a streambank to protect it from erosional forces. They are also used to increase channel roughness to reduce flow velocities and shear stress along eroding banks. Large-woody-debris jams create a hydraulic shadow, a low-velocity zone for some distance downstream that allows sediment to settle out and stabilize. By locating a log jam along an eroding bank, the bank downstream of the jam becomes a deposition zone rather than an erosion zone. The deposition zone tends to become vegetated and continues to grow in volume over time.

Prior to designing and constructing an engineered log jam as a bank-protection technique, it is important to understand the existing physical characteristics and geomorphic processes present at a potential project site and along the reach (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance).

Engineered log jams are best applied on long, uniform bends in alluvial channels. They are also appropriate when the mechanism of failure is toe erosion since they provide roughness and redirect erosive flows away from an eroding bank. When applied along a bend, they are apt to grow significantly as they recruit wood, so changes to the opposite bank should be expected. Engineered log jams are also useful in degrading channels for capturing and storing sediment and large woody material.[3] They can slow the rate of erosion in an equilibrium channel that is migrating laterally or where there is potential for a chute-cutoff, though they still allow for gradual meander migration. Large-woody-debris jams occur naturally at the inlet of many side channels. Jams can be assembled at the inlet of pre-existing or constructed side channels to regulate the amount of flood flow entering the side channel. This protects the banks in the side channel, prevents the side channel from capturing the main channel and protects existing spawning and rearing habitat in the side channel.

Engineered log jams may be appropriate when the mechanism of failure is scour. They should be placed upstream from the scour hole to redirect flow away from the obstacle that is creating the scour or to dissipate some of the energy that is causing the scour. They should not be placed directly in a scour hole. In tight-radius bends or other constricted reaches, they may not be very effective, and their application can further exacerbate existing erosion problems or move them upstream. Care in sizing and spacing engineered log jams is crucial to avoid creating a constriction.

In aggrading channels, engineered log jams may be appropriate, depending upon the severity of aggradation. They can be effective strategically if placed in a mildly aggrading channel where they can collect and store sediment. Their presence in such circumstances will better define the low-flow channel. Engineered log jams also recruit floating, large woody debris, which reduces the likelihood of the jam becoming buried and ineffective over time. When a channel has been disturbed and is carrying a high bedload, jams can be constructed in upstream reaches to stabilize sediment movement. Over the long term, engineered log jams reduce aggradation and erosion in the downstream reach. These jams can be placed either at the bank or in midchannel.

Engineered log jams provide excellent fish habitat by developing deep scour pools and associated tailout spawning areas, as well as complex cover. The structural complexity and hydraulic diversity associated with log jams provide ideal habitat for a variety of life stages and species of fish. For these reasons, engineered log jams receive high marks as a habitat-restoration and mitigation tool.

To learn more about the applicability of engineered log jams based on the mechanism of failure and causes of streambank erosion, review the screening matrices found in Chapter 5, *Identify and Select Solutions.*

Emergency

Engineered log jams are not appropriate for emergency situations. They cannot be constructed quickly, nor can they be assembled during high-flow events.

EFFECTS

Depending upon their size relative to the channel, the constriction caused by an engineered log jam may result in scour at the opposite bank or point bar. Engineered log jams generally produce scour adjacent to themselves. The scour at the margin of the jam and the associated downstream deposition moves the location of the thalweg away from an eroding bank. One observed effect is the tendency for a side channel to form on the back side of the jam, against the bank.[1] This is a result of the jam causing an obstruction to flows above the bankfull elevation. Jams tend to split the flow, and the flow directed along the bank may create a side channel. If side-channel development is anticipated and undesirable, extend the jam into the bank and floodplain, and anchor it to a stable location.

Engineered log jams offer a distinct advantage over most rock structures such as barbs and groins. As scour holes develop adjacent to the log jam, the interlocking nature of log jams allow them to deform and settle; effectively retaining the structural integrity of the structure.[2]

DESIGN

Conceptual design drawings of engineered log jams are shown in *Figure 6-10* and *Figure 6-11*.

Stability

The design of an engineered log jam requires a thorough analysis of channel hydraulics, which should be conducted by a qualified engineer. Engineered log jams can be designed with or without the use of anchoring hardware. Properly designed and located log jams can be very stable with life expectancies equal to or exceeding the design life of traditional bank protection techniques (e.g., groins, drop structures, revetments).[2]

Stabilizing key members (large logs with rootwads attached) can be accomplished at most flows by the ballasting effect of large logs and/or boulders.[1] Determining the necessary ballast mass requires a detailed stability analysis of fluid drag, buoyancy, lift and friction-resisting forces, and weight of the ballast logs and/or boulders.[4] A structure is stable when the sum of the resisting forces exceeds the sum of the driving forces (e.g., drag, lift and buoyancy). Hydraulic conditions often result in sediment deposition on the downstream side of a log jam. This deposition buries much of the wood and will increase the effective weight and, hence, the stability of the log jam. The process of deposition can occur naturally or be accelerated by placing excavated sediments during initial construction to bury the key members.[2]

Designing an unanchored, engineered log jam requires excavating the streambed to provide a trench for the key member(s). The depth of excavation depends on channel hydraulics, substrate characteristics, channel dimensions and the size of wood. Once a key member is placed in a trench, the trench is covered with excavated sediment to provide additional ballast and frictional resistance to drag forces. Large woody material (whole trees with rootwads attached) are stacked (stacked members) on the key members for ballast. Next, whole trees, logs and/or rootwads are racked (racked members) on the upstream side of the key-piece rootwad(s).

The number of pieces racked against the rootwad(s) depends upon the need for immediate protection, channel dimensions and hydraulics and the likelihood of recruiting additional debris.

Unanchored, engineered log jams must be dense, with racked and stacked pieces carefully interlocked. The more dense the rack, the less flow will pass through it, thereby increasing the stability of the log jam. Scour under part of a loosely assembled structure may destabilize it and allow portions to be washed away. Dense structures, on the other hand, act as a unit. They settle uniformly and hold ballast well.

Engineered log jams can be anchored with pilings (see *Figure 6-10*). In small-grained substrates, a row of log pilings can be driven vertically into the streambed using the excavator bucket. In larger substrate, pile-driving equipment may be required, as well as steel tips on the logs. The logs need to be long enough to extend below estimated scour depths. A second row of pilings should be driven into the streambed at least 20 feet downstream, and brace logs should be anchored between them. Large woody debris is then racked against the upstream side of the brace logs and the first row of pilings, just as they are for unanchored engineered log jams. The braces are needed because there is a limit to the size and, consequently, the strength of logs that can be driven with an excavator. The braces distribute the shearing force of the racked logs between the two rows of pilings. The upstream row of piles is in the area where scour will form around the log jam. The downstream row is positioned in the deposition zone, safe from the undermining effects of scour.

In cases where the substrate will not allow logs to be driven, steel pilings can be used. If they can be driven deep enough, a single row may be sufficient. The buildup of debris will eventually hide the pilings from view.

Other methods of anchoring include attaching cable to the key logs and using an adhesive (e.g., epoxy) to glue the cable to boulders for ballast. If possible, the boulders should be buried in the bed to act as deadman anchors. Another approach is to partially bury logs into the bank so that they still extend into the channel, perpendicular to the direction of flow. Logs are then racked against the upstream side of the partially buried log. Some sites may require brace logs and/or a rock toe as additional reinforcement. To learn more about how to anchor large woody debris, refer to Appendix I, *Anchoring and Placement of Large Woody Debris.*

Dimensions and Orientation

The shape of engineered log jams depends upon channel hydraulics, desired results and cost. In naturally formed jams, the most stable configuration is one where key members are oriented parallel to the high flow, with their rootwads upstream. Racked wood is generally positioned perpendicular to the flow direction. In many cases, debris collects upstream against the bank and forms a concave shape (from plan view) that is more streamlined. Using different methods of anchoring the jam may allow different shapes and alignments to form, and collection of additional wood on the engineered log jam during floods will potentially change the shape and dimensions of the jam.

The correct spacing and dimensions of jams are closely related. When positioning a series of engineered log jams along an eroding channel bend, they should begin below the cross-over riffle at the head of the bend. Spacing should be similar to that recommended for groins, but bear in mind that engineered log jams may become longer than groins as woody material is captured and collected over time. Groins are discussed as a separate technique in this chapter. The effective length (L_e) of an engineered log jam is the distance the structure extends into the channel, measured perpendicular to the bank. It does not include that portion that is keyed into the bank. Effective length must be considered when establishing spacing requirements. The furthest upstream jam in a series should be expected to grow the most as it will intercept additional floating woody material before it reaches subsequent jams. This phenomenon allows increased spacing between the first and second structures. Downstream structures may accumulate debris, but it will probably collect at a slower rate than the first jam in the series. Expect the accumulation to occur in both the upstream direction and laterally. This growth must be anticipated and may present a problem if channel constriction is an issue.

The size of materials used in the engineered log jam will depend upon the method of anchoring. The required size of pieces will be based on the calculations of drag, friction, lift and buoyancy. It's also important to take into consideration the anticipated rate of wood decomposition, wood density and the length of project life. Racked pieces do not usually function as structural members of engineered log jams, so they can be any size, particularly if accumulation of additional debris on the rack is anticipated. Determining the correct size for structural members should be accomplished by a qualified engineer.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Engineered log jams provide valuable fish and wildlife habitat. Because they are so valuable to fish and wildlife, only construction impacts need to be mitigated. Immediately following placement of engineered log jams, there may be temporary, short-term impacts on spawning. Existing spawning areas may shift or scour; while others may accrete with fines while new spawning areas are forming. It may take the channel a period of time to adjust to the jams. However, the long-term habitat benefits of engineered log jams far out-weigh these short-term impacts.

Construction-related impacts do, however, require mitigation. Care should be used in gaining equipment access to the site to minimize construction impacts. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this treatment.

Mitigation Benefits Provided by the Technique

The structural and hydraulic diversity that engineered log jams provide creates habitat for a multitude of fish species at nearly every stage of life. Engineered log jams create excellent cover, holding and rearing habitats. At the tailout from the scour hole created by an engineered log jam, spawning habitat may be created. The detritus they accumulate, particularly smaller twigs and leaves that decay rapidly, also serves as a food to some aquatic insects that fish consume.

RISK

Engineered log jams pose inherent risks to infrastructure and human stream users. These risks include:

- safety hazards caused by the log jams or the cables that anchor them (this risk can be somewhat reduced by placing warning signs upstream from the log jams to alert boaters),
- blockage of culverts or bridge openings by large woody debris that has been dislodged from a log jam upstream,
- unanticipated erosion across the channel or to the adjacent streambank,
- increased channel roughness and constriction, and/or
- increased flood stage.

Careful, well-calculated design and positioning of engineered log jams can minimize all of these risks. Refer to Matrix 3 in Chapter 5 for more detail on mitigaation benefits of this treatment.

Reliability/Uncertainty of Technique

The use of engineering log jams as a streambank-protection technique is relatively new, with little available research information to document their performance. Monitoring and performance reporting is encouraged to aid in further development of this technique by future practitioners. Appendix J, *Monitoring* provides more information on how to observe and record project performance over time.

CONSTRUCTION CONSIDERATIONS

Equipment and Materials Required

Large woody debris should be of a size (length and width) and species that can remain intact and stable for many years. Avoid using hardwood species such as alder or cottonwood, which decay rapidly. Coniferous species such as cedar, fir and pine are better choices. If sufficiently large key members are not available or can not be transported in one piece to the site, several trees could be cabled or pinned together to form a composite key member. Large and long logs imported from off-site locations may need to be cut into pieces for transport and then reassembled on site by splicing, gluing and tacking pieces back together.

Use of on-site wood resources can greatly simplify construction and reduce costs. Appropriating single logs from dry gravel bars is an option with minimal short-term impacts. Consider the density or loading of large wood in the reach before deciding to use on-site wood. If the channel is deficient of large wood, it may be necessary to import wood for the structure(s). One of the factors that will help determine whether off-site wood can and should be imported to the site is whether or not equipment can move wood of the required size and length from a distant site to the work site.

Wood buoyancy can be a problem during construction since much of the log needs to be installed below the water surface. To address this problem, the site may need to be dewatered to allow for placement and anchoring of large pieces. The use of previously saturated wood can simplify construction by reducing buoyancy problems during installation. See Appendix M, *Construction Considerations* for information about dewatering. Turbidity may also be a significant problem during installation due to the amount of digging in the channel bed required during installation. This can be avoided by dewatering the installation site, or by creating a coffer system that isolates the immediate site from flowing water.

Protection of the existing riparian zone is a high priority, particularly in drier climates where replacement of the canopy can take decades. The use of walking excavators, winches and hand labor may be required at some sites.

Timing Considerations

Construction should be conducted during a period where impacts to critical resident and anadromous fish life stages, such as spawning or migration, are avoided and when dewatering for construction is possible. Low-flow conditions are ideal for the placement of engineered log jams and may be essential for dewatering efforts. Dewatering eases installation and prevents siltation of the stream during construction. In-stream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can be found in Appendix M.

Cost

Costs for installing engineered log jams are site-specific and are affected primarily by availability of wood materials, dewatering capabilities and equipment access. Engineered log jams constructed in Washington State have ranged in cost between $1,800 to $80,000 to install.

Large woody debris can vary considerably in cost from virtually free (as locally salvaged wood), to quite costly (large-diameter, full-length cedar trees that may have to be sawn for transport and later re-assembled). Large woody debris can cost between a few hundred dollars to a thousand dollars per piece. Equipment costs can also be substantial, especially when specialized equipment is required, such as helicopters for wood delivery, spider hoes for access and considerable manual labor for installation. Appendix L, *Cost of Techniques* provides additional information and a case study on estimating project costs.

MAINTENANCE

Maintenance of engineered log jams includes replacement, realignment or removal of pieces following storm events equal to or greater than what they were designed to withstand. If anchored, the anchoring hardware may also need to be readjusted or replaced. Any biotechnical bank protection between the log jams will also need maintenance.

MONITORING

Monitoring engineered jams should determine if the structures are performing in accordance with design flow criteria and whether they are providing the habitat and bank protection desired. Because large-woody-debris projects generally involve impacts to the channel and banks, they will require comprehensive monitoring of both channel and bank features, with particular attention to habitat monitoring. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[5] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

Monitoring to evaluate structural integrity should be conducted annually and following any flow events that meet or exceed design flow events. This can be accomplished by surveying precise locations of key members relative to a stationary point on shore by determining whether the jam has lost key members and by conducting a visual inspection of anchoring systems.

Details on how to develop a monitoring plan can be found in Appendix J.

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4 D'Aoust, S. and R. G. Millar. 2000. Stability of ballasted woody debris habitat structures. Journal of Hydraulic Engineering.

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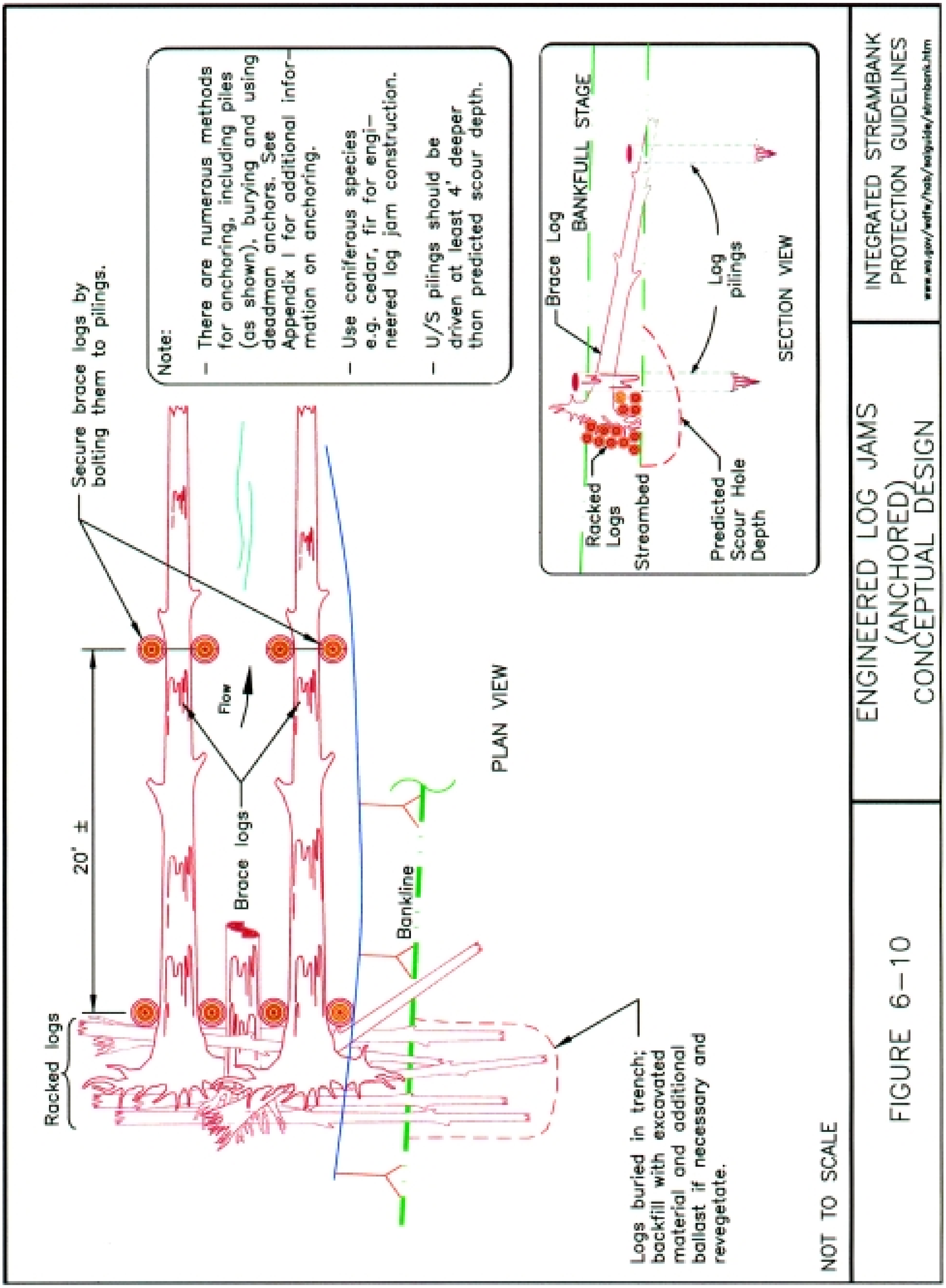
a. Cyspus River. 2001.

c. Nooksack River. 2001.

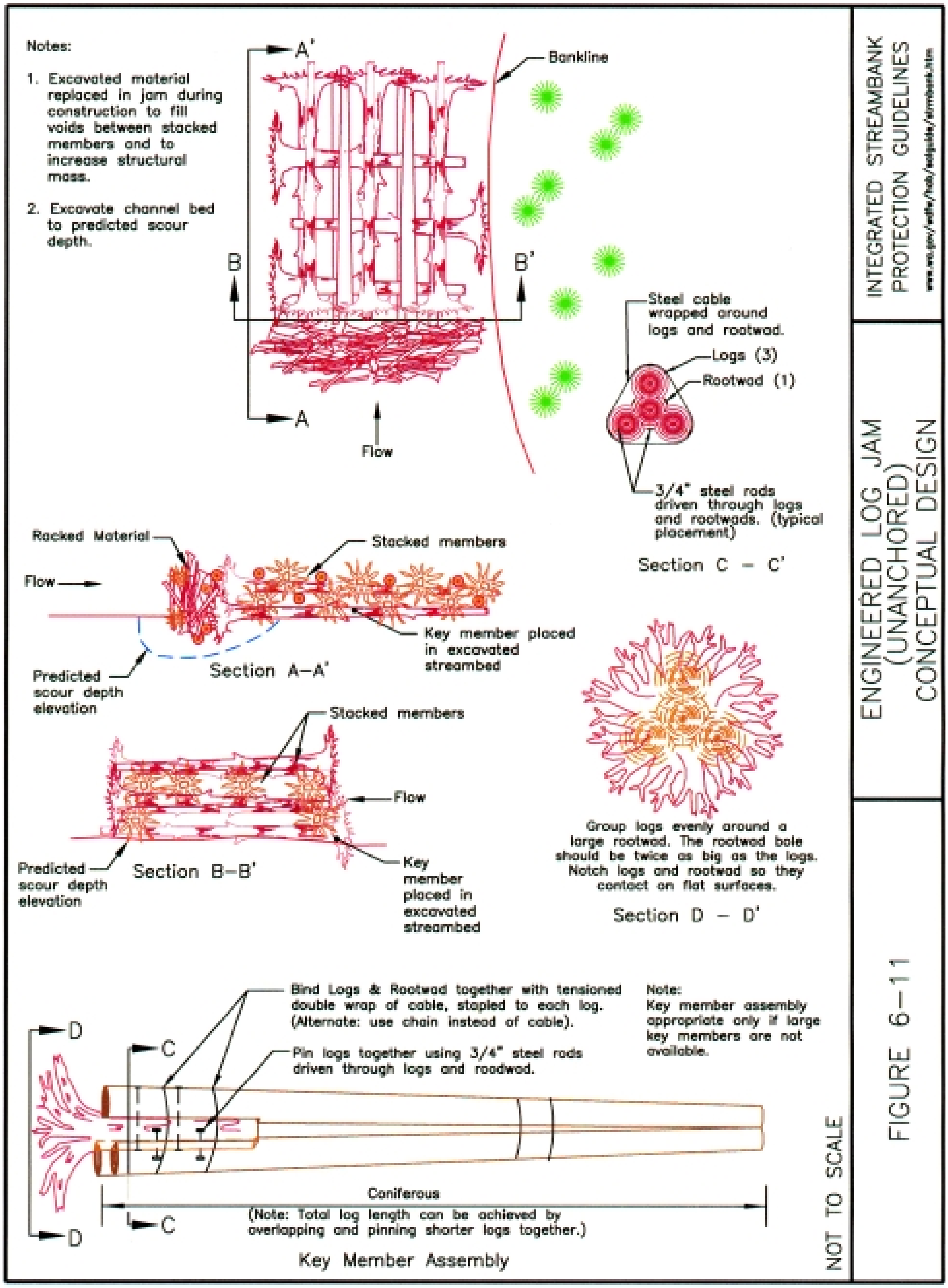
b. Tucannon River. 2001.

d. Stillaguamish River. 1998.
Source: Tim Abbe, Phillip Williams and Associates.

Figure 6-9. Examples of engineered log jams throughout Washington State.



Racked logs
20' ±
Secure brace logs by bolting them to pilings.
Brace logs
Flow
Bankline
PLAN VIEW
Logs buried in trench; backfill with excavated material and additional ballast if necessary and revegetate.
NOT TO SCALE
Note:
– There are numerous methods for anchoring, including piles (as shown), burying and using deadman anchors. See Appendix I for additional information on anchoring.
– Use coniferous species e.g. cedar, fir for engineered log jam construction.
– U/S pilings should be driven at least 4' deeper than predicted scour depth.
Racked Logs
Streambed
Predicted Scour Hole Depth
Brace Log
BANKFULL STAGE
Log pilings
SECTION VIEW
FIGURE 6–10
ENGINEERED LOG JAMS (ANCHORED) CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES



Notes:
1. Excavated material replaced in jam during construction to fill voids between stacked members and to increase structural mass.
2. Excavate channel bed to predicted scour depth.
A'
A
B
B'
Bankline
Flow
Steel cable wrapped around logs and rootwad.
Logs (3)
Rootwad (1)
3/4" steel rods driven through logs and rootwads. (typical placement)
Section C – C'
Rocked Material
Stacked members
Flow
Key member placed in excavated streambed
Predicted scour depth elevation
Section A–A'
Stacked members
Flow
Predicted scour depth elevation
Section B–B'
Key member placed in excavated streambed
Group logs evenly around a large rootwad. The rootwad bole should be twice as big as the logs. Notch logs and rootwad so they contact on flat surfaces.
Section D – D'
Bind Logs & Rootwad together with tensioned double wrap of cable, stapled to each log. (Alternate: use chain instead of cable).
Pin logs together using 3/4" steel rods driven through logs and roodwad.
Note:
Key member assembly appropriate only if large key members are not available.
D
C
Coniferous
(Note: Total log length can be achieved by overlapping and pinning shorter logs together.)
C
D
Key Member Assembly
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
ENGINEERED LOG JAM (UNANCHORED) CONCEPTUAL DESIGN
FIGURE 6–11

DESCRIPTION

Drop structures are low-elevation weirs that span the entire width of the channel. They are designed to spill and direct flow away from an eroding bank, dissipate and redistribute energy and provide grade stabilization. Drop structures are similar to porous weirs; however, because they are not as porous, they create substantially more backwater than porous weirs. *Figure 6-12* (at the end of this technique discussion) shows various applications of drop structures throughout Washington State.

Drop structures are typically constructed with rock or logs, though sheet pile and concrete are also used. Log and rock drop structures have been used extensively in Washington State to stabilize channel grades, to backwater culverts and to provide bank protection (primarily in fish passage and habitat-restoration projects).

APPLICATION

Applications for drop structures include grade control in degrading reaches, flow realignment, fish passage, channel diversity (pool habitat) and energy dissipation. They are most applicable in channels that have slopes of up to about three percent. The Washington Department of Fish and Wildlife has constructed log drop structures for the purposes of reducing channel slope and improving fish passage, especially through culverts.

It is important to determine whether drop structures are the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Drop structures are commonly used in degrading channels to restore the channel bed to a more stable profile and elevation. They can also act as grade-control structures by preventing a nickpoint from migrating upstream. Drop structures are inappropriate in aggrading reaches. Aggrading reaches will deposit sediment around and over the drop structure, thereby counteracting their intended function. They should also be avoided where there is the potential for an avulsion. See the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on determining the applicability of drop structures based on the mechanism of failure and causes of streambank erosion.

Variations

Drop structures are typically constructed in a symmetric, upstream-pointed chevron or arch configuration. Drop structures have also commonly been installed as straight features across the channel, though they tend to flatten the channel cross section and eliminate diversity in the channel. Straight drop structures are, therefore, not recommended from a habitat-diversity perspective. On the other hand, drop structures that are configured in S-patterns or other asymmetrical layouts across the channel can simulate natural shelves and drops on the channel bed, potentially enhancing habitat diversity.

Deformable Drop Structures

Over time, the length (measured from the upstream edge to the downstream edge) of the drop structure may narrow as rocks fall into scoured holes. Eventually, the components of the structure will become more tightly packed together; however, this will not compromise the structure's strength. Structural stability is provided through careful selection and placement of boulders across the channel. Fractured rock is often necessary to lock the structure together. Arches can only be effective across relatively narrow channels, usually less than 20 feet. The expectation is that the arch may eventually break apart, and the boulders will spread out to form a cluster. This is expected to occur gradually as the bank and bed are stabilized by vegetation and debris. The cluster of boulders remains to form a cascade; an outcome similar to that expected for a porous weir rather than a distinct drop structure.

Emergency

Drop structures are not useful in emergency streambank protection. They completely span the stream channel and usually require construction from within the channel, which may not be possible during an emergency situation. However, on smaller channels that are actively degrading or headcutting, rock may be placed as a grade-control measure during emergency conditions to arrest formation or progression of a nickpoint.

EFFECTS

Drop structures increase backwater conditions by raising the effective bed elevation. This commonly induces sediment deposition and increases the water stage upstream of the structure at a variety of flows. Elevated stage may be a concern for channels within flood-regulated jurisdictions. Deposition upstream of a drop structure is particularly common in moderate to high bedload channels. In degrading channels, upstream backwater effects are not as likely due to minimal sediment availability. In these channels, bank erosion and flooding upstream may decrease. However, downstream effects from scour may create a fish passage barrier. Additionally, a fish barrier may result if the upstream-to-downstream difference in water-surface elevation is excessive.

Even with their potential risk of creating fish barriers, an important benefit of drop structures is the habitat they can provide. They create turbulence cover and a diversity of plunge pools, eddies and velocity chutes. They also catch debris, provide aeration and collect and sort gravel in the tailout for spawning habitat. Realigning the thalweg away from a downstream eroding bank will reduce the depth of near-bank pools; however, loss in pool habitat may be compensated by the plunge-pool habitat created by the drop structure.

Depending upon its shape, the structure may affect the channel cross section. Drop structures that are flat and straight across the channel tend to create a channel cross section that is flat and uniform. The pool created in this case is at the base of the structure and spans the entire channel. Drop structures that have a "V" cross section geometry create a thalweg in the pool and generate more diversity. The pool is longer but narrower and may not span the channel.

DESIGN

Conceptual design drawings are shown in *Figure 6-13* and *Figure 6-14*

Dimensions

The width of the drop structure spans the entire bankfull width of the channel. Straight structures are not recommended. Structures configured as a chevron (shaped like a "V") can be symmetrical or asymmetrical, depending upon the thalweg alignment as it approaches the structure and the desired thalweg alignment immediately downstream. Generally, each leg of the "V" will span to the thalweg. Drop structures have been installed in channels up to 400 feet wide. Drop-structure *length*, or the distance between the upstream and downstream ends, is typically designed to be less than 15 feet to accommodate equipment access and to protect the structure's stability.

The upstream water stage, allowable head differential and desired hydraulics dictate the height of the drop structure, measured at the apex of the arch or chevron. If designing multiple drop structures, the height of the structures should be such that the low-flow head differential from one structure to the next is no more than one foot. The head differential criterion is necessary to ensure fish passage and varies based on passage needs of specific species. If designing a single drop structure, the height is normally set at low-flow water stage while maintaining less than one foot of head differential through the structure.

The allowable head differential of one foot must be satisfied at all flows between the low- and high-flow fish-passage design criteria. The low-flow criterion is the two-year, seven-day, low-flow discharge or 95-percent exceedance flow during the migration months for the species of concern. The high-flow criterion is the flow that is not exceeded for more than 10 percent of the time during the months of adult fish passage. The two-year flood flow may be used as the high-flow when stream-discharge data is unavailable. Note that the one-foot head differential applies for passage of adult chinook, coho, sockeye and steelhead. Adult trout (greater than six inches), and pink and chum salmon have an allowable head differential of 0.8 feet. If upstream juvenile fish passage is critical, the drop should not exceed six inches.

Orientation

Drop structures are typically placed in an upstream pointing arch or chevron configuration, or in a straight line across the channel (roughly perpendicular to the flow). If chevron shaped, the alignment of each leg is angled at approximately 45 degrees from the approaching stream flow. If the chevron-shaped drop structure consists of rock, it may eventually evolve into more of a parabolic shape. A chevron-shaped drop structure is hydraulically very similar to a barb; it is basically two barbs that extend from opposite banks toward one another and connect at the thalweg.

When applied in a degraded channel, the height of a drop structure (or a series of drop structures) is set to raise the channel-bed elevation and restore the desired water-surface profile. Care is needed in this case to ensure downstream degradation is not exacerbated. The sediment-storage capacity of a drop structure can be enough to instigate additional degradation downstream. This is especially true if the initial degradation is due to a decrease in sediment supply. Drop-structure spacing is based on the desired channel gradient and angle of flow leaving the structure. The Washington Department of Fish and Wildlife recommends the use of chevron-type drop structures within streams having maximum gradients of three percent and straight-weir-type drop structures in streams having up to five-percent gradients. Chevron weirs concentrate flow energy at the thalweg. Straight weirs spread the energy across the channel and are therefore more efficient at energy dissipation, which allows them to be placed in steeper streams.

Configuration

The drop structure should slope from the banks toward the apex. Generally, the horizontal-to-vertical ratio for this slope should not exceed 5:1. At the bankline, the top of the structure should not exceed the elevation of the channel-forming flow. A notch is often placed in the structure so that boaters and/or fish can pass through during low-flow stages. The length of the legs on a V-shaped structure can vary; and, therefore, the location of the apex varies across the channel. A meandering thalweg and additional channel complexity should be taken into account in positioning the apex. Typically, the apex is located within the center third of the channel. Landward of the bankline, the drop structure should be keyed into the bank to provide scour protection from overbank flow spilling back into the channel. The key will extend from the bankline into the bank at a slope of 1.5:1 to 2:1. A minimum length for a rock drop structure bank key is four times the D_{100} diameter of the header rocks.[1] For sizing of rocks, refer to the technique descriptions in this chapter for *Riprap* and *Porous Weirs*. A minimum length for a log drop structure bank key is a minimum of five feet into the bank.

Large woody debris can be incorporated into the drop structure for added habitat benefit, additional roughness and flow realignment. Such material can be incorporated near the bankline by anchoring a tree trunk with attached rootwad into the drop structure. The tree trunk should run parallel to the bankline. Care must be taken when installing large woody debris since it may also create a constriction and additional backwater. Please refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for further guidance.

It is also important to minimize bank disturbance and vegetation removal during construction. Buried cut-off logs or rocks can be incorporated into the bank key. Buried logs or rocks should be oriented perpendicular to the overbank flows. Revegetating the bank at both keys is necessary for added structural strength and habitat needs. The bank may need to be protected for a short distance upstream and downstream of the key. Large woody debris and/or rock can be placed along the bank as launchable material (see the technique description in this chapter on *Riprap*, for more information about launchable rock). Placement of large woody debris and/or rock at this critical location will help to prevent erosion, which could otherwise result in flanking of the drop structure at high flows.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Placement of drop structures in the channel will fix the bed profile and prompt adjustments in the thalweg alignment. Existing spawning areas may be impacted by new scour patterns that result from these channel modifications. Natural channel evolution, including dynamic erosional and depositional processes, will be reduced. This represents a lost opportunity for future development of habitat complexity resulting from periodic inputs of gravel and woody debris. Habitat losses can be mitigated to some extent by incorporating woody debris into the design of drop structures, as previously mentioned.

The depth of downstream pools adjacent to eroding banks will likely be reduced by redirection of the thalweg away from the eroding bank unless the structure is specifically designed to maintain or create those pools. These near-bank pools provide some of the best types of rearing habitat, especially when there is wood in them and cover from the overhanging bank. Loss of near-bank pool habitat can be mitigated by creating scour pools and placing large woody debris on the downstream side of the drop structure.

The construction of rigid, nondeformable structures such as embedded rock-and-log drop structures requires excavation into the streambed. Construction typically requires significant channel disturbance, which must be mitigated with sediment control and dewatering. Deformable structures are often built on the existing streambed and may therefore not require dewatering. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Surface turbulence will create hiding cover for juvenile fish. The structure will also provide interstitial hiding areas, particularly near the bank. During high flow, the turbulence may prevent the structure from being very useful as flood refuge for fish. If the required head differential between the low- and high-flow fish-passage design flows is met, fish passage will not be a problem. If there is excess head spilling over the drop structure, adult chum salmon and juvenile salmonids may be prevented from passing upstream.

Drop structures may provide habitat complexity by breaking up a long glide or riffle into different gradients. They also sort and capture spawning-sized gravel in the tailout downstream from the scour holes. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this bank treatment.

RISK

Habitat

Drop structures will cause the bed and thalweg to shift and the banks to accrete. Depending upon the channel size, bedload movement and particle size, it may take time for the channel to adjust to this structure. In the adjustment period, spawning areas may scour or accrete, and any eggs or alevins in the bed could be damaged. Relative to other habitat-enhancement options, drop structures tend to provide very uniform habitat features with little diversity if placed in a series.

Infrastructure

The risk to infrastructure situated on the streambanks is relatively low. Drop structures tend to focus stream energy towards the center of the channel and away from the banks. If drop structures are improperly designed and/or constructed, however, the excessive backwater they may create can place upstream property and structures at risk. Drop structures that are constructed too high across the channel or that lack proper sloping toward the channel center can cause increased erosion at the bank key, which may result in flanking of the structure.

Reliability/Uncertainty of Technique

Many rock and log drop structures installed more than 20 years ago continue to function well. If constructed properly and maintained well, it is reasonable to expect that drop structures will serve their designated purpose for many years.

CONSTRUCTION CONSIDERATIONS

Materials Required

Drop structures that are made of rock should use rock that is sound, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular rock is preferred over rounded rock for its ability to lock tightly together. Rock that resembles native material should be selected when possible.

Drop structures can also be constructed using logs. The type of wood selected may be important if longevity of the bank protection is a concern. Avoid using species that decay rapidly, such as alder or cottonwood. Coniferous species such as cedar, fir and pine are better choices.

Other materials necessary for a drop structure includes filter material (fabric and/or backfill), concrete block and riprap for ballasting and anchoring (for log drop structure), rebar, and large woody debris for mitigation and habitat components. For further discussion of filter materials and large woody debris, refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* and Appendix I.

Timing Considerations

Drop structures should be constructed during low-flow conditions to minimize instream disturbance. It is typically necessary to work within the stream channel to construct drop structures, which means it may be necessary to dewater the channel. Dewatering can be accomplished using coffer dams to isolate the channel during construction. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

Cost

Drop structures can be a relatively low-cost approach to reducing erosive energy along a streambank. The greatest cost factor is the size of the channel. Drop structures cost approximately $75 to $200 per linear foot. The cost will be determined primarily by the cost of rock available, equipment and operator rates. Rock materials typically range in cost from $25 to $80 per cubic yard. However, dewatering, if required, will greatly increase the cost of the treatment. Additionally, access for large equipment may require that either a temporary access road be constructed, or that specialized equipment such as a spider hoe and tracked dump trucks be used to cross riparian areas for channel access and materials delivery. Refer to Appendix L, *Cost of Techniques* for further discussion of materials costs and construction costs.

MAINTENANCE

Maintenance may include replacement of rocks that shift or are dislodged by extreme flows. Replacement of rocks, logs or vegetation may also be necessary at the bank key-in points after overbank flow events.

MONITORING

Because drop-structure projects involve impacts to both the channel and the banks, the integrity of the structure itself, the channel and bank features and habitat will all need comprehensive monitoring. Monitoring of drop-structure projects should be initiated prior to construction and should include a baseline-conditions survey of the physical channel, its banks and its habitat value. This should include, at a minimum, surveys of five cross sections at intervals equal to the channel width upstream, five cross sections downstream and one cross section at the location of the drop structure. This will allow comparison of modified conditions to preproject conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation from fixed photo points of the project area and the upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring.*

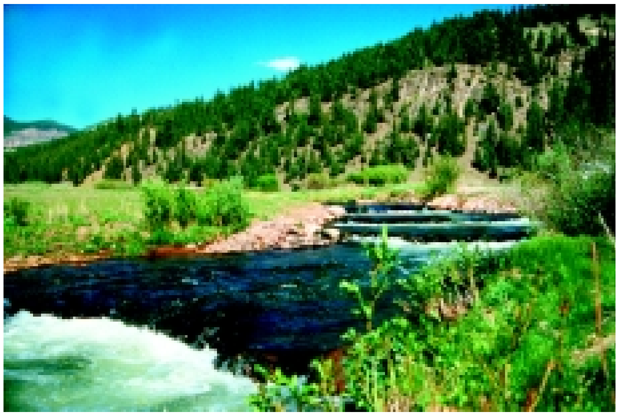
Monitoring drop structures should include preproject surveys and annual surveys thereafter of key members, and visual assessments of their configuration, dimensions and hydraulic function. A general, qualitative description of the drop structure should also be recorded and may include such observations as the general effect on channel flow characteristics and a visual description of the drop structure. The general integrity of the drop structure should be evaluated, including the identification of any significant settling of header or footer rocks as determined from survey and comparison of photos.

Impacts to the channel and to habitat must be carefully monitored. Channel changes occurring following installation can be documented by reviewing annually any cross sections that were surveyed prior to installation and at the time of completion. Patterns of sediment deposition or scour should be noted. Changes to available habitat also should be documented on a schedule conforming with fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[2] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

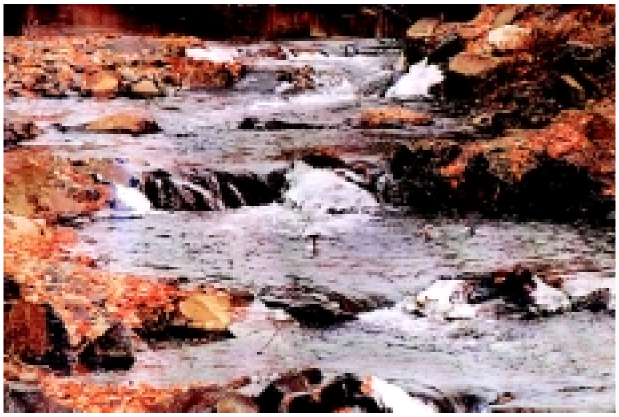
1 U. S. Department of Agriculture, Natural Resources Conservation Service. 2000. Design of Rock Weirs. Technical Notes, Engineering - No. 24. Portland, OR

2 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.



a. Rock Drop Structures. Bellows Creek, CO. 2000.
Source: Inter-Fluve, Inc.

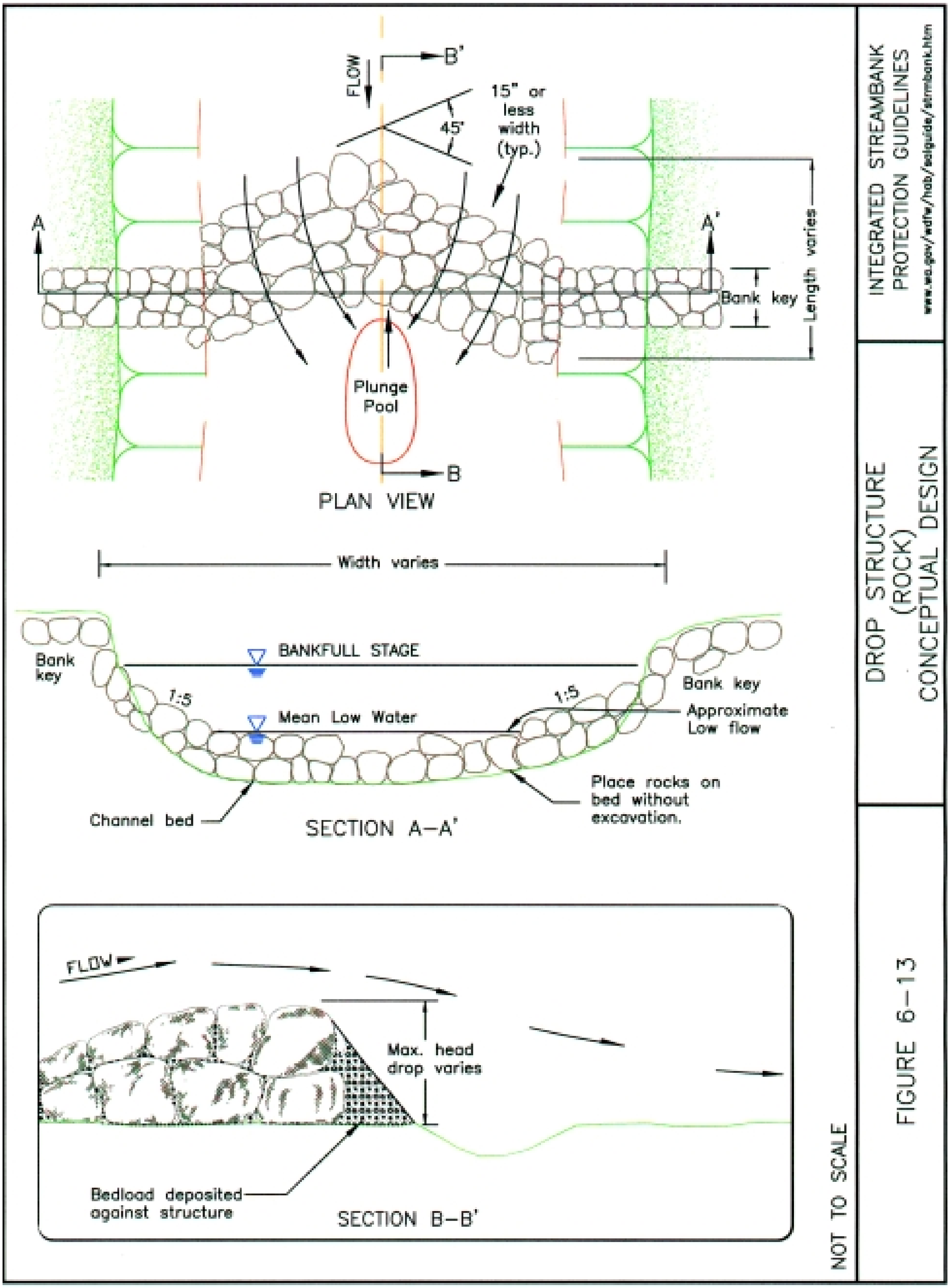
c. Vee Log Drop Structure. Little Hoko River, Tributary to Strait of Juan De Fuca. 1996.



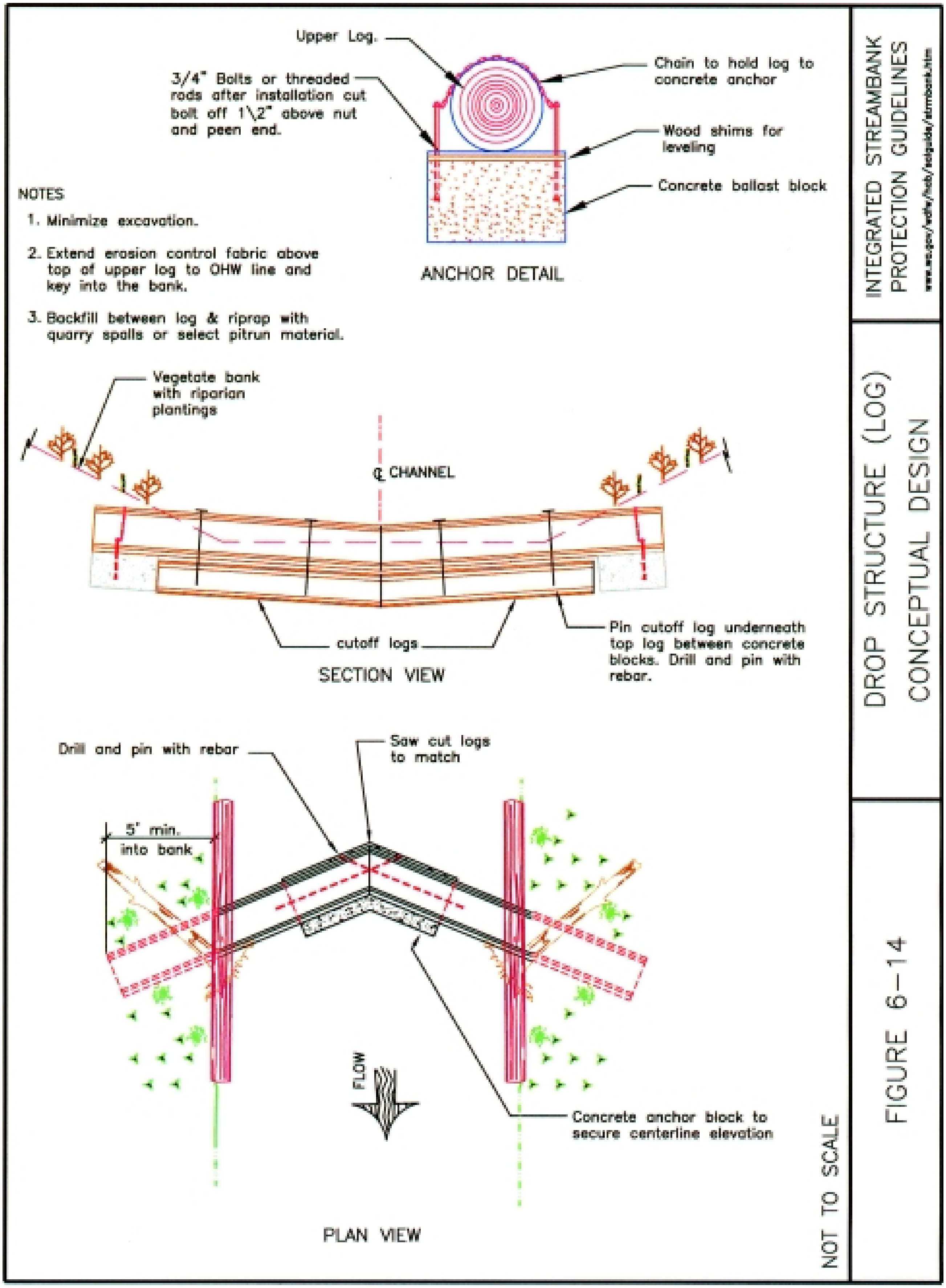
b. Rock Drop Structures. Taneum Creek, Tributary to Yakima River. 2001.
Source: Allan Potter, Geomax.

d. Vee Log Drop Structure.

Figure 6-12. Various applications of drop structures throughout Washington State.



FLOW
B'
15" or less width (typ.)
45°
A
A'
Bank key
Length varies
Plunge Pool
B
PLAN VIEW
Width varies
Bank key
BANKFULL STAGE
1:5
1:5
Mean Low Water
Bank key
Approximate Low flow
Channel bed
SECTION A–A'
Place rocks on bed without excavation.
FLOW
Max. head drop varies
Bedload deposited against structure
SECTION B–B'
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
DROP STRUCTURE (ROCK) CONCEPTUAL DESIGN
FIGURE 6–13


Upper Log.
3/4" Bolts or threaded rods after installation cut bolt off 1\2" above nut and peen end.
Chain to hold log to concrete anchor
Wood shims for leveling
Concrete ballast block
ANCHOR DETAIL
NOTES
1. Minimize excavation.
2. Extend erosion control fabric above top of upper log to OHW line and key into the bank.
3. Backfill between log & riprap with quarry spalls or select pitrun material.
Vegetate bank with riparian plantings
℄ CHANNEL
cutoff logs
Pin cutoff log underneath top log between concrete blocks. Drill and pin with rebar.
SECTION VIEW
Drill and pin with rebar
Saw cut logs to match
5' min. into bank
FLOW
Concrete anchor block to secure centerline elevation
PLAN VIEW
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
DROP STRUCTURE (LOG) CONCEPTUAL DESIGN
FIGURE 6–14

DESCRIPTION

Porous weirs, also called vortex rock weirs,[1] are low-profile structures consisting of loosely arranged boulders that span the width of the channel. They are used to protect streambanks by redirecting the flow away from the bank and toward the center of the channel. This technique also provides energy dissipation and promotes increased sedimentation along streambanks. Scour holes and pool habitat are created by flow passing through the openings in the weir structure, which, in turn, accommodates fish passage. *Figure 6-15* (at the end of this technique discussion) shows an example of porous weirs.

APPLICATION

Porous weirs have been installed primarily in high-bedload streams and channel-reconstruction projects for bank protection. They can also be used to control the grade of the channel bed in small streams and to provide fish passage. They are most effective in gravel- and cobble-bed streams with slopes less than three percent.

Porous weirs are similar to drop structures in that they span the entire width of the channel and are used to redirect flow away from the banks. Unlike porous weirs, however, drop structures are continuous, solid structures without gaps or openings. Porous weirs, by design, have spaces between the boulders to allow fish and sediment to pass through and to enhance channel complexity. Porous weirs are deformable, whereas drop structures are rigid. The principal purpose of a drop structure is to control channel-bed grade, while porous weirs are used primarily for flow redirection and to provide channel roughness.

It is important to determine whether porous weirs are the appropriate solutions for the particular mechanism of failure and causes of bank erosion in question (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Porous weirs are appropriate for sites where the mechanism of failure is toe erosion. Their ability to provide grade control and bed roughness also make them useful in degrading channels. Porous weirs are unsuitable for use in aggrading or high-gradient channels. They should also be avoided where there is the potential for an avulsion. Porous weirs are typically installed in conjunction with bank-protection treatments. See the screening matrices in Chapter 5, *Identify and Select Solutions*, for additional guidance on the applicability of porous weirs based on mechanism and causes of streambank erosion.

Thalweg Alignment

Porous weirs redirect erosive velocities away from the bank to the center of the stream. They can also be used as a component of a larger streambank-protection project. The weir can add to the integrity of downstream bank-protection practices by realigning the low-flow channel.

Sediment Transport

Porous weirs, if designed correctly, increase the sediment-transport capacity at the site. This is accomplished not only by making the spaces between header rocks wide enough to allow sediment to pass through, but also by mobilizing the sediment itself. Porous weirs accelerate stream flows, increasing shear stress at the bed, which leads to increases in the channel's ability to pick up and transport bedload at the site. Sustained sediment transport will help maintain or develop a low width-to-depth ratio at the site. Porous weirs typically do not affect sediment transport throughout the reach, however. Properly constructed, they have a low profile across the channel bed, which minimizes backwater conditions; and channel-forming flow events (about a 1.5-year to 5-year flood event) should be able to overtop them.

Bed Roughness

While porous weirs do a reasonable job of providing bed roughness, other techniques, such as random placement of boulders and large woody debris in the channel, might complement them and should be considered.

Grade Control

Porous weirs may act as grade-control structures in small streams when the rock is large enough that it won't become dislodged during high flows. Porous weirs should not be expected to provide grade control in larger rivers or steep channels that have the capacity to mobilize boulders (steeper than a two-percent grade).

Fish Passage

Porous weirs can be used to provide passage for fish through steep reaches, or a series of weirs can replace fish barrier drops.

Emergency

Porous weirs are not good candidates for emergency streambank protection. They completely span the stream channel and usually require construction from within the channel, which may not be possible during an emergency situation.

EFFECTS

Porous weirs redirect flow toward the channel center and away from the banks. This change in the flow direction may have both desired and undesired impacts to adjacent channel segments. For further discussion of the potential impacts of thalweg redirection, refer to Appendix F, *Fluvial Geomorphology*.

Because porous weirs constrict flows in a channel segment, they create two hydraulic conditions: 1) accelerated flow through the weir, and 2) backwater upstream of the weir. Accelerated flows may create scour between and around boulders and lead to increased sediment transport at the weir. This may result in deposition immediately downstream of the weir and formation of tailouts. Additionally, backwater upstream of the weir will exhibit reduced velocities and greater depths at a variety of flows. This may result in deposition upstream of the weir.

DESIGN

Conceptual design drawings of porous weirs are shown in *Figure 6-16*.

Dimensions

A porous weir spans the entire width of the channel and usually has a "V" shape pointing upstream. Each leg of the "V" can have either equal or different lengths, depending upon the thalweg alignment as it approaches the weir and the desired thalweg alignment immediately downstream.

In order to allow bedload to move through the weir with minimal restriction, the weir should not be placed higher than 15 percent of bankfull stage height. This height is measured at the thalweg from the top of the footer rock to the top of header rock. The height of the weir should be kept to a height that results in only nominal backwater conditions. Excessive height can cause structural failure, trigger upstream bank erosion and create a barrier to fish passage. To allow passage for the weaker swimming fish, such as chum salmon or juvenile salmonids, the difference in water-surface elevations above and below the weir should not exceed 0.8 feet. It is possible to place a notch at the weir's apex to accommodate boat and fish passage. If upstream juvenile fish passage is critical, the drop should not exceed six inches.

Rock Size

The smallest rock size used in a weir should be greater than one-third the size of the largest rock. Material sizing should follow standard riprap-sizing criteria for turbulent flow (refer to the discussion in this chapter addressing the technique, *Riprap*), with rocks that will remain immobile during the selected design flow (a minimum of a 20-year flow is recommended). The largest rocks should be used in the exposed weir section. Do not use the Isbash Curve when sizing rock for rock weirs; it will result in sizes too small for this application.

Orientation

The legs of the weir should be pointed upstream at an angle between 30 and 40 degrees. If the channel's bankfull width is greater than 40 feet, D. Rosgen recommends weirs that are shaped as a "W" (pointing upstream).[1]

The crest of the weir slopes from the bank down to the header rock in the thalweg such that the boulders nearest the bank are the last to be submerged as stage increases. The weir is completely submerged at bankfull depth.

Location

Porous weirs should be located immediately upstream from, or directly adjacent to, an eroding bank, preferably at the crossover-riffle section. The location of the weir should be near the head of a riffle to supplement and steepen the riffle. However, care must be applied when siting a weir at the crossover riffle. The crossover riffle distributes flow across the channel and, to some degree, protects the downstream bank. By siting a weir at the crossover riffle, flow will be concentrated and not distributed across the channel. This may exacerbate downstream erosion. Furthermore, location at the head of a riffle increases the riffle slope and decreases the slope upstream of the riffle.

Porous weirs are typically used in a series if the intended purpose is fish passage or grade control with an elevation change between weirs of less than one foot. For fish passage, spacing depends upon the channel slope, length of backwater and length of thalweg created downstream. For grade control, porous weirs should be placed no closer than the net drop divided by the channel slope. The net drop is measured between similar channel features (e.g., between channel-bed elevations above and below the drop, or between water-surface elevations above and below the drop). As an example, a one-foot-high weir in a stream with a two-percent gradient will have a minimum spacing of 50 feet (1.0/0.02). Studies indicate that natural pool-riffle spacing varies between three and 10 channel widths and average about six channel widths.[2]

Configuration

Footer rocks are the foundation that stabilizes the weir. They are placed below header rocks to anchor the overriding header rocks, to reduce scour and to protect the structure from possible undermining. The top of the footer rocks becomes the new bed elevation. Footer rocks need to be placed firmly into the channel bed. The depth of embedment should be approximately equal to the D_{100}.[3]

Header rocks are placed on top of footer rocks. Header rocks at each bankline are placed such that the top of the rock corresponds with bankfull stage. The gap between header rocks is 0.25 to 0.5 of the rock diameter. Too large a gap will reduce velocities needed to move bedload and dissipate energy. Too small a gap will trap sediment and may cause backwater conditions.

It is critical to key the weir into both banks and to place large rocks on the downstream face near the banks. The key provides protection from scour associated with overbank flow spilling back into the channel. Installing a key helps to prevent erosion at this critical location by reducing the potential for flanking of the weir at high flows. A minimum length for the bank key is four times the D_{100}.[3] It is also important to minimize bank disturbance and vegetation removal during construction. Buried, large woody debris can be incorporated into the bank key. Such debris should be oriented perpendicular to the overbank flows. Revegetation of the bank at both keys is necessary for added structural strength and habitat needs.

Large woody debris can be incorporated into the weir for added habitat benefit, additional roughness and flow realignment. This debris is incorporated as additional bank protection by replacing header rock(s) near the bankline with tree trunks and attached rootwads. Tree trunks should be situated parallel to the bankline as added bank protection and habitat. (Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for further guidance.)

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Placement of porous weirs in the channel will alter the thalweg alignment. Existing spawning areas may be impacted by new scour patterns that result from the redirected thalweg. Porous weirs, however, allow flow and sediment to pass through the structure, which may result in establishment of new spawning areas, possibly avoiding the need for mitigation as a result of the loss of spawning areas. It is important to configure the weir such that it does not significantly backwater upstream reaches, particularly during flows that result in scour and habitat development. Relocation of the thalweg could represent a lost opportunity for future development of near-bank pool habitat. Habitat value may be increased by incorporating large woody debris into the structure along the bankline, as mentioned in the previous section.

Refer to Chapter 4, *Considerations for a Solution* and the matrices in Chapter 5 for additional guidance concerning mitigation.

Mitigation Benefits Provided by the Technique

Porous weirs may provide habitat by creating turbulence cover and a diversity of deep scour holes, eddies and velocity chutes. They also catch debris, provide aeration and collect and sort gravel in the tailout for spawning habitat. The spacing between header rocks will create scour pools that are good feeding stations for larger trout, coho (if trout are absent) and smaller fish. The surface turbulence will create hiding cover for juveniles. The structure will also provide interstitial hiding areas, particularly near the bank. During high flows, turbulence may prevent the structure from being very useful for flood refuge. If the spacing between header rocks is maintained and the head differential across the structure is minimized, fish passage should not be a problem.

Porous weirs may provide habitat complexity by breaking up a long glide or riffle into different gradients. As previously mentioned, the depth of the downstream pool adjacent to the eroding bank will likely be reduced by redirection of the thalweg away from the eroding bank. These bankline pools provide some of the best types of rearing habitat, especially those with wood in them and cover from the overhanging bank. The reduction in pool habitat can be mitigated by creation of scour pools and placement of large woody debris on the downstream side of the weir. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this treatment.

RISK

Habitat

Existing spawning areas may be impacted by scour patterns that result from the redirected thalweg. By realigning the thalweg away from a downstream eroding bank, the pool adjacent to an eroding bank will be reduced. This loss in pool habitat may be compensated by new pool habitat created through scour induced by the weir.

Porous weirs will cause the bed and thalweg to shift and the banks to accrete. Depending upon the channel size, bedload movement and particle size, it may take time for the channel to adjust to this structure. In the adjustment period, spawning areas may scour or accrete and any eggs or alevins in the bed could be damaged.

Infrastructure

The risk to infrastructure situated on the streambanks is relatively low. Properly designed porous weirs focus stream energy towards the center of the channel and away from the banks.

Reliability/Uncertainty of Technique

Most of the design criteria are based primarily on gravel-bed rivers in Colorado. Design processes will be refined as more research is done for Washington river systems, including habitat needs.

CONSTRUCTION CONSIDERATIONS

Materials Required

Rock used to construct porous weirs should be sound and dense, free from cracks, seams and other defects that would enable weathering, freezing and thawing, or other natural causes to make the rock deteriorate. Rock should be angular in shape.

Timing Considerations

Porous rock weirs should be constructed during low-flow conditions to minimize instream disturbance. It is necessary to work within the stream channel to construct porous weirs. It may be necessary to dewater the channel. Dewatering can be accomplished using coffer dams to isolate work areas. Specific permitting requirements may preclude construction of porous weirs during certain times of the year (e.g., fish-spawning seasons, etc.). Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*. The removal or disturbance of existing riparian vegetation during construction should be minimized.

Cost

Porous-weir structures can be a relatively low-cost approach to reducing erosive energy along a streambank. The greatest cost factor is the size of the channel. Weir structures range in cost from approximately $75 to $200 per linear foot. The cost will be determined primarily by the cost of rock available and equipment and operator rates. However, dewatering, if required, may greatly increase the cost of the treatment. Additionally, access for large equipment may require either temporary-access-road construction or the use of specialized equipment, such as a spider hoe and tracked dump trucks, to cross riparian areas for channel access and materials delivery. Refer to Appendix L, *Cost of Techniques* for further discussion of materials costs and construction costs.

MAINTENANCE

Maintenance requirement for porous weirs includes the replacement of rocks that shift or are removed by extreme flows. Any mitigation measures, such as the placement of large woody debris, may also require maintenance. This could include replacement or re-anchoring of large woody debris that may be removed or loosened by high flows.

MONITORING

Because porous-weir projects involve impacts to the channel and banks, they will require comprehensive monitoring of the integrity of the structure itself, channel and bank features, and in-channel habitat. Monitoring of porous-weir projects should be initiated prior to construction with baseline condition surveys of the physical channel, its banks and its habitat value. This should include five cross sections at intervals equal to the channel width upstream, five downstream and one at the location of the control at a minimum. This allows for the comparison of modified conditions to pre-project conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation from fixed photo points of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring*.

Monitoring of porous-weir structures should include pre-project conditions and the subsequent annual survey of key members and visual assessments of their configuration, dimensions and hydraulic function. A general qualitative description of the weir structure should also be recorded and may include such observations as the general effect on channel-flow characteristics and an approximate visual description of the structure. The general integrity of the structure should be evaluated including the identification of any significant settling of header or footer rocks as determined from survey and comparison of photos.

Impacts to the channel and to habitat must be carefully monitored. Channel changes occurring following installation can be documented by reviewing an annual survey of cross sections surveyed prior to installation and at the time of completion. Patterns of sediment deposition or scour should be noted. Similarly, changes to available habitat should be documented on a schedule dictated by fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[4] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

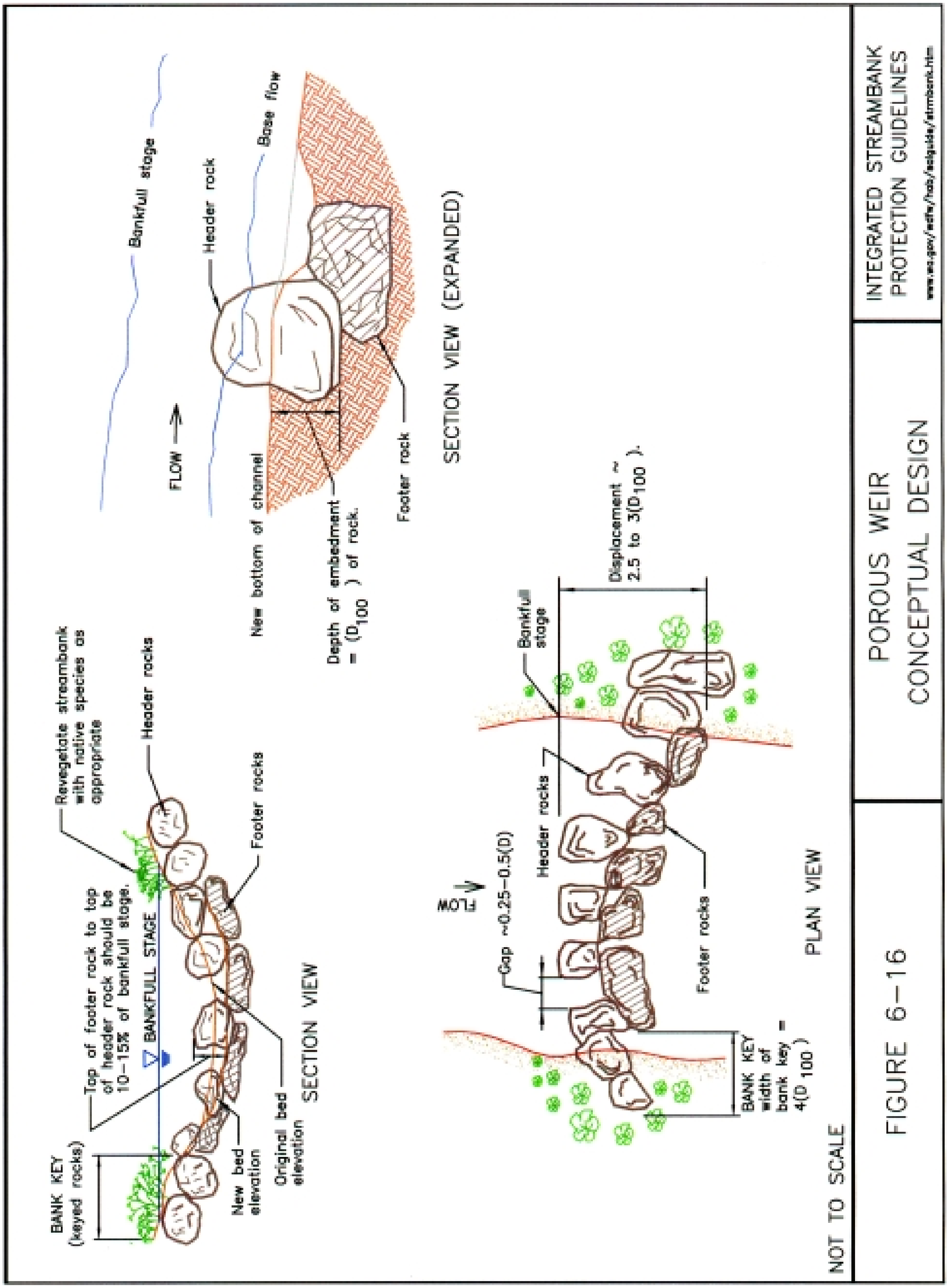
1 Rosgen, D. 1996. Applied River Morphology, Wildland Books, Pagosa Springs, CO.

2 U. S. Department of Agriculture, Natural Resources Conservation Service. 1998. Stream Corridor Restoration, Principles, Processes, and Practices.

3 U. S. Department of Agriculture, Natural Resources Conservation Service. 2000. Design of Rock Weirs. Technical Notes, Engineering - No. 24. U. S. Department of Agriculture, Portland, OR.

4 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

Figure 6-15. Porous Weir. Blue Creek, Tributary to Walla Walla River. 1998.


BANK KEY (keyed rocks)
Top of footer rock to top of header rock should be 10–15% of bankfull stage.
BANKFULL STAGE
Revegetate streambank with native species as appropriate
Header rocks
Footer rocks
New bed elevation
Original bed elevation
SECTION VIEW
FLOW
Gap ~0.25–0.5(D)
Header rocks
Footer rocks
Bankfull stage
Header rocks
Footer rocks
BANK KEY width of bank key = 4(D100)
Displacement ~ 2.5 to 3(D100).
PLAN VIEW
Bankfull stage
Base flow
Header rock
FLOW
New bottom of channel
Depth of embedment = (D100) of rock.
Footer rock
SECTION VIEW (EXPANDED)
NOT TO SCALE
FIGURE 6–16
POROUS WEIR CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES

Anchor Points
Structural Techniques

DESCRIPTION

Anchor points are either natural (e.g., tree or rock outcroppings) or artificial hard structures (e.g., rock or log trenches) at the upstream and/or downstream end of an isolated scour hole. They act to prevent or limit erosion along the bank downstream or upstream from an existing scour hole. They can be a low-cost, low-impact approach to managing isolated streambank erosion sites. *Figure 6-17* (at the end of this technique discussion) shows examples of anchor points.

APPLICATION

Typical Application

Anchor points are the preferred bank-protection technique when the mechanism of failure is scour (see Chapter 2, *Site Assessment* for more information about scour). Scour holes dissipate energy (functioning as an energy sink) with increasing volume.

The concept of anchor points is based on the principle that local scour is self-limiting; scour ceases when a scour hole has enlarged sufficiently to dissipate excess energy. Downstream and/or upstream anchor points may limit scour both longitudinally along the bank and laterally into the bank. Further expansion of the energy sink is then limited to the vertical dimension into the bed, forming a deep pool. It may initially scour further into the bank, but the extent is limited if the anchor points are successful. Protecting existing natural anchor points, such as trees, rock outcrops or debris jams, or constructing new anchor points so the scour does not expand and migrate upstream or downstream will limit the erosion along the bank. If there is not a natural anchor point, the most preferred constructed anchor point is a rock- or log-filled trench.

Anchor points may be used as a stand-alone technique, or they may be supplemented by other techniques. They are not intended to be used in braided channels or other channel systems where flow direction and hydraulics change significantly with flow level. In most braided channels, where high-flow direction differs considerably from low- and moderate-flow directions, it is difficult to predict where and at what flows anchor points will be effective. Furthermore, where anchor points may protect banks at the design flow, they may create excessive erosional forces at other flows. For further discussion of site and reach limitations, refer to Chapter 2 and Chapter 3, *Reach Assessment.* Refer to Chapter 5, *Identify and Select Solutions* and associated screening matrices for further guidance on the applicability of anchor points based on the mechanism of failure and causes of streambank erosion.

Protection of Existing Anchor Points

If there is an existing anchor point, techniques to protect it include constructing rock reinforcement around the natural anchor point or a log anchor point adjacent to it. For example, if the anchor point is a tree, constructing a rock toe around the base of the tree will protect the tree from being undermined by scour. The buttressing effects of large trees can be very effective at reducing further erosion. This natural anchor point may also need protection from surface scour that results from the overbank flow. Planting willows or other flow-resistant plants and protecting the downstream surface with rock or wood is recommended. Using launchable riprap will result in less damage to tree roots than excavating trenches around existing trees.

Rock or Log Trench

Where natural anchor points do not exist, a rock- or log-filled trench can be used. A trench is cut inland from the eroding bank and filled with rock or logs to form the anchor point at the bank line. Constructing a log-trench anchor point next to an existing anchor point can support and protect the existing anchor point. A rock- or log-filled trench is almost identical to a buried groin, except that it is built as a single structure; groins are built in a series to prevent toe and bank-surface erosion (see the discussion in this chapter addressing *Buried Groins* for additional information).

Emergency

Anchor points can be used for emergency treatment in some situations. They can be installed quickly with limited materials and equipment and with a minimum of design effort. The potential consequences of failure of installed anchor points are minimal, because the erosion they are intended to address is usually isolated and self-limiting. Additionally, anchor points can be easily mitigated.

EFFECTS

Anchoring the downstream and/or upstream end of the scour hole can limit the extent of bank erosion caused by scour. Because the anchor point limits erosion, the forces may continue to increase the volume of the energy sink by deepening an existing pool formed by scour or by further lateral erosion. The habitat benefits of existing and continued scour include preservation of the scour hole, the opportunity for either natural or constructed revegetation of the bank of the scour hole and the potential for additional accumulation of woody debris. All of these effects provide valuable pool, cover and diversity habitat.

Construction impacts are likely to be temporary and might include riparian and water-quality damage. Anchor points generally do not have long-term negative impacts on habitat, except by potentially altering the shape and location of a developing scour hole. Refer to Appendix F, *Fluvial Geomorphology* for further discussion of the potential impacts of limiting the rates and location of bank erosion.

DESIGN

A conceptual design drawing of anchor points is shown in *Figure 6-18*.

Protection of Existing Anchor Points

Protection of existing anchor points is entirely site-dependent. Usually, only enough work is needed to support the existing anchor point. If the anchor point is a tree or tree root, individual rocks can be pushed into the scour hole around the root structure or excavated into the bed to the expected scour depth. Launchable riprap can be placed around an existing tree functioning as an anchor point, to help secure the tree and eliminate risk of damage to the tree roots during installation.

Length

For constructed anchor points, the length of the trench should extend landward to prevent overbank flow from cutting a channel around the anchor point. For structural purposes, a length about three times the height of the structure is usually adequate. To prevent risk from overbank scour, tie the anchor point into higher ground or to a point where woody vegetation provides protection from surface erosion. The top elevation of the anchor point should conform to the existing ground; anchor points are not intended to change the amount or direction of overbank flow.

Rock-Filled Trench

The dimensions of the rock trench should mimic those of a buried groin (see the discussion in this chapter addressing *Buried Groins*). The lower elevation of the rock trench at the bank should be equal to the depth of scour. At that depth, the trench should extend into the bank a distance at least equal to the height of the bank. Beyond that, the depth of the trench and the size of the material are designed to satisfy the objective of surface scour behind the anchor point. In noncohesive soils, the shape of the trench will be trapezoidal or triangular and could require filter fabric to limit the rock fill from settling. In the final analysis, there should be sufficient rock so that, if the soil is eroded away, an efficient groin will result. In addition, enough fines should be present in the rock fill to support roots. Further discussion of design details of design for rock installations are available in this chapter under the section called, *Riprap*.

Log-Filled Trench

Log trenches should be filled with material appropriate for the size of the stream. In small streams, brush bundles may be adequate. In larger streams, a minimum of 12- to 18-inch-diameter logs will be required. Logs situated at the bottom of the trench should be embedded 15 to 20 feet back into the bank to resist movement. Pinning the logs together with rebar increases strength and the effective diameter of the logs (see Appendix I, *Anchoring and Placement of Large Woody Debris*). Logs can be installed in a vertical trench if ballast and support are provided. For additional design considerations on log trenches, see the discussion in this chapter addressing *Buried Groins*.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Usually, anchor points require little mitigation. However, installation of rock or log trenches will result in damage to riparian vegetation associated with excavation and backfill, though replacement vegetation can be planted in the trench backfill. Since logs can be installed in a vertical trench, much less riparian area may be affected. Supporting an existing root anchor point with rock will result in the loss of the complex scour hole with the overhanging root structure. In these cases, the appropriate mitigation for this loss of habitat could be achieved by placing debris, such as large woody debris, and anchoring this material by the supporting rock, or by revegetation of the bank of the scour hole to develop additional bank complexity and cover. Excavating anchor-point trenches may affect water quality unless stream flow is diverted away from the site or the trench is excavated entirely landward of the streambank. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Anchor points may increase the depth of a scour pool by limiting its migration landward or along the bank. Anchor points may accumulate debris. The increased depth and debris provide additional refuge habitat or deep-water habitat.

RISK

Habitat

Anchor points generate little risk to habitat because they do not significantly affect the channel, its banks or its processes.

Infrastructure

When applied appropriately, anchor points reduce the risk to adjacent infrastructure by limiting erosion along the channel bank and laterally into the bank.

Reliability/Uncertainty of Technique

There is a high degree of uncertainty regarding the hydraulic impact associated with this technique, because there is only a limited amount of experience with designing anchor points, and design criteria are not well tested. For these reasons, anchor points may be best applied where a low to moderate level of risk can be tolerated.

CONSTRUCTION CONSIDERATIONS

Construction considerations for the installation of anchor points include site access, dewatering, the availability of key materials and the timing of implementation.

Materials Required

Anchor points can be constructed of either rock or logs. Mature, woody, bank vegetation can be an effective anchor point. In some cases, in addition to rock, filter fabric is required to prevent installed rock from settling and to prevent piping loss of fine materials through the rock. Refer to the discussion in this chapter regarding *Riprap* for further information about materials required. The use of logs with attached rootwads provides an additional habitat value once the rootwads are exposed. Since logs are buoyant, an anchoring and ballast system is necessary. (see Appendix I).

Timing Considerations

Anchor points should be installed during low flow when dewatering is possible, and resident and anadromous fish are less likely to be impacted by construction activities. In order to install rock materials to the depth of scour, excavation within the channel bed will be necessary and, consequently, will require temporary dewatering systems. Dewatering allows for ease of installation and prevents siltation of the stream during construction. This can be accomplished with a coffer dam during low water; however, anchor points can also be constructed during high flow by installing riprap on the bank to launch around the anchor point. To limit the introduction of sediment fines to the channel, trench excavation should begin inland and proceed toward the stream bank.

Construction during critical periods in salmonid life cycles such as spawning or migration should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Cost

Anchor points are a low-cost approach to bank protection since they can provide a localized treatment as an alternative to protection along greater lengths of bank. Furthermore, since habitat impacts are less than many other options, full project costs are often relatively low. Construction costs are largely limited to materials and equipment, usually a single excavator. Consequently, costs will be largely determined by the availability of materials.

Materials and installation for rock anchor points are similar to those for riprap. Rock materials may range from $60 to $80 per cubic yard. Gravel filter materials range from $40 to $60 per cubic yard if they are imported. However, local sources may be available. Filter fabric may be used as an alternative to gravel filters and ranges in price from $0.50 to $3.00 per square yard. Materials for log anchor points will be similar to costs described in large woody debris treatments. Logs may vary in cost from $200 to $750 per log. Refer to Appendix L, *Cost of Techniques* for further discussion of materials and construction costs.

MAINTENANCE

Typical operation and maintenance requirements for anchor points include periodic inspection and installation of supplemental riprap rock or other hard material if needed. Any damage to the anchor point or mitigation features should be repaired or replaced. If erosion continues, or is exacerbated by the anchor point, the bank-protection design should be re-evaluated.

MONITORING

Monitoring should include visual inspection of the integrity of the structure, and an initial survey of the scour-hole depth and area. This will enable subsequent observations to measure development of the scour hole associated with the anchor point and to photograph the site and treatment. Anchor-point visual inspection should focus on potential weak points in the design, such as transitions between the anchor point and the unprotected bank. The adjacent native soils above and behind the treatment may reveal collapse or sinking, indicating piping loss or movement of rock materials.

Each monitoring event should include a survey of the scour hole, including depth and area, visual inspection and photo documentation. Monitoring frequency should be annual and conducted during low flows when visual inspection of the toe is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J, *Monitoring*. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[1] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

1 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

a. Deschutes River.

b. Newaukum River.

Figure 6-17. Examples of natural anchor points Washington State.

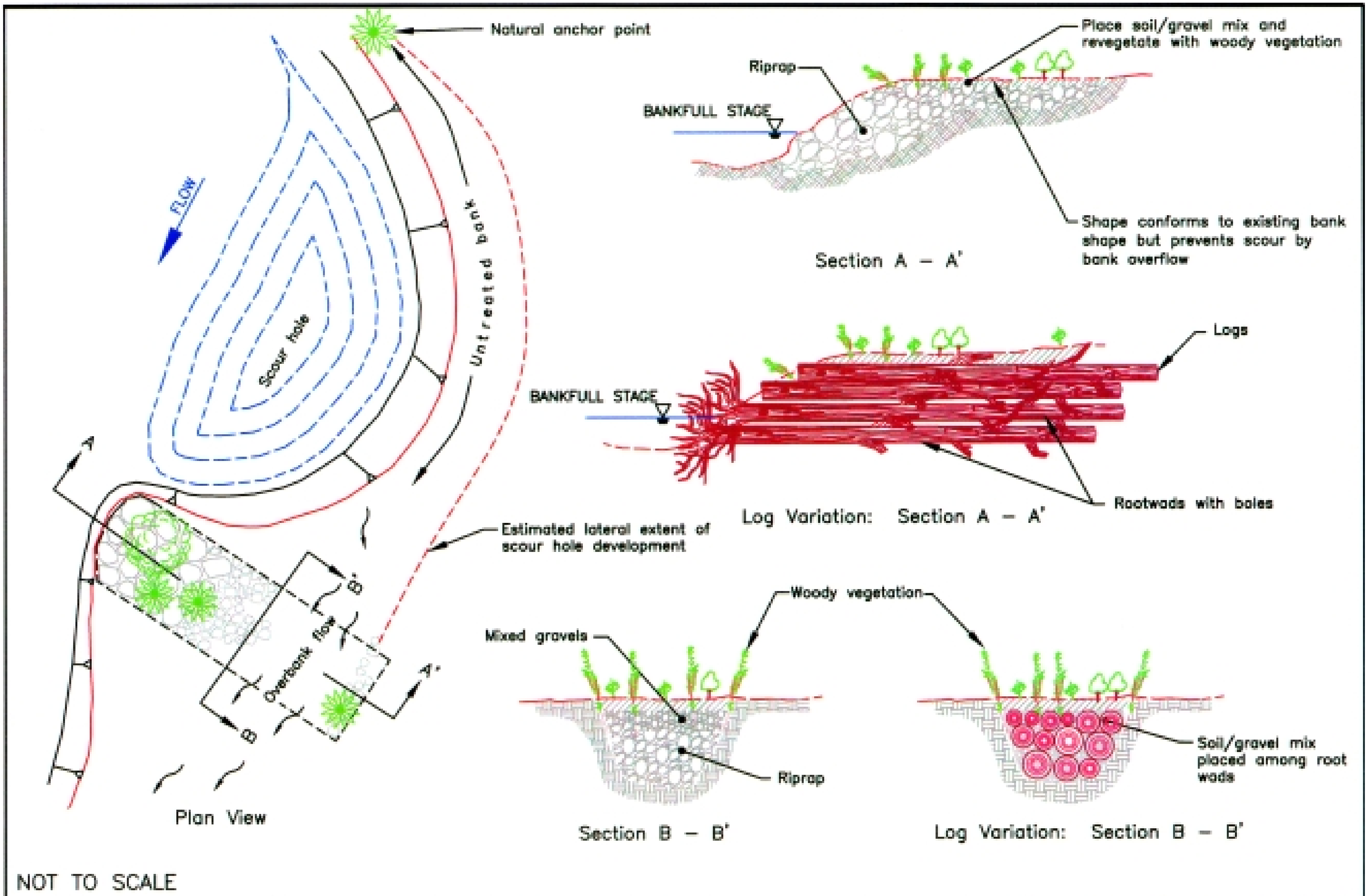


FIGURE 6–18	ANCHOR POINTS CONCEPTUAL DESIGN	INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

Roughness Trees
Structural Techniques

DESCRIPTION

In many instances, the first step in controlling streambank erosion is to slow down the water velocity and reduce hydraulic shear stress. Doing so will help sediments accumulate at the site, which enables vegetation to establish itself. An effective way of slowing water velocity is to add roughness to the channel. This increases friction, which, in turn, slows down the flow. Such roughness can be introduced by installing large woody debris into the channel and along the banks. This streambank-protection technique is often referred to as "roughness trees" or "tree revetments." When positioned properly, roughness trees trap sediment, allowing the establishment of vegetation, which ultimately results in the stabilization of actively eroding banks. Nature provides many examples of how this dynamic works with the simple act of a tree falling into a stream. If its trunk and rootwad fall parallel to the bank (with the rootwad upstream), it's often easy to see where sediment has accumulated and vegetation has taken hold. *Figure 6-19* (at the end of this technique discussion) shows examples of roughness trees.

APPLICATION

Tree-roughness applications are usually applied to low-gradient alluvial channels and long, sweeping bends with vertically eroding banks where the energy is dissipated uniformly and toe erosion is the primary mechanism of bank failure (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment*). This technique is most appropriate where streambank soils are fine-textured. Due to the ability of roughness trees to collect and retain sediments, roughness trees can be very useful on aggrading reaches of stream, where bank erosion is associated with excess sediment supply. While typically applied to low-energy systems,[1] roughness trees may be applied to high-energy systems if the trees are large enough or anchored sufficiently to resist erosional forces of flood flows.

In general, this technique should be employed with caution, as improper tree placement may result in local scour, leading to bank failure at the upstream end of each rootwad. Roughness trees are not recommended where the mechanism of failure is mass failure, subsurface entrainment or channel avulsion. See the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of tree roughness based on mechanisms and causes of streambank erosion.

Variations

Variations on this treatment relate to the positioning and orientation of installed trees relative to the bank, the size of trees and the anchoring system. For example, roughness trees are typically placed with the rootwad or end of the tree angled upstream into the flow with the trunk or butt, individually anchored into the streambank. A row of trees can also be placed parallel to the water's edge, or cabled together to simulate the effect of larger trees. Ballast rocks may be incorporated into the treatment as an anchoring alternative to cables. While trees can be laid in a single tier along the base of an eroding streambank, they can also be stacked or tiered to accommodate higher banks or oriented in different positions to fit the particular conditions of a site. Roughness trees can be placed along a very steep bankline (e.g., the edge of the channel's meander corridor) to trap eroding bank materials. As the upper surface of the bank erodes, the roughness trees provide a platform for the sediment to settle, eventually resulting in the establishment of vegetation.

Emergency

This technique has limited emergency application. However, if a winter flood has eroded large portions of streambank, large wood could be installed to protect the bank, though the usefulness of this would depend upon the specifics of the site and the availability of sources of large wood nearby.

Access to the bank would also be a factor for consideration. In some cases, trees that have been undermined on-site could be repositioned to maximize their influence at reducing bank erosion. Opportunities like these occur in smaller streams because anchoring trees during high flow on larger streams may be impossible.

EFFECTS

Roughness trees reduce velocity, recruit sediment and create areas suitable for natural colonization of riparian plants. In doing so, they provide fish habitat benefits in terms of habitat complexity, cover and flood refuge. While roughness trees tend to limit the potential for gravel and wood recruitment, they can be considered degradable and ultimately deformable (with the exception of various nondegradable anchoring components such as cables and large rock). Consequently, their long-term impact to habitat is considered minimal. Roughness trees do not typically impact aquatic habitat in the short term and can provide habitat value in the form of cover and complexity along the bank.

Roughness trees have very site-specific impacts and effects, with minimal impacts to upstream or downstream reaches. The exception is when excessively large wood is used in small channels, resulting in significant impacts to channel hydraulics and depositional patterns that can be transferred upstream and/or downstream.

DESIGN

Conceptual design drawings of roughness trees are shown in *Figure 6-20*.

When designing a roughness-tree treatment, it is important to correctly size the tree relative to the stream or river. Ideally, the rootwad diameter should be equal to or greater than the bankfull discharge depth; the trunk diameter should be at least 50 percent of the bankfull discharge depth, and the total tree length should be at least 25 percent of the bankfull width. However, these dimensions are only a guideline, and they may be unrealistic for application east of the Cascades due to limited availability of such on-site resources. If trees large enough to resist the anticipated hydraulic forces of a project site are not available, smaller trees may be bound together to simulate a large tree.

In designing this technique, practitioners should be aware that it may be difficult to end up with installed roughness trees with the desired amount of "roughness" (dense quantities of fine limbs, branches and leaves). Typically, by the time trees are transported to the site, handled by an excavator and completely set in place, most of the desirable fine branches may be broken off. Every precaution should be taken to keep valuable branches intact on the trees.

The anchoring of trees requires a through understanding of the forces that are exerted on the installed trees, particularly during flood flows (see Appendix I, *Anchoring and Placement of Large Woody Debris*). Soils should also be sufficiently fine-grained to allow for anchoring. In some cases, ballast rock may be sufficient to anchor trees; but, often, it is necessary to key cabling into a trench or to a duckbill anchor. Regardless of the anchoring system, it is recommended that whole trees with rootwads be used with this technique.

For this technique, trees are usually placed at the toe of an eroding bank, with only minimal disturbance to the existing bank line. Trees should be oriented with the root mass, or larger end of the tree, pointing upstream and the trunk anchored into the streambank. Placement should proceed from upstream to downstream, so that the larger branches or root mass of the downstream tree can be placed over the upstream tree. If any trees are to be interconnected, it may be possible to connect them before final placement, but access constraints usually require that trees be interconnected after they are positioned in place. Trees should be installed such that they extend below the water line at low flows.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Normally, this low-impact technique can be accomplished with minimal disturbance to habitat. However, there may be some impacts associated with construction that will require mitigation. Refer to Chapter 4, *Considerations for a Solution* for further discussion of mitigation requirements and to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Roughness trees are used to mitigate damage to riparian habitat, aquatic cover and flood refuge. Roughness trees' ability to provide resilient riparian areas may increase riparian complexity and structure. Improved riparian structure, health and complexity is beneficial to wildlife species that rely on riparian areas. Because of the habitat benefits they offer, the installation of roughness trees is considered a technique that compensates for habitat impacts. Refer to Matrix 3 in Chapter 5 for more detail on mitigation benefits provided by this bank treatment.

RISK

Risk associated with using roughness trees is usually due to poorly installed trees that shift and migrate during flood flows, causing damage to bridges and other infrastructure adjacent to the stream. During high flows, areas around large wood can be hazardous to boaters, jeopardizing human safety and property. Local river groups (rafters, fishing groups, etc.) should be notified when new wood material is placed in rivers, so that recreational users will be aware of the exact location and placement of the material. Placing warning signs upstream of the wood material to alert boaters can also help reduce this risk. Another potential risk is the blockage of culverts or bridge openings by trees that dislodge from the treatment. Regular inspection of culverts and bridges, and repositioning of displaced wood will contribute to ongoing project success.

Habitat

Woody debris improves high- and low-flow cover habitat for both adult and juvenile salmonids. While roughness trees may cause some minor, local scour (and channel-bed complexity associated with scour), they actually work to reduce scour along the bank in the long run. Roughness trees may collect and hold smaller-sized large wood and organic material. This, in turn, allows better nutrient retention and, ultimately, a greater variety and composition of macroinvertebrates for fish to eat.

Infrastructure

Large material such as anchoring rock and roughness trees must be properly sized and secured to prevent them from moving out of place and into the position of harming any infrastructure such as bridges or culverts. As roughness trees are a relatively passive and uncertain approach to bank protection, they should not be used where infrastructure is already threatened.

Reliability/Uncertainty of Technique

The reliability of this technique depends heavily on the abilities of the designer and implementer. They must be skilled at assessing whether this is the correct technique to be applied and whether the size of the trees they select can withstand flood flows. This technique is a relatively passive approach to bank protection and should only be implemented where some degree of uncertainty in outcome is acceptable.

CONSTRUCTION CONSIDERATIONS

Materials Required

A tree source is needed. Depending on the size and quantity of the wood, heavy machinery, such as an excavator, may be required to move and place large wood delivered to the site. In most cases, anchoring materials will be needed. Refer to Appendix I for further information on anchoring materials. If large trees of the proper size for the channel in question are available, anchoring materials may not be needed. Any decisions not to anchor should be based on sufficient analysis to demonstrate that the trees' length, diameter and rootwad diameter are sufficient to resist the forces of flood flows.

Timing Considerations

From a construction perspective, trees must be installed during low flow to avoid complications arising from buoyancy during installation. Any work that occurs in the channel has to be completed in designated work periods to avoid conflicts with spawning resident or anadromous fish. Critical periods in salmonid life cycles such as spawning or migration should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

Cost

Roughness trees can be constructed with minimal cost relative to other structural treatments, since all necessary materials are often available on site, near site or at low cost. The cost of roughness trees (not including dewatering or other independent construction costs) may range from $40 to $80 per linear foot of streambank treated. The cost of roughness trees largely depends upon the availability of wood materials. Refer to Appendix L, *Cost of Techniques* for further discussion of materials and construction costs and for associated costs of dewatering.

MAINTENANCE

Maintenance will be necessary if monitoring reveals that anchors are failing or that roughness trees are not providing the protection anticipated.

MONITORING

Monitoring should include keeping an eye out for scour that jeopardizes the stability of the treatment. In particular, the anchoring system should be monitored and linked to maintenance if its failure would put downstream infrastructure at risk. Additionally, photo documentation should include the toe of the bank to determine whether bank erosion has been halted or reduced as a result of the installation.

Monitoring frequency should be annual and conducted during low flows, when visual inspection of the toe is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J, *Monitoring*. Monitoring should enable the observer to determine if the structure performs according to criteria under design flows and if it provides the habitat and bank protection desired. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[5] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

1 Flossi, G., S. Downie et al. 1998. California Salmonid Stream habitat Restoration Manual, Third Edition. State of California Resource Agency. California Department of Fish and Game.

2 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

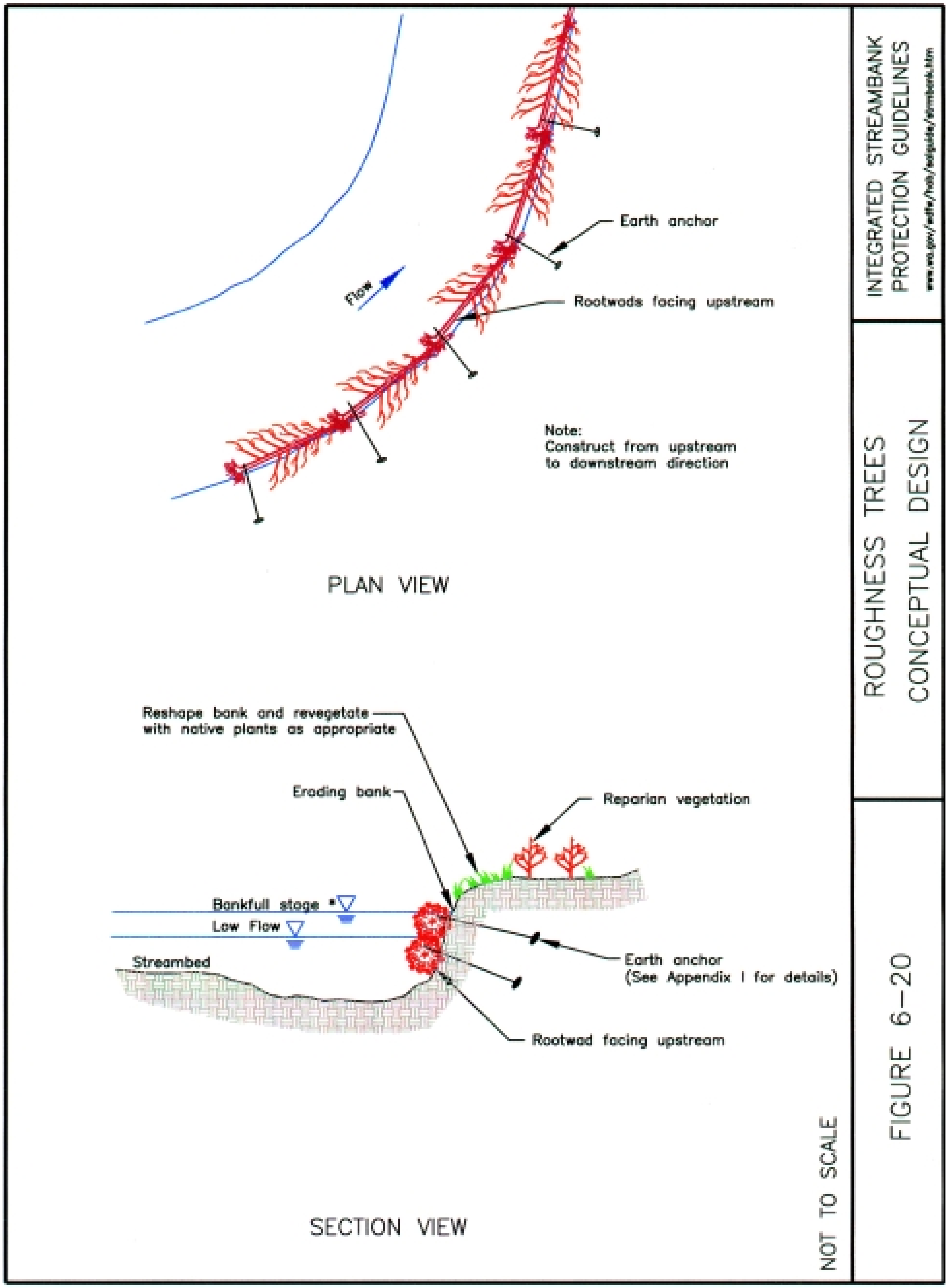
a. Unknown creek.
Source: Inter-Fluve, Inc.

b. South Fork, Nooksack River. 2002.

c. John Day River, OR.

d. South Fork, Coppei Creek, Tributary to Touchet River. 2000.

Figure 6-19. Examples of roughness trees.



Flow
Earth anchor
Rootwads facing upstream
Note:
Construct from upstream
to downstream direction
PLAN VIEW
Reshape bank and revegetate
with native plants as appropriate
Eroding bank
Reparian vegetation
Bankfull stage
Low Flow
Streambed
Earth anchor
(See Appendix I for details)
Rootwad facing upstream
SECTION VIEW
NOT TO SCALE
INTEGRATED STREAMBANK
PROTECTION GUIDELINES
ROUGHNESS TREES
CONCEPTUAL DESIGN
FIGURE 6–20

DESCRIPTION

Riprap is a type of bank armor consisting of rock, typically bedded upon a filter layer of gravel or synthetic filter fabric, with an excavated toe or launchable toe (see *Figure 6-21* at the end of this technique discussion shows examples of riprap).

Historically, riprap has been the most extensively used method for controlling bank erosion in the United States. Recently, however, concerns over the poor aquatic-habitat value of riprap and local and cumulative effects of riprap use on river morphology, have made the application of riprap controversial. For these reasons, riprap revetments are recommended only where bank failure would have intolerable consequences or where site conditions are extreme. Extreme site conditions might include high erodibility, high shear stress or mass-failure conditions.

APPLICATION

Typical Application

Riprap is typically used in bank protection and reinforcement of new stream alignments. Despite recent controversies, it is still the most widely used form of bank protection. Riprap is effective when used near infrastructure where a high risk of failure is unacceptable and where there is insufficient land between the top of the bank and adjacent infrastructure to allow alternative treatments to be used, such as toe protection and bank reshaping/revegetation. Often, riprap is used simply because it has a long history of use and the public (and many designers) are unaware of the availability and effectiveness of alternative bank treatment methods.

A properly designed and maintained riprap revetment can adjust to most scour conditions as well as general aggradation of the streambed. Assuming large enough rock is available, riprap can also be designed to withstand very high shear forces. However, the environmental consequences of riprap can be severe and should always be taken into account when selecting a bank-treatment technique.

It is important to determine whether riprap is the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Riprap can be useful for sites where the mechanism of failure is toe erosion, certain types of local scour, or mass failure (if used in mass-failure application, then it must be designed at a buttress). Riprap is not appropriate on sites lying within the meander-migration corridor, or on rapidly degrading reaches where the mechanism of failure has the potential for an avulsion or chute cutoff. See the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of riprap based on the mechanism of failure and causes of streambank erosion. Additionally, riprap's effects on local and large-scale river morphology can be troublesome (see *Effects*, later in this technique discussion).

Vegetated Riprap

A streambank surface can be vegetated by filling the voids in the riprap with soil and planting seed, by installing plant cuttings or rooted plants, or by using both of these techniques (*Figure 6-23*). Vegetation on a riprap surface offers a number of advantages. It makes for a more aesthetically pleasing bank, as well as creating favorable habitat features for fish and wildlife, including shade, leaf litter, browse and additional roughness to slow overbank flow and capture nutrient-laden sediments. Vegetated riprap is often required as mitigation for some of the habitat impacts caused by unvegetated riprap.

Large Woody Debris Placement

The impacts to aquatic habitat from riprap can be partially mitigated by the installation of large woody debris. Recent research has shown that fish of all species are generally more associated with banks stabilized with large woody debris.[1] Although large riprap provides pockets of low-velocity flow, riprap generally provides very little cover or aquatic habitat complexity. Large woody debris installed with riprap provides cover, low-velocity areas and general habitat complexity, provided it is partially or fully submerged. Large woody debris also provides roughness, which decreases velocities and dissipates energy in the form of turbulence around the large woody debris. This encourages sediment deposition, reduces overall bed scour and limits downstream effects. Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for more information.

Roughened-Rock Toes

Although riprap traditionally extends to the top of the streambank, its use can, in many cases, be limited to the area lying below the line of perennial vegetation. In this capacity, riprap stabilizes the bank toe, where scour tends to be greatest and allows for a more habitat-friendly treatment of upper streambanks. For a more extensive discussion of the use of riprap as toe protection, see the discussion in this chapter addressing the technique, *Roughened-Rock Toes*.

Windrow Riprap

Riprap is sometimes installed landward from the top of bank as a means of intercepting future bank erosion. This technique, called windrow riprap, relies on future bank erosion to expose the riprap that has been placed in a long mound, or in a trench, oriented parallel to the channel bank. As erosion accesses the windrowed riprap, the rock (or a combination of large woody debris and rock) falls into place along the face of the eroding bank. Eventually, if the riprap is large enough in size and of sufficient volume, the eroding bank will be completely armored. This technique is applied to establish a line of defense when erosion is threatening but has not yet reached important infrastructure. This approach can be used to halt erosion of upland acreage at the edge of a defined meander corridor. This concept is also presented in the context of buried groins (see the discussion in this chapter addressing the technique, *Buried Groins*).

Emergency

Riprap can be installed under emergency conditions by dumping or placing the rock from the top of the bank. As previously discussed, another way to install riprap involves placing rock material at the top of the bank, so that, as the channel erodes, the rock is launched.[2] This type of emergency installation can be carried out during flood events or immediately after floodwaters have receded. Riprap installed under emergency conditions will likely require further construction after the flood recedes to ensure it is has an adequate key and to incorporate habitat features as mitigation. Riprap may also need to be replaced by a more appropriate treatment measure that addresses the mechanism and causes of bank erosion.

EFFECTS

Riprap is very effective at arresting bank erosion and can provide relatively permanent protection against further erosion at the location where it is installed. This approach also results in a permanent lost opportunity for sediment and large-woody-debris recruitment. Downstream meander migration is arrested as well, increasing bank erosion upstream and/or downstream from the riprap protection. Because riprap is relatively permanent, it represents a long-term restraint on stream movement and must be mitigated for loss of habitat and lost opportunity.

Riprap also results in increased velocity and reduced complexity and diversity along the channel margin, thereby diminishing habitat value. These effects can be mitigated to some degree by incorporating large woody debris into the treatment and maintaining a riparian buffer. The application of riprap may deepen the channel at the bank toe and may steepen the bank slope to the point bar. This increased scour depth must be anticipated so that the toe is installed below this depth to prevent undermining.

Salmonids have been found along riprap-treated banks, but the habitat is not preferred in most cases.[1] Fish tend to like the complexity of wood structures more than rock, so logs toes and rootwads are preferred over riprap toes. Study results indicate riprap revetments with large woody debris attract more fish than plain rock. Riprap revetments along the Skagit River have had a dramatic, adverse impact on juvenile chinook, coho and chum habitat.[3] Population levels of summer coho parr and subyearling chinook averaged 3.7 and 5.4 times higher in wood cover than in riprap.

Riprap tends to transfer energy downstream. An increase in bank erosion and/or a loss of habitat in an adjacent reach can be anticipated and must be mitigated. Too often, the need for hardened banks is self-perpetuating, both in time and in the downstream direction. This increase in upstream bank erosion must be anticipated, and future impacts to habitat must be mitigated. Techniques that use hydraulic or biotechnical means to slow bank erosion must be investigated before the decision to use riprap is made. Roughening the bank with large woody debris and vegetation increases energy dissipation and is considered partial mitigation.

Given the roles of channel migration, sediment dynamics and large woody debris in a natural river system, riprap (particularly the cumulative effects of multiple riprap projects) can have significant detrimental effects on habitat and the natural fluvial processes of a river.

For a more extensive discussion of the effects of riprap on river morphology and aquatic habitat, see Appendix K, *Literature Review of Revetments*.

DESIGN

Conceptual design drawings of riprap are shown in *Figure 6-22* and *Figure 6-23*.

Riprap vs. Alternative Solutions

The first step in design is to conduct a feasibility study to determine whether riprap is the most appropriate solution based on the site and reach assessment and to ascertain whether the associated upstream and downstream effects are tolerable (see Chapter 2 and Chapter 3 for guidance). Some of the factors to be considered are stream energy (slope multiplied by discharge at the design flow), shear stress (slope multiplied by depth multiplied by a factor for radius of curvature), radius of curvature, erodibility of bed and bank material, steepness and height of banks, habitat potential and needs, acceptability of failure, and mitigation potential.

Riprap Layout

Riprap layout starts with determining the new toe-of-bank line, the upstream and downstream limits of the riprap, and the bank-face slope. These parameters determine the top-of-bank line. Occasionally, this procedure is done in reverse, particularly when property lines or structures at the top of bank limit the location of the top-of-bank line.

The revetment should include the entire area of bank erosion unless other techniques are used in combination with riprap. The location of channel features both in and outside the reach will play a role in determining where the new bank toe will be placed. Natural hard points, such as large, stable trees or rock outcroppings, are good places to begin or end the toe. Irregular toe lines increase roughness and habitat value. Smooth banks tend to increase velocity and transfer energy downstream.

To maintain bank stability, bank slopes that are 2:1 or flatter are recommended by most riprap design references, although 1.5:1 is allowable in some cases. Terracing often has hydraulic as well as habitat benefits and is a recommended practice.

Rock Size

The size of rock should be determined by accepted riprap design methods (see *Table 6-1*). Larger rock is assumed to have greater habitat value and energy dissipation. The largest rock should be used when large woody debris is incorporated in the design. As rock size increases more attention should be paid to proper bedding and granular filter design.

Filter Layer

A granular or fabric filter is necessary where soils are fine and erodible. Filters allow water behind the toe to drain without allowing soil to be transported out by the seepage or turbulence from river flow. Granular filters are composed of one or more layers of well-graded gravel. Bank-soil analysis and rock size are critical pieces of information necessary for designing a filter layer. Although a filter fabric is generally cheaper to furnish and install than a granular filter, the granular filter may be more stable. Filter fabrics can restrict rooting and produce a slip plane along which rock slopes can fail. These possibilities should be considered when deciding whether or not to use filter fabric in lieu of granular filter. Granular filters are not recommended where velocities exceed 10 feet per second.[4] See Appendix H, *Planting Considerations and Erosion-Control Fabrics* for information about fabric filters.

Depth of Scour

Scour can undermine riprap at the toe of the bank, so preventive steps must be taken to protect the bank where riprap is installed. This protection can be achieved in either of two ways:

1. a supply of riprap material sufficient to armor all expected scour is deposited on the bank. As scour erodes the bank, the ground under the riprap is undermined, and the riprap tumbles down (is launched) to the toe of the bank; or
2. a riprap layer is installed at the bank toe in advance of scour action to the depth of the scour that is expected.

The first form, known as a launched (or launchable) toe is becoming increasingly popular because it requires less excavation than the second option. However, it does require a larger volume of rock than the second option, since some rock is lost during the launching action; and final positioning of the rock cannot be determined with precision. Launched toes are used mostly in channels with fine-grained beds. Launched toes used inappropriately (for instance, along banks whose toes are eroded by some force other than scour) can result in excess rock in the channel. This extra "launchable" rock then narrows the channel and reduces habitat value.

If the second option is used, it will be necessary to calculate the anticipated depth of scour. Several methods for calculating depth of scour are presented in Appendix E, *Hydraulics*. In addition, most of the references listed in *Table 6-1* contain methods for calculating scour depth.

Top Elevation of Rock

Riprap is often applied from the toe to the top of the bank. However, riprap is seldom necessary above a certain elevation on the bank because shear force on banks decrease with height above the streambed. Consequently, the upper banks are subjected to significantly less shear than the lower-bank areas. This important characteristic of shear often allows for vegetated upper banks, thereby increasing the potential for eventually providing cover and shade. A method for estimating the shear distribution on banks is presented in Appendix E.

For further discussion about the top elevation of rock along a bank, refer to the discussion in this chapter addressing *Roughened-Rock Toes*.

Transitions

An anchor point must be located at the upstream and downstream ends of a riprap project to prevent flow from getting around and behind the revetment and eroding the bank. The design references listed in *Table 6-1* include design methods for such transitions.

It is not uncommon for a scour hole to form at the downstream end of a revetment. This hole can become an important habitat feature. Allowing this hole to form and then protecting it is a reasonable and effortless way of dealing with it. Another option is to actually create the hole at the time of construction and place a hard point downstream to limit its extent. This offers some degree of control over the exact positioning and extent of the hole. A third option is to prevent the hole from forming by installing a small groin at the bottom end of the project to kick the flow away from the bank. Roughening the toe with wood, large rock or an irregular bankline will also help prevent formation of a scour hole.

Design References

There are numerous sources of information available for riprap design. *Table 6-1* lists some of the more commonly used sources.

Vegetated Riprap

Riprap is typically vegetated by applying soil in the joints of the rock and planting seed, cuttings or rooted, woody species.

Care must be taken in arranging the soil to make sure it fills the voids between rocks but does not hold the rocks apart from one another. Rocks held apart by soil will settle when the soil is washed out by floodwaters or surface runoff, which may result in destabilization of the riprap layer. Because a small amount of this settling is inevitable, the riprap/soil layer should be slightly thicker than it would have been had no soil been used. The soil should not be installed by pouring it over the surface of the rocks; doing so will only cause the soil in this location to be readily washed away by stream flow or surface runoff. Instead, the surface of the soil should lie about one half of the mean rock diameter below the top of the rock.

Author	Title	Date
U.S. Army Corps of Engineers	*Hydraulic Design of Flood Control Channels* Engineer Manual 1110-2-1601	1994
Vanoni, V. A. (American Society of Civil Engineers)	*Sedimentation Engineering* American Society of Civil Engineers (ASCE) Manuals and Reports on Engineering Practice – No. 54	1977
U.S. Geological Survey	*Rock Riprap Protection for Protection of Stream Channels Near Highway Structures* Water-Resources Investigations Report 86-4128	1986
California Dept. of Public Works, Div. of Highways	*Bank and Shore Protection in California Highway Practice*	1970
U.S. Dept. of Transportation, Federal Highway Administration	*Design of Riprap Revetment* Hydraulic Engineering Circular, No. 11	1989

Table 6-1. Design references.

Once the soil is in place, live cuttings can be planted in the soil-filled joints between the rocks (see the discussion in this chapter addressing the technique, *Woody Plantings*). On existing riprap banks, stakes can be driven through the rock layer and soil can be placed in the voids created. If the rock is large, a pilot hole should first be created using a steel rod. Often an apparatus called a "stinger" (a large, steel rod connected to the arm of an excavator or backhoe) is required to penetrate the rock layer. Details regarding the stinger are included in the technique discussed in this chapter called *Woody Plantings*. In new riprap installations, live cuttings are inserted in conjunction with rock placement.

Planting in joints creates a more aesthetically pleasing bank and more terrestrial habitat. Vegetation planted this way can offer shade, cover and nutrient input to the stream. Woody plants will provide additional roughness and encourage deposition of fine sediment on the bank surface. The fine sediment, in turn, will foster the establishment of additional vegetation.

The discussion in this chapter addressing the technique, *Woody Plantings* and Appendix H contain additional information on incorporating woody plant species into bank treatments. The Natural Resources Conservation Service offers the following instructions regarding live-cutting size and installation procedures:[4]

- cuttings must have side branches removed and bark intact;
- cuttings must be long enough to extend well into the soil below the riprap rock and filter layer;
- cuttings should be tapped through the openings between rocks (a pilot hole created by a steel rod is usually required to avoid undue damage to the stakes);
- the cuttings should be oriented perpendicular to the bank face, with the growing tips protruding slightly from the bank surface; and
- cuttings should be placed in a random configuration.

Additionally, cuttings should be installed at the appropriate time of year. The discussion in this chapter addressing the technique, *Woody Plantings*, offers additional information on planting timing.

Placement of Large Woody Debris

Large-woody-debris installation can mitigate some of the habitat losses along a bank that has been reinforced with riprap. Information on the correct placement and anchoring of large woody debris is covered in Appendix I.

The presence of large woody debris will induce local scour forces that are not present in the standard riprap design methods. Riprap design should predict the effects that placement of woody debris will have on scour (see Appendix E) so that it the treatment can withstand this scour depth.

BIOLOGICAL CONSIDERATIONS

Traditional riprap is considered to offer little aquatic or terrestrial habitat. Peters et al.,[1] found that riprap sites consistently had lower fish densities than control sites and recommended using large-woody-debris cover whenever possible to increase the habitat value of riprap. It is strongly recommended that the mitigation strategies discussed below, or other, similar strategies, be employed to provide habitat value to riprap revetment. See Appendix G, *Biological Considerations* for a more detailed discussion of the environmental effects of riprap.

Mitigation Methods for the Technique

Mitigation needs for riprap revetments include riparian function, cover, spawning habitat, flood refuge, complexity and diversity, lost opportunity, and construction. Mitigation methods that address these needs include:

- use vegetated riprap to mitigate for riparian function impacts;
- create or enhance vegetated riparian buffer to mitigate for riparian function impacts;
- set back riprap from the channel to partially mitigate for lost opportunity impacts or include a bench in the revetment at bankfull depth;
- set large rock that creates large interstitial spaces for habitat to mitigate for flood-refuge impacts;
- place large woody debris to create roughness, pools and cover to mitigate riprap impacts to cover, complexity and diversity;
- place large boulders in the channel to create roughness and pool habitat that will mitigate riprap impacts to cover, complexity and diversity;
- increase overall complexity of the bank and channel through changes in planform, terracing, and leaving or enhancing natural features; and/or
- where possible, use riprap only to construct the bank toe, and construct the upper bank using a more "habitat-friendly" technique.

It is left to the designer to creatively apply these methods, as well as to develop alternative methods for creating aquatic and terrestrial habitat. See Chapter 4, *Considerations for a Solution* and Matrix 3 in Chaper 5, for additional information on mitigation needs and techniques.

Mitigation Benefits Provided by the Technique

Riprap provides no mitigation benefit.

RISK

Stream Function and Morphology

As discussed above, riprap can have significant, detrimental effects on the natural fluvial processes of a river by altering and interfering with natural channel migration, sediment dynamics and large-woody-debris input. Imbalances caused by riprap may lead to increased erosion elsewhere, expanding the need for bank treatment along a reach. Cumulatively, multiple riprap projects tend to lead to channel shortening, incision and degradation of aquatic and riparian habitat.

Habitat

Riprap revetments that are not mitigated by woody-debris placement or a similar alternative offer very little aquatic-habitat complexity. Although salmonids are found to use the areas adjacent to riprap revetments, it is not considered to be preferred habitat. The addition of large woody debris increases fish usage. The riparian habitat offered by the upper banks of a riprap revetment is likewise low in diversity and relatively poor in quality. Again, mitigation measures such as aggressive revegetation increase the habitat value markedly.

Infrastructure

Riprap is a proven, effective, low-risk method of protecting infrastructure. It is often the chosen bank-treatment alternative when bank failure cannot be tolerated. Unfortunately, riprap is also habitually used to protect low-risk or relatively low-energy areas where the environmental cost of the riprap may not outweigh the benefits or where other bank-treatment methods could have addressed the mechanism and causes of failure more effectively.

Reliability/Uncertainty of Technique

Compared to most other bank-treatment alternatives, uncertainty in this technique is relatively low. This is due to the simplicity of the technique, the durability of rock used in revetments, the availability of reliable design/installation guidelines and a proven, long-term track record.

Public Safety

Rock riprap revetments pose a minimal hazard to recreational users, although they may create high-velocity reaches that pose risks to inexperienced boaters. Some measures taken to enhance fish habitat, such as large-woody-debris placement, can make riprap revetments more hazardous to recreational boaters, unless the large woody debris is completely submerged. Other mitigation measures, such as adding vegetation to the riprap along the bank surface, will tend to create a safer bank. In general, safety concerns should be balanced with habitat concerns and the level and type of recreational use customary at the site.

CONSTRUCTION CONSIDERATIONS

Materials Required

Traditional riprap requires graded, angular rock and filter material. Installation will require access roads designed for street-legal dump trucks or a road for loaders to transfer the rock from trucks to the site if truck access at the site is impossible or impractical. Refer to Appendix M, *Construction Considerations* for further discussion of site access. If riprap is vegetated or large woody debris is added, the following additional materials may be needed:

- logs with rootwads attached and anchoring materials,
- vegetation (such as live cuttings or salvaged willow clumps), and/or
- soil and seed.

Further discussion of large woody debris and anchoring is provided in Appendix I. Further discussion of plant materials and planting is provided in Appendix H.

Timing

Riprap should be installed during low flow, when dewatering is possible, and when resident and anadromous fish are less likely to be impacted by construction activities. In order to install rock materials to the depth of scour, excavation within the channel bed will be necessary. This means the channel will need to be dewatered temporarily. Dewatering makes installation much easier and prevents siltation of the stream during construction. Dewatering can be accomplished with a coffer dam during times of low water flow.

Every effort must be made to avoid construction during critical periods in the salmonid life cycle, such as spawning or migration. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information)*. Further discussion of dewatering can also be found in Appendix M.

Whenever vegetation is installed in conjunction with riprap revetment, the timing of seeding and planting should maximize the survival rate of the vegetation (see the discussion in this chapter addressing the technique, *Woody Plantings*).

Cost

Riprap installation cost depends upon materials availability, construction access and dewatering requirements. The cost of a riprap bank treatment may range from $30 to $90 per foot of bank treated. Cost may exceed this range on very-high-energy river systems. Dewatering and site access are further described in Appendix M.

Materials required for riprap treatments include angular rock and filter materials. Because angular rock generally must be manufactured and imported, the cost will depend largely on availability and transport costs. Rock materials may range from $60 to $80 per cubic yard. Gravel filter materials range from $40 to $60 per cubic yard if they are imported. However, local sources may be available. Filter fabric may be used as an alternative to gravel filters and ranges in price from $0.50 to $3.00 per square yard. Refer to Appendix L, *Cost of Techniques* for further discussion of materials and construction costs.

MAINTENANCE

Typical operation and maintenance requirements for riprap include periodic inspection of existing riprap and installation of supplemental riprap if needed. Planted riprap, or riprap that incorporates large woody debris, may require repair or replanting as necessary. Mitigation measures may also have operation and maintenance requirements.

MONITORING

Monitoring of riprap treatments is limited to visual inspection of the integrity of the riprap treatment. The survival rate of vegetation and anchoring success of large woody debris placed in the treatment also needs to be monitored.

Riprap inspection should focus on potential weak points in the design, such as transitions between undisturbed and treated banks. The adjacent native soils above and behind the treatment may reveal collapse or sinking, indicating piping loss or movement of rock materials. Monitoring should also include inspecting for loss of rock materials over time.

Monitoring frequency should be conducted annually during low flows, when visual inspection of the toe is possible. Additionally, the treatment should be inspected following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J, *Monitoring*.

Impacts to the channel and to habitat must be carefully monitored. Channel changes occurring following installation can be documented by reviewing an annual survey of cross sections conducted prior to and following installation. Changes to available habitat should be documented on a schedule dictated by fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[5] Habitat monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

1 Peters, R. J., B. R. Missildine and D. L. Low. 1998. Seasonal Fish Densities Near River Banks Stabilized with Various Stabilization Methods. U. S. Fish and Wildlife Service, North Pacific Coast Ecoregion. Western Washington Office. Aquatic Resources Division, Lacey, WA.

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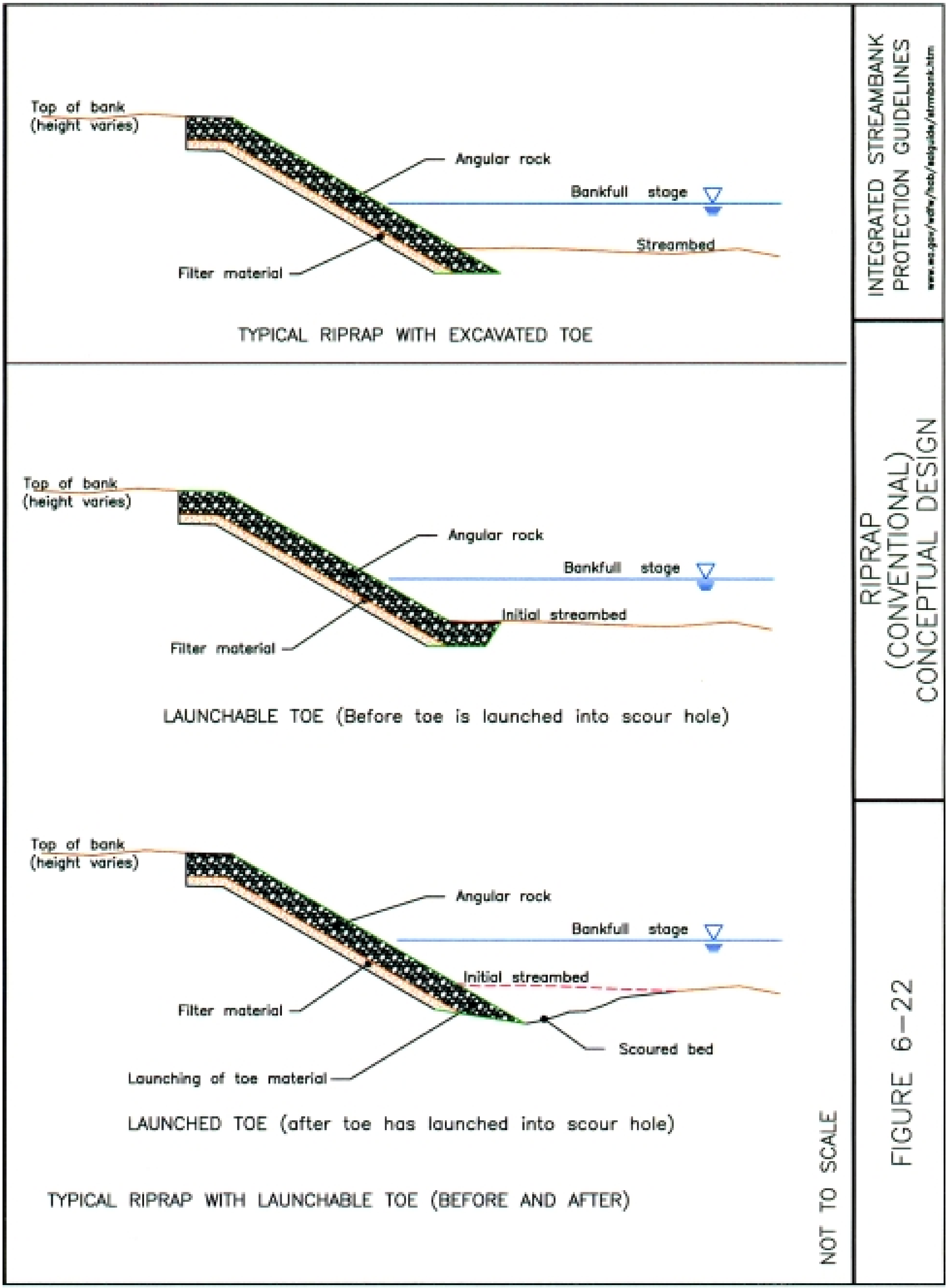
a. Riprap placed during an emergency. Tahuya River. 2002.

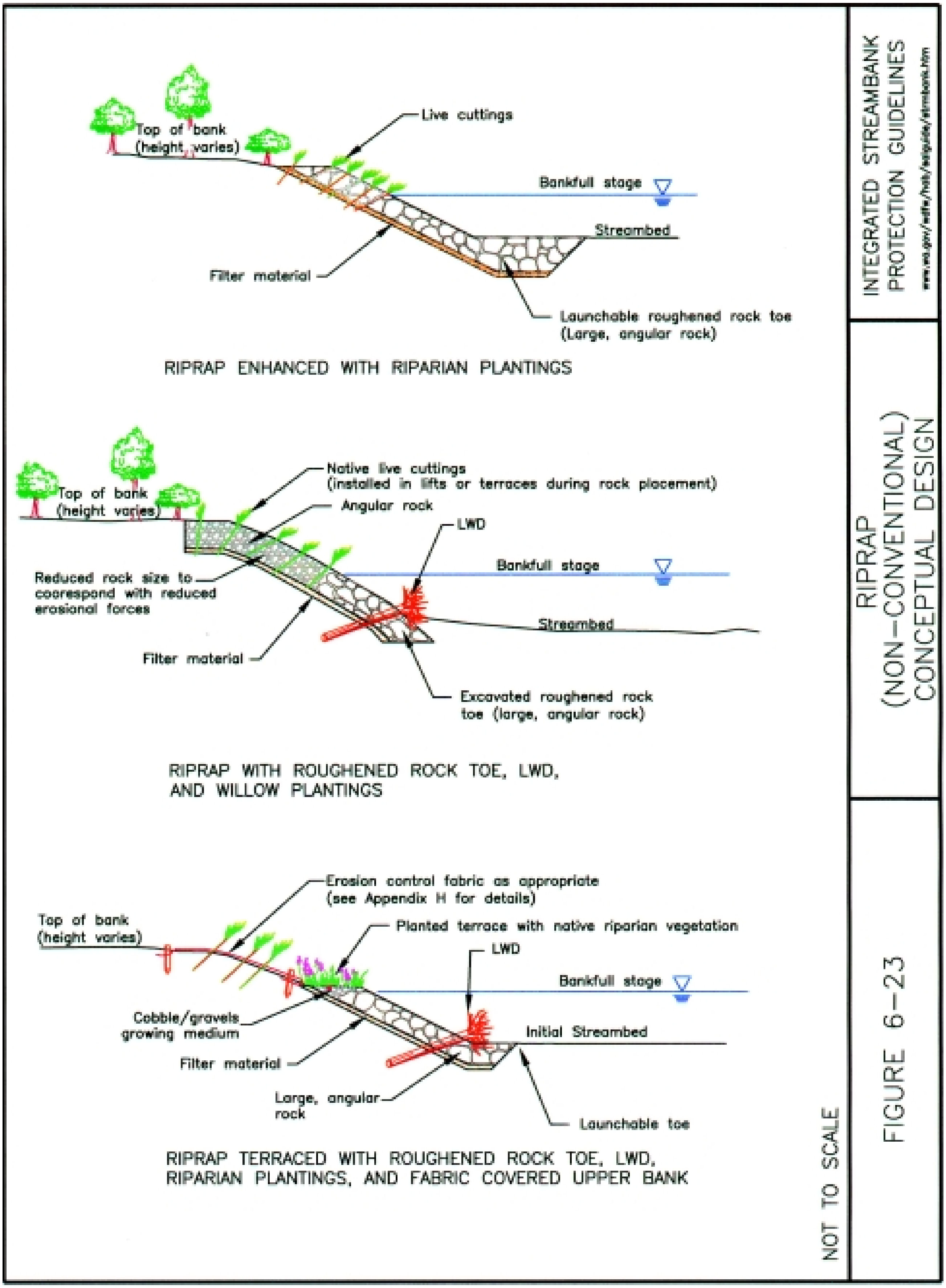
b. Nooksack River.

c. Newaukum River.

d. Vegetated Riprap. Site unknown.

Figure 6-21. Examples of riprap.


Top of bank
(height varies)
Angular rock
Bankfull stage
Streambed
Filter material
TYPICAL RIPRAP WITH EXCAVATED TOE
Top of bank
(height varies)
Angular rock
Bankfull stage
Initial streambed
Filter material
LAUNCHABLE TOE (Before toe is launched into scour hole)
Top of bank
(height varies)
Angular rock
Bankfull stage
Initial streambed
Filter material
Scoured bed
Launching of toe material
LAUNCHED TOE (after toe has launched into scour hole)
TYPICAL RIPRAP WITH LAUNCHABLE TOE (BEFORE AND AFTER)
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
RIPRAP (CONVENTIONAL) CONCEPTUAL DESIGN
FIGURE 6-22


Top of bank
(height varies)
Live cuttings
Bankfull stage
Streambed
Filter material
Launchable roughened rock toe
(Large, angular rock)
RIPRAP ENHANCED WITH RIPARIAN PLANTINGS
Top of bank
(height varies)
Native live cuttings
(installed in lifts or terraces during rock placement)
Angular rock
LWD
Bankfull stage
Reduced rock size to
coorespond with reduced
erosional forces
Streambed
Filter material
Excavated roughened rock
toe (large, angular rock)
RIPRAP WITH ROUGHENED ROCK TOE, LWD,
AND WILLOW PLANTINGS
Erosion control fabric as appropriate
(see Appendix H for details)
Top of bank
(height varies)
Planted terrace with native riparian vegetation
LWD
Bankfull stage
Cobble/gravels
growing medium
Initial Streambed
Filter material
Large, angular
rock
Launchable toe
RIPRAP TERRACED WITH ROUGHENED ROCK TOE, LWD,
RIPARIAN PLANTINGS, AND FABRIC COVERED UPPER BANK
NOT TO SCALE
INTEGRATED STREAMBANK
PROTECTION GUIDELINES
RIPRAP
(NON–CONVENTIONAL)
CONCEPTUAL DESIGN
FIGURE 6–23

Log Toes
Structural Techniques

DESCRIPTION

Log toes are structural features that prevent erosion at the toe of a streambank. The toe refers to that portion of the streambank that extends from the channel bottom up to the lower limit of vegetation or to a distinct break in slope between the top of the bank and the streambed. Log toes can provide the foundation for nonrock, nonstructural, upper-bank treatments such as reinforced soil or resloped banks. Log toes are generally constructed of logs and gravel fill between logs, but may also include components made of large woody debris to provide additional habitat value. Log toes may also incorporate rock material to provide added protection.[1, 2, 3] Log toes differ from log cribwalls in two primary ways:

1. log toes are not structural retaining walls, and
2. the top elevation of log toes does not exceed the lower limit of vegetation on the bank.

Log toes are installed parallel to and at the toe of a streambank, often extending under a reconstructed bank to provide protection against erosion where erosional forces are the greatest - at the toe of the streambank. Log toes can be implemented either as a stand-alone streambank-protection technique, or as the toe element for other streambank-protection techniques. *Figure 6-24* (at the end of this technique discussion) shows various applications of log toes throughout Washington State.

Log and rootwad toes represent a more natural approach to toe protection. They may provide greater habitat value than rock for all life phases of fish and other aquatic organisms.[4] In addition, woody toe protection will deteriorate as native vegetation matures and begins to provide support and structure to the banks - an important goal of integrated streambank protection.

LOG TOES

APPLICATION

Log toes play an important role in bioengineered approaches to streambank protection and in reshaped banks. Even so, they should be considered experimental at this point because so few have yet been designed and constructed in a systematic way. In most situations, an armored toe will provide adequate protection against erosional forces by controlling erosion where it is most prominent, at the toe[5] and by providing a relatively permanent foundation for upper-bank treatments. This approach can be applied anywhere that rock toes would otherwise be used but only where there is less risk to infrastructure and where habitat mitigation is required. For additional information, see the discussion in this chapter regarding the technique called *Roughened-Rock Toes*.

It is important to determine whether a log toe is the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Log toe protection is suitable for sites where the mechanism of failure is toe erosion. It is also appropriate as armoring against all types of scour if applied landward of the scour hole. Log toes are not recommended in high-energy reaches where the turbulence and shear stress would be too great, where there exists the potential for an avulsion or chute cutoff or at sites that are undergoing rapid aggradation or degradation. In aggrading reaches, the bed elevation is increasing and may overwhelm the toe. In degrading reaches the toe may be undercut and fail. In both cases, the banks experience high levels of turbulence and erosion. Use of a log toe within a channel-migration zone is preferred over a more structural technique, such as a rock toe or revetment. See the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of log toes based on the mechanism of failure and causes of streambank erosion.

Variations

Log toes can be installed to be either deformable or nondeformable. *Nondeformable toe-protection* techniques are designed to remain unchanged over time and to withstand erosional forces at all or most flows, thereby reducing the potential for erosion. This is accomplished with large, rot-resistant logs that do not protrude into the channel significantly (where drag could cause rotation). If log toes are to be used as nondeformable bank protection, it is important to select a type and size of wood that will resist rotting and wear. Quality of installation is also important in preventing such protection from deforming.

Deformable toes are designed to provide temporary protection, degrade with time and wear at a rate predetermined by design criteria once streambank vegetation is well established. In this type of application, log toes should be constructed using the smallest-diameter and shortest-length logs that can withstand the erosional forces acting along the bank. A deformable toe "buys time" for planted vegetation to develop root strength and eventually provide natural toe protection once the log toe disintegrates. In areas of low risk to infrastructure, the deformable toe allows restoration of natural channel migration to occur at a pace that is tempered by bank vegetation, just as it is in natural settings.

Log toes can be constructed to include large woody debris or rootwads to provide additional habitat value.[6] Large woody debris and/or rootwads installed among the logs and projecting out from the toe enhance habitat value and roughness along the bank.[3] Log toes alone may provide pockets of low-velocity flow and may provide valuable cover along the bank in spaces among the logs.

Emergency

Log toes cannot be installed in emergencies. Because logs are buoyant and must be either weighted down or anchored, log toes can only be constructed in dewatered conditions.

EFFECTS

Log toes can be very effective at controlling bank erosion. Log toes are not permanent treatment measures, which may be an advantage, since permanent protection eliminates a source of sediment and large woody debris, thereby affecting the natural balance of erosion and deposition within a channel. Also, permanent treatments arrest downstream meander migration, increasing bank erosion upstream and/or downstream from the protected bank. Because logs have a limited life span, this technique should be combined with upper-bank treatments that use bank vegetation to provide longer-term bank protection.

Log toes also result in increased velocity and reduced complexity and diversity along the channel margin, thereby affecting habitat value (though considerably less so than rock toe treatments). These effects can be mitigated to some degree by incorporating rootwads in the treatment or by varying the degree to which logs project into the channel. The hardened toe may deepen the channel at the toe and may form a point bar along the opposite bank. This increased scour depth must be anticipated so that the toe is installed low enough not to be undermined.

Rootwads incorporated in a log-toe design may produce deep scour holes due to exaggerated turbulence around them.[1] While this may provide valuable cover and holding habitat, scour must be accounted for in both the depth of the toe and in armoring the adjacent banks. Vertical log toe revetments may produce very deep scour. Studies have shown that vertical bridge abutments incur twice the scour than sloped abutments.[7] As a result, vertical revetments are not recommended.

Log toes allow for vegetated upper banks, thereby increasing the potential for eventually providing cover and shade, as compared to riprap. Additionally, many types of wood debris incorporated in log toes may sprout and grow to provide valuable root structure to the bank toe. Wood cuttings can be incorporated within a log toe to facilitate root development.

DESIGN

A conceptual design drawing is shown in *Figure 6-25*.

The first step in design is to identify whether a log toe is an appropriate solution based on the site and reach assessments (see Chapter 2 and Chapter 3 for guidance) and whether the associated upstream and downstream effects are tolerable. Many different toe-protection combinations of rocks, logs, rootwads and vegetation have been tried with varying success. Some of the factors to be considered are shear stress, depth of scour, habitat needs and potential mitigation requirements.

There are no established design criteria available for log toe structures with respect to shear stress. Consequently, log-toe design will require creative design analysis and best professional judgement. For example, log toes may be applied under virtually any shear conditions, yet how to determine the correct size of individual logs and how they are installed and anchored (which should be adjusted to accommodate differing shears) is not documented or well established.

Depth of Installation

Log toes should be installed to the maximum calculated depth of scour (refer to Appendix E, *Hydraulics* for further information). Because it is difficult to install log toes to depths greater than five feet below the bed, log toes are not recommended in areas where scour exceeds five feet. In contrast to rock toes, log toes cannot be installed as launchable material due to their buoyancy.

Log Sizing and Anchoring

The size of the logs must be large enough to withstand the hydraulic energy in the stream. However, because there are no established methods for determining the correct size of logs or method of anchoring, best professional judgement is required. Log sizes (diameter and length) should be large enough to withstand the drag forces of the river and should be anchored securely to the bank by burial.[8, 9, 10, 11, 12]

Buoyancy forces are generally not a concern if the log toe is incorporated as part of a reconstructed bank. Here, the weight of the earthen materials piled on top of the log toe is sufficient to counter the buoyancy forces. Similarly, rotational forces should not be a concern because the logs do not project into the flow. However, installation must be conducted in a water-free environment so that logs do not float during installation.

If an earthen bank treatment is not installed on top of the log toe, however, buoyancy will be the most crucial consideration for anchoring. Drag and buoyant forces need to be considered when large woody debris is incorporated into the log toe.

Some log toes have also been combined with large rocks. The rocks act as ballast and mechanically bind the structure together. It is very difficult to build a log toe along a large, deep river without using rock. See Appendix I, *Anchoring and Placement of Large Woody Debris* for more information about anchoring and ballasting.

Height of Installation

Determination of the upper elevation of the log toe is an important design consideration. The log toe should be installed at least to an elevation that corresponds with the lower limit of perennial vegetation on a streambank - the ordinary high-water line. As an alternative, criteria can be set based on shear forces along the bank and the ability of the upper-bank treatment to withstand these forces. In this case, the log toe treatment should extend to an upper elevation where such upper-bank treatments are able to withstand shear forces along the bank. The relative height of the hardened protection on the bank is a function of the erodibility of the bank and the shear stress present at the site. Refer to Appendix E for more information on bank resistance to shear stress.

Locating the New Toe Line

The location of property lines and structures has an influence over where to locate the installed bank line. But it is the location of channel features, both inside and outside the reach, that plays a role in determining where the new toe will be placed. Natural hard points, such as large, stable trees or rock outcroppings, are natural places to begin or end the toe. For additional information, see the discussion in this chapter regarding the technique called *Anchor Points.*

Base the new location for the top of the bank on the bank slope, in reference to the toe line and distance to at-risk property. Design considerations that should be addressed but are often overlooked include the location and condition of the project staging area, access for construction equipment, truck-turning needs and impacts and traffic patterns. Removal of existing riparian trees and shrubs or even disturbance of their roots should be avoided or kept to an absolute minimum. Both short-term and long-term impacts to wildlife can be greatly reduced by applying the highest possible standards of minimizing vegetation disturbance and removal.

Toe protection should be located to extend beyond the upstream and downstream limits of the bank erosion. Anchor points (rock- or log-filled trenches placed perpendicular to the toe and cut back into the bank) must be located at the upstream and/or downstream ends of the project.

Filter and Matrix Material

Log toes have a considerable amount of open space among the logs. These spaces should be filled with material consisting of a well-graded mixture of gravel, sand and other fine-grained material (similar in composition to local alluvial material is best). Additionally, a filter should be installed between the upper surface of the log toe and the upper-bank material (behind and on top of the installed logs). Filters allow water behind the toe to drain, yet don't allow soil to be transported out by the seepage or turbulence from river flow. Filter material can be either synthetic fabric or gravel material. In either case, they reduce the potential for piping loss of native soil materials through the treatment structure. A filter is generally not needed under the log toe, as logs are less dense than the native soils and alluvial material in which they are installed.

Large voids in log toes need to be plugged with rock and backed with a gravel filter to insure that the bank material is not carried out by turbulence or seepage. The toe will fail if the soil behind it is washed out, causing flow over the top to drop down and form a plunge pool behind the toe.

Placement of Large Woody Debris

If large woody debris is used, it should be incorporated into the log toes roughly perpendicular to flow direction and/or logs intentionally placed to project into the current as debris catchers. The use of large woody debris in log toes needs to consider buoyancy and rotational forces. Large woody debris must be sufficiently anchored within the log toe to eliminate the risk of pulling free and damaging the treatment. Often, the depth from the installed debris to the channel bed increases as a scour hole develops beneath the debris. Similarly, large woody debris should be installed such that the top of the wood is submerged or partially submerged to reduce the rate of decay. For more information on placement and anchoring of large woody debris, refer to Appendix I.

Transitions

Transitions are the points where the log toe treatment meets the upstream and/or downstream streambank. Anchor points are recommended as transition features for log toes. Should the biotechnical bank protection above the toe fail, the anchor points guide the flow out from behind the toe and back into the channel. Without these structures, the river could scour behind the toe along its length and cause bank failure. Anchor points must be located at the upstream and/or downstream ends of the project to prevent flow from eroding behind the bank treatment. For additional design information on anchor points, refer to the techniques described in this chapter called *Riprap* and *Anchor Points*.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Log toes may be constructed as a deformable or nondeformable treatment. By locking a streambank in place, the nondeformable treatment results in lost opportunity for sediment supply, recruitment of woody debris and off-channel spawning and rearing habitat (for further discussion of lost opportunity, refer to Chapter 4, *Considerations for a Solution*). Short-term lost opportunity will need to be mitigated. Once a log toe has degraded, lost opportunity is no longer a concern. Log toes can be expected to last from years to decades depending upon factors such as type of wood, size of wood, consistency of submersion and flow characteristics.[13]

If designed to degrade over time, log toes can provide for immediate toe protection without permanently jeopardizing recruitment of gravel, large woody debris or off-channel habitat. Where recruitment is permanently jeopardized, mitigation will be required. Refer Chapter 4 for further discussion of mitigation requirements and to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Log toes can be designed and constructed to incorporate rootwads as partial mitigation for cover, complexity and diversity, and flood refuge. Rootwads will produce a velocity break and small-scale cover for both juvenile and adult fish. Fish tend to prefer wood for cover better than rock, so logs and rootwads are recommended over rock toes.[4] Access to woody debris, both in summer and winter, is critical for many salmonids.

Log toes are constructed of native materials (if available) and may be considered degradable. The wood material may provide complexity and diversity to the streambank and may result in vegetated bank toes if the wood generates shoots. Additionally, log toes offer an advantage over riprap treatments in that the upper bank can be designed to provide considerable riparian habitat, cover and shade. Design of upper banks should therefore incorporate vegetation elements that provide the maximum degree of habitat potential to the stream channel. Refer to Matrix 3 in Chapter 5 for more detail on mitigation benefits provided by this bank treatment.

RISK

Log toe treatments are similar to rock toe treatments in that they provide a relatively low-risk and reliable approach to streambank protection, except that less non-native material is required for log toes, and there is a greater potential for habitat mitigation than with rock toes. Log toes are relatively new, and design experience is limited. As noted earlier, they should be considered experimental. The use of rootwads and log toes that project into the stream's main flow may be a hazard to humans recreating in or along the stream. For this reason, risks associated with recreational activities (e.g., fishing, boating) should be taken into account before selecting this technique. Signage upstream from a log toe may be helpful in warning recreational users of potential hazards and should be included as a design consideration.

Habitat

Log toes harden the bank into a relatively uniform and permanent position and shape, resulting in short-term lost opportunity for sediment supply, recruitment of large woody debris and off-channel habitat. Even so, log toes are considered superior to rock toes in terms of providing habitat elements, and log toes will eventually degrade; rock will not. Therefore, log toes can be considered as deformable (albeit over long periods of time) and, as such, will not result in permanent lost opportunity.

Infrastructure

When applied correctly, log toes reduce the risk to adjacent infrastructure by limiting erosion along the channel bank and laterally into the bank.

Reliability/Uncertainty of Technique

Similar to rock toes, log toes provide a reliable approach to arresting or preventing erosion. However, the uncertainty in this approach is twofold. First, there are no established guidelines or methods for determining the correct log size needed or for installing the treatment. Second, there is additional uncertainty regarding the integrity of upper-bank components. However, development of design guidelines will eventually be possible if adequate monitoring of these projects is conducted relative to their design criteria.

CONSTRUCTION CONSIDERATIONS

Materials Required

Materials necessary for log toe treatments include logs, material to fill spaces among logs, filter material (gravel or fabric) and large woody debris for mitigation and habitat components. For further discussion of filter materials and large woody debris, refer to the treatment described in Appendix H, *Planting and Erosion-Control Fabrics* and Appendix I.

The type of wood selected may be a important if longevity of the protection is a concern.

Avoid using species such as alder or cottonwood that decay rapidly, unless deformable treatments are desired. Coniferous species such as cedar, fir and pine are better choices. However, on smaller streams, logs that may ultimately sprout should be considered as supplemental to promote woody growth on the streambank. There are manufactured alternatives to using logs. One such product is manufactured by ELWd Systems.[14] Natural logs are simulated using organic materials and come in a range of lengths and diameters. They have been used on several log toe projects in western Washington.

Logs should be scaled appropriately to the channel characteristics and hydrology. Logs need to have sufficient length under the bank to resist being pulled out. Logs in a log toe are not intended to protrude into the channel (except to catch debris) and, therefore, will not need to resist significant drag forces. It is more important to select logs that can be installed as an integrated unit than to select large-diameter logs.

Timing Considerations

Log toes are best constructed during low flow when dewatering is possible and, when resident and anadromous fish are less likely to be impacted by construction activities. In order to install logs to the depth of scour, excavation within the channel bed will be necessary and, consequently, will require temporary dewatering systems. Dewatering allows for ease of installation and prevents siltation of the stream during construction. This can be accomplished with a coffer dam during low water.

Critical periods in salmonid life cycles, such as spawning or migration, should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

Cost

Log toe treatments can be constructed with minimal cost relative to other toe treatments, since all necessary materials are often available on site, near site or at low cost. The cost of log toe treatments alone (not including upper-bank treatment, dewatering or other independent construction costs) may range from $20 to $60 per linear foot of toe treatment. Cost of the toe treatment itself will be most dependent upon availability of log materials. The cost of log toe treatments largely depends upon the size of the river (which impacts dewatering costs) and wood materials required. Additionally, the cost of the associated upper-bank treatment will greatly affect overall cost. Refer to Appendix L, *Cost of Techniques* for further discussion of materials and construction costs and for associated costs of dewatering and upper bank treatments.

MAINTENANCE

Maintenance needs are generally minimal if logs are installed under a constructed upper-bank treatment, as opposed to being anchored to the toe at the surface of the bank. Maintenance can be relatively challenging, as it may be difficult to place additional logs to patch up destabilized sections of the log toe treatment without dewatering the work area. Repair of damaged bank-toe sections may be best accomplished by using rock instead of logs.

In addition to maintaining the toe treatment, any mitigation components incorporated will need to be monitored and maintained. Large woody debris and other installed habitat components will also require monitoring and maintenance.

MONITORING

Monitoring log toe treatments is limited to survey and visual inspection, including regular photo documentation. Monitoring components should include survey and inspection of the integrity of the log toe treatment and associated upper-bank treatments. Monitoring components of upper-bank treatments is further discussed under the relevant upper-bank treatments (e.g., bank reshaping, soil reinforcement, herbaceous plantings, woody plantings, coir logs) described in this chapter.

Monitoring should include detailed as-built surveying and photo documentation of the project area and upstream and downstream reaches to evaluate performance relative to design. Details on development of a monitoring plan are discussed in Appendix J.

Log-toe-monitoring activities should focus on potential weak points in the design, such as transitions between undisturbed and treated banks and between the log toe and the upper bank. Monitoring should include surveying the location and elevation of the log toe at upstream and downstream limits, and at 50-foot intervals along the treatment. The adjacent native soils above and behind the treatment may reveal collapsed or sinking fill, indicative of piping loss or movement of log materials. Additionally, monitoring should include inspection for degradation and/or loss of log-toe materials over time.

Monitoring frequency should be annual and should be conducted during low flows, when visual inspection of the toe is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[15] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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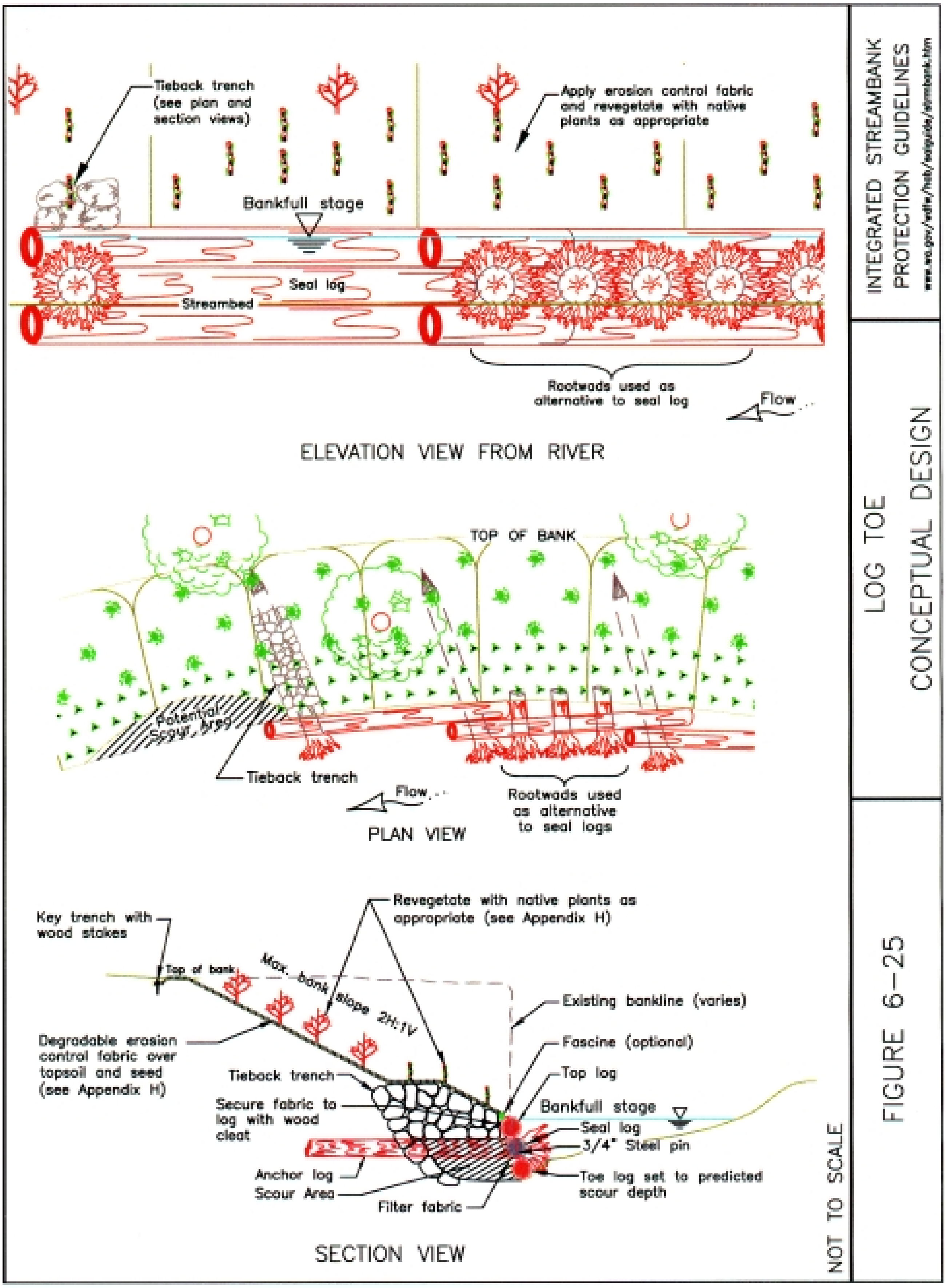
a. Log Toe with rootwads, boulders, soil reinforced lifts and plantings. One year after construction. Green River. 1994. Source: King County Department of Natural Resources.

b. Log Toe with rootwads, boulders, soil-reinforced lifts and plantings. Four years after construction. Green River. 1998. Source: King County Department of Natural Resources.

c. Log Toe with bank reshaping and plantings. Dungeness River. 1995.

Figure 6-24. Various applications of log toes throughout Washington State.



Tieback trench (see plan and section views)
Apply erosion control fabric and revegetate with native plants as appropriate
Bankfull stage
Seal log
Streambed
Rootwads used as alternative to seal log
Flow
ELEVATION VIEW FROM RIVER
TOP OF BANK
Potential Scour Area
Tieback trench
Flow
Rootwads used as alternative to seal logs
PLAN VIEW
Key trench with wood stakes
Revegetate with native plants as appropriate (see Appendix H)
Top of bank
Max. bank slope 2H:1V
Existing bankline (varies)
Degradable erosion control fabric over topsoil and seed (see Appendix H)
Fascine (optional)
Tieback trench
Top log
Secure fabric to log with wood cleat
Bankfull stage
Seal log
3/4" Steel pin
Anchor log
Scour Area
Filter fabric
Toe log set to predicted scour depth
SECTION VIEW
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
LOG TOE CONCEPTUAL DESIGN
FIGURE 6–25

Roughened-Rock Toes
Structural Techniques

DESCRIPTION

Roughened-rock toes are structural features that prevent erosion at the toe of a streambank (see *Figure 6-26* at the end of this technique discussion). The toe is where a streambank is most vulnerable because that is where the erosional forces are greatest. When roughened-rock toes are properly installed, they can withstand these forces and provide the foundation for upper-bank biotechnical treatments, such as reinforced soil lifts or vegetative plantings.

Smooth-rock toes alone generally provide little habitat complexity or cover. Roughened-rock toes, by definition, are designed with angular components, which provide greater roughness. Large woody debris may be incorporated into roughened-rock toes as a habitat feature and to provide additional roughness. Roughened-rock toes extend from the maximum predicted depth of scour to the lower limit of vegetation - the point of elevation on the bank where plant growth cannot be expected to hold the soil together. A roughened-rock toe can be created by launching material from the bank during scour events, which ultimately provides the toe with protection to the depth of scour.

APPLICATION

Roughened-rock toes are used in bank protection and in the reinforcement of new stream alignments. In most situations, an armored toe will provide substantial protection against erosional forces by controlling erosion where it is most prominent, at the toe and by providing a relatively permanent foundation for upper-bank treatments. This approach can be applied anywhere that riprap would otherwise be used; but there must be less risk to infrastructure, and habitat mitigation must be incorporated into the treatment. Roughened-rock toes can also be employed as a complementary toe treatment for bioengineered streambank protection and for reshaped banks.

It is important to determine whether a rock toe is the appropriate solution for the particular mechanism of failure and causes of erosion in question (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Roughened-rock toe protection is appropriate for sites where the mechanism of failure is toe erosion. It is also suitable armoring against all types of scour if applied landward of the scour hole. This treatment is not appropriate at sites where the potential for an avulsion or chute cutoff exists or at sites that are undergoing rapid aggradation or degradation. In aggrading reaches, the bed elevation is increasing and may overwhelm the toe. In degrading reaches the toe may be undercut and fail.

It is also not advisable to use a nondeformable, roughened-rock toe within a channel-migration zone since it will interrupt the natural, riverine-channel-migration process and will likely cause future erosion problems upstream and downstream. See the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of rock toes based on the mechanisms of failure and the causes of streambank erosion.

Variations

Roughened-rock toes can be installed in such a way that they are either nondeformable or deformable. Nondeformable bank-protection techniques are designed to resist change over time. They are designed to withstand erosional forces at all or most flows, thereby reducing the potential for erosion. Roughened-rock toe protection is typically designed as a nondeformable bank-protection technique.

Deformable bank-protection techniques, on the other hand, allow for a natural rate of erosion to occur along reconstructed streambanks. These techniques are designed to provide temporary protection, but will degrade with time once streambank vegetation is well-established, according to predetermined design criteria. In such cases, roughened-rock toes may be designed to deform by constructing them from gravel wrapped in biodegradable erosion-control fabrics. The fabric-wrapped gravel provides a structural treatment for as long as the fabric's integrity remains. As the fabric gradually begins to degrade, the gravel can be gradually eroded. By that time, the above-water portion of the bank will be vegetated, thereby resisting erosion.

Roughened-rock toes are often constructed with large woody debris incorporated into them to provide habitat value and roughness features. Recent research has shown that fish of all species are more likely to gravitate to banks that are stabilized with large woody debris than those banks that are reinforced with rock alone.[1] The impacts to aquatic habitat from rock toes can be partially mitigated by the installation of large woody debris. Submerged or partially submerged large woody debris installed in concert with a roughened-rock toe provides cover, reduces velocity areas and creates habitat complexity. The additional roughness provided by the large woody debris dissipates energy in the form of turbulence, which results in sediment deposition and reduction in bed scour and downstream effects. Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for more information on placement and anchoring of large woody debris.

Toe reinforcement can also be constructed using logs instead of rock. Log toes are described in this chapter under the technique entitled, *Log Toes*.

Emergency

When a bank is actively failing during an emergency, rock is typically installed to armor the toe of the bank and arrest further erosion. Rock toes can be installed by dumping or placing the rock from the top of the bank and allowing it to fall into the channel along the bank toe. Another installation technique is achieved by placing rock at the top of the bank, so that, as the bank erodes, the rock is launched.[2] This type of emergency installation can be carried out during flood events or immediately after flood waters have receded. Rock installed under emergency conditions will require further construction after the recession of flood waters to ensure it has an adequate key (situated below the design scour depth) and to incorporate habitat measures as mitigation. In such cases, there is the potential for salvage and re-use of some rock materials following the emergency. The rock may also need to be replaced by a more appropriate treatment measure that addresses the mechanism of failure and causes of bank erosion, as discussed in Chapter 2 and Chapter 3.

EFFECTS

Rock toes are very effective at arresting bank erosion and can provide relatively permanent protection against further erosion. This approach also eliminates the streambank as a source of sediment and recruitment of large woody debris, which affects the natural balance of erosion and deposition within a channel. Also, downstream meander migration is arrested, increasing bank erosion upstream and/or downstream from the rock toe protection. Because rock toes are permanent, they represent a long-term restraint on stream movement and must be mitigated for loss of habitat and lost opportunity.

Rock toes also result in increased velocity and reduced habitat complexity and diversity along the channel margin. These effects can be mitigated to some degree by incorporating large woody debris into the treatment and by maintaining a riparian buffer. A hardened toe may deepen the channel at the toe and may steepen the slope to the point bar. This increased scour depth must be anticipated so that the toe is installed below this depth to prevent bank undermining. In contrast to riprap approaches, which extend up the bank, rock toes allow vegetation to continue growing along the upper banks, thereby increasing the potential for cover and shade.

Fish tend to prefer the complexity of wood structures more than rock, so log toes are the preferred bank-protection option over rock toes. Salmonids are found along riprap banks, but the habitat is not preferred in most cases where they have a choice.[1] Rock toes and revetments with large woody debris have been shown to have more fish abundance than plain rock.

Rock toes tend to transfer energy downstream. An increase in bank erosion and/or a loss of habitat in an adjacent reach should be anticipated and must be mitigated. Too often, the installation of hardened banks creates a snowball effect, wherein the placement of one hardened-bank treatment creates the need for more hardened bank segments to control the upstream and downstream erosion problems caused by the first hardened-bank treatment. Alternative techniques that use hydraulic or biotechnical means to slow bank erosion must be considered before the decision to armor the bank is made. If bank hardening simply must be done, roughening the toe with wood will dissipate flow energy along the bank and will count as partial mitigation.

DESIGN

The first step in design is to identify whether a rock toe is an appropriate solution based on the site and reach assessment (see Chapters 2 and 3 for guidance) and whether the associated upstream and downstream effects are tolerable (see Chapter 5 for guidance). Many different combinations of rocks, logs, rootwads and vegetation have been tried with varying success. Some of the factors to be considered are shear stress, radius of curvature, erodibility of bed and bank material, habitat needs, and mitigation potential. Design elements for rock toes include depth of installation, size gradation of installed rock, thickness of installation and a filter between native soil and rock. Conceptual design drawings are shown in *Figure 6-27.*

Depth of Scour

There are two approaches for installing rock to accommodate scour. Rock toes can be installed to the depth of anticipated scour or by installing a launchable volume of rock on the channel bed at the toe of the bank (refer to Appendix E, *Hydraulics* for further information on calculating scour). In the latter case, an additional volume of rock is necessary to fill scour holes as they develop. The launchable volume should be placed at the toe of the bank as an extra thickness of rock above the channel bed. Valuable habitat has been needlessly eliminated when launched toes have been used on beds that do not scour, so it's important to be certain that launched toes are the appropriate solution for the circumstances at hand.

Rock Size

The correct size of rock should be determined by accepted riprap design methods (see design references in the discussion about *Riprap* in this chapter). Since larger rock is assumed to have greater habitat value and energy dissipation, rock toes should include rock along the toe line that is larger than that which is required to resist erosion alone. Similarly, large rock should be used when large woody debris is incorporated into the design to help secure the debris. As increasingly larger sizes of rock are incorporated, extra attention should be paid to proper bedding and granular-filter design.

Top Elevation of Rock Toe

Determination of the upper elevation of the rock toe is an important design consideration. The rock toe should be installed at least to an elevation that corresponds with the lower limit of vegetation on a streambank - the ordinary high-water mark. Alternatively, criteria may be set based on shear forces along the bank and on consideration of the ability of the upper-bank treatment to withstand these forces. Properly designed and installed rock toes can generally withstand shears of between two and four pounds per square foot for rock having a D_{50} (mean diameter) of between six inches and 12 inches, respectively. In this case, the rock toe treatment should extend to an upper elevation at which associated upper-bank treatments are able to withstand shear forces along the bank. On high-shear-stress banks, the top of the rock may have to be located higher on the bank than in streams with lower flood depth and lower slope. A method for estimating the shear distribution on banks and a list of shear resistance to various bank treatments is presented in Appendix E.

Locate the New Toe Line

The locations of property lines and structures have an influence on the location of the bank line, but the location of channel features both in and outside the reach will play a role in determining where the new toe will be placed. Natural hard points, such as large, stable trees or rock outcroppings, are natural places to begin or end the toe. Irregular toe lines increase roughness and habitat value. Smooth banks tend to increase velocity and transfer energy downstream.

Begin and end toe protection outside the area of bank erosion. An anchor point (a rock- or log-filled trench placed perpendicular to the toe and cut back into the bank) must be located at the upstream and/or downstream ends of the project to prevent flow from eroding behind the toe. The scour hole that usually appears at the downstream end of a project may be an important habitat feature. Allowing this hole to form and then protecting it is one option. Another option is to create the hole at the time of construction and place a hard point downstream to limit its extent. These scour holes are less likely to form if the toe is roughened with wood, large rock or an irregular bankline.

Bank Slope

Upper-bank slopes that are 2:1 or flatter are recommended by most riprap design references, although 1.5:1 is allowable in some cases. Steeper upper-bank slopes require the use of soil pillows or other soil-stabilization techniques. Terracing has hydraulic as well as habitat benefits and is a recommended practice. It also improves constructability. Determine the new location of the top of the bank on the basis of bank slope in reference to property lines and structures.

Filter Material

Filters are often necessary underneath and behind installed rock because they reduce the potential for piping loss of native soil materials through the rock, and they prevent the installed rock from sinking into soft native materials, while allowing water to drain through them. Additionally, when rock toes are used as the foundation for upper-bank treatments, gravel filters are necessary on top of the installed rock toe to prevent loss of upper-bank materials through the rock toe. For additional information about filters and preventing loss of bank materials, refer to the discussion in this chapter on *Subsurface Drainage Systems*.

Filter material can be either synthetic fabric or gravel material. Granular filters are composed of one or more layers of well-graded gravel. There are design specifications that depend on bank soil analysis and rock size. It should be noted that fabrics may inhibit installation of live cuttings, restrict rooting and produce a slip plane along which rock slopes can fail.

Placement of Large Woody Debris

Large woody debris placed into rock toes should be designed to withstand buoyancy and rotational forces. The debris must be well anchored into the rock to eliminate the risk of the wood's buoyancy or leverage causing the it to pull free and impact the integrity of the toe treatment. Large woody debris installed in rock toes should be positioned such that it provides cover and has the potential to collect additional debris and bed material. For further detail on placement of large woody debris and anchoring, refer to the Appendix I.

Transitions

Transition points are the places where the roughened-rock treatment meets the upstream and/or downstream streambank. Anchor points are recommended as transitions on rock toes. These are rock-filled trenches placed perpendicular to the toe and cut back into the bank. An anchor point must be located at the upstream and/or downstream ends of the project to prevent flow from eroding behind the revetment. The design references that are listed in *Table 6-1* (see the discussion about *Riprap* in this chapter), includes design methods for such transitions.

Should the biotechnical bank protection above the toe fail, the anchor points guide the flow out from behind the toe and back into the channel. Without these trenches, the river could easily scour behind the toe along its length and cause bank failure.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Rock toes are typically designed as a nondeformable toe treatment. By locking a streambank in place, rock-toe treatments result in lost-opportunity impacts for sediment supply, woody-debris recruitment and for off-channel spawning and rearing habitat. For further discussion of lost opportunity, refer to Chapter 4, *Considerations for a Solution.*

Rock toes reduce habitat potential by armoring the streambank toe and reducing variability and complexity, as well as increasing velocity. In an effort to mitigate these impacts, large woody debris can be placed within the rock toe. Additionally, it is possible to install rock toes in an irregular fashion such that the rock itself provides some degree of variability along the toe. Refer to Chapter 4 for further discussion of mitigation requirements and to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

There is no mitigation benefit provided by rock toes perse; however rock toes offer an advantage over riprap treatments in that the upper bank can be designed to provide considerable riparian habitat, cover and shade. Design of upper banks should incorporate vegetation elements and riparian buffer management to provide the maximum degree of habitat potential to the adjacent stream channel.

Beneficial techniques that should be considered and possibly included in rock-toe projects are listed below (these features mitigate for themselves):

- planting vegetation in the joints between the rocks or using vegetated riprap to restore streambank vegetation;
- creating or enhancing vegetated riparian buffer;
- setting large rock that creates large, interstitial spaces for habitat;
- placing large woody debris to create roughness, pool and cover;

- placing large boulders in the channel to create roughness and pool habitat;
- increasing overall complexity of the bank and channel through changes in plan form; and/or
- using terracing and leaving or enhancing natural features on the upper bank.

RISK

Rock-toe treatments are similar to riprap treatments in that they provide a relatively low risk to infrastructure and reliable approach to streambank protection. Their advantage over riprap is that less non-native material is required, and there is a greater potential for habitat mitigation than strict riprap offers because it allows the upper bank to be constructed using vegetation. Rock toes with large woody debris that are not designed to be submerged can, however, pose a risk to recreational boaters and swimmers.

Habitat

Rock toes generally reduce habitat potential by hardening the bank in a relatively uniform and permanent position and shape. Additionally, they eliminate the potential for the development of undercut bank habitat, further limiting complexity and diversity along the bank. This results in lost opportunity for sediment sources and recruitment of large woody debris from eroding banks and lost potential for spawning-area development due to increased velocities along the banks. For additional discussion of impacts of rock treatments on habitat, refer to Appendix K, *Literature Review of Revetments.*

Infrastructure

Rock toes are suitable for infrastructure protection if upper-bank treatments are also designed with infrastructure protection. However, rock toes may increase the likelihood of erosion in adjacent sections of the streambank (upstream and/or downstream). This may lead to increased risk to upstream and/or downstream property owners and infrastructure.

Reliability/Uncertainty of Technique

Similar to riprap, roughened-rock toes provide a reliable approach to arresting or preventing erosion. The uncertainty of this approach stems from the corresponding uncertainty associated with upper-bank treatments that may be used in concert with rock toes.

CONSTRUCTION CONSIDERATIONS

Materials Required

Materials necessary for rock toes include angular rock, filter material (fabric or gravel) and large woody debris for mitigation and habitat components. Selection of appropriate rock materials is addressed in the design references cited in this chapter under *Riprap*.

It is important to minimizing root removal and disturbance of existing riparian trees and shrubs. Both short-term and long-term impacts to wildlife can be greatly reduced by minimizing vegetation disturbance and removal. It may be possible to build a rock toe while leaving many of the riparian trees in place. The designer and contractor will likely want the trees removed to make access and rock placement easier. However, on-site trees often can be worked around, and every effort should be made to protect them. Live trees on site should not be used for instream structures. Large woody debris should be imported from off-site sources nearby.

The creation of large voids in revetments can be avoided by using well-graded rock. However, there are biological benefits to using very large rock with correspondingly large interstitial spaces. These spaces create refuge and habitat for fish and invertebrates, and they roughen the face of the riprap. There should be a layer of smaller rock behind the large surface layer to act as an intermediate filter. Avoid pounding the rock face until it becomes smooth.

Timing Considerations

Rock toes can be installed during high-flow conditions if they are placed as launchable material. However, rock toes are best constructed during low flows, when dewatering is possible. In order to install rock to the depth of scour, excavation within the channel will be necessary and, consequently, will require temporary dewatering systems. Dewatering eases installation and prevents siltation of the stream during construction. Dewatering can be accomplished with a coffer dam during low-flow conditions.

Working in a stream during critical periods in resident and anadromous fish life cycles, such as spawning or migration, should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Cost

The cost of rock toe treatments is largely dependent upon the size of the river, which impacts the size of required rock materials and site-specific dewatering costs. Rock-toe treatments may range from $20 to $40 per foot of treatment. The cost of the associated upper-bank treatment will greatly affect overall cost. Additional cost components include dewatering and site access. Costs for these elements are discussed generally in Appendix L, *Cost of Techniques* and in Appendix M.

Essential materials include rock and filter materials. Angular rock for rock toes usually must be imported from off-site locations and varies in cost according to the source and transport distance. Rock materials typically vary from $60 to $80 per cubic yard installed. Gravel filter materials range from $40 to $60 per cubic yard if they are imported. However, the price may be more affordable if local sources are available. Filter fabric may be used as an alternative to gravel filters and ranges in price from $0.50 to $3.00 per square yard.

For further discussion of costs, refer to Appendix L.

MAINTENANCE

Maintenance needs are generally minimal if rock is sized and installed properly. Maintenance is also relatively simple and rarely requires anything more than additional rock material. Vegetation and large woody debris placed in the rock toe may require replanting or repair if they are damaged. Mitigation measures may also require maintenance.

MONITORING

Monitoring rock toe treatments is limited to survey and visual inspection, including regular photo documentation. Monitoring components should include survey and inspection of the integrity of the rock-toe treatment and monitoring of the associated upper-bank treatments. The survival rate of vegetation and anchoring success of large woody debris placed in the rock toe also needs to be monitored.

Monitoring should include detailed as-built surveying, as well as photo documentation of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring*.

Rock-toe monitoring activities should focus on potential weak points in the design, such as transitions between undisturbed and treated banks, and between the rock toe and the upper bank. Monitoring should include a survey of the location and elevation of the rock toe at upstream and downstream limits and at 50-foot intervals along the treatment. The adjacent native soils above and behind the treatment may reveal collapse or sinking, indicative of piping loss or movement of rock materials. Additionally, monitoring should inspect for loss of rock-toe materials over time.

Monitoring frequency should be annual and should be conducted during low flows when visual inspection of the toe is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[3] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

1 Peters, R. 1998. Seasonal Fish Densities Near River Banks Treated with Various Stabilization Methods. First Year Report of the Flood Technical Assistance Project. U.S. Fish and Wildlife Service. December 1998.

2 USDOT. 1989. Design of Riprap Revetment. Federal Highway Administration Hydraulic Engineering Circular, No. 11

3 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

a. Roughened-Rock Toe with reinforced large woody debris and plantings. Cedar River. 1999.

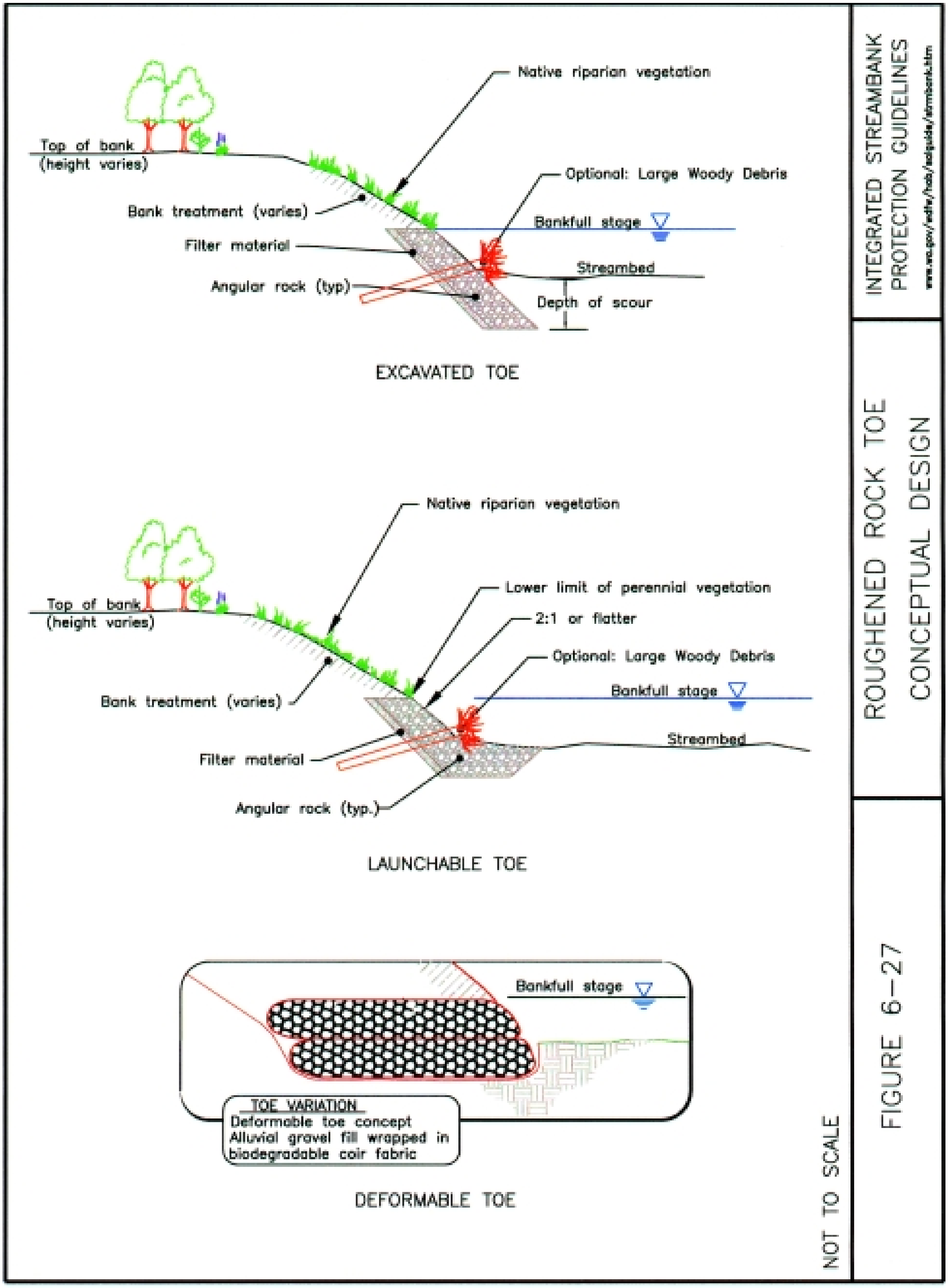
b. Roughened-Rock Toe with reinforced large woody debris, soil lifts and plantings. Nooksack River. 1999.

c. Roughened-Rock Toe with planting bench, reinforced soil lifts and plantings. Latah Creek. 2002.

d. Roughened-Rock Toe with reinforced soil lifts and plantings. Deschutes River. 1996.

e. Roughened-Rock Toe with reinforced soil lifts and plantings. Touchet River. 2000.

Figure 6-26. Various applications of roughened-rock toes throughout Washington State.



Native riparian vegetation
Top of bank
(height varies)
Optional: Large Woody Debris
Bank treatment (varies)
Bankfull stage
Filter material
Streambed
Angular rock (typ)
Depth of scour
EXCAVATED TOE
Native riparian vegetation
Lower limit of perennial vegetation
Top of bank
(height varies)
2:1 or flatter
Optional: Large Woody Debris
Bank treatment (varies)
Bankfull stage
Streambed
Filter material
Angular rock (typ.)
LAUNCHABLE TOE
Bankfull stage
TOE VARIATION
Deformable toe concept
Alluvial gravel fill wrapped in
biodegradable coir fabric
DEFORMABLE TOE
NOT TO SCALE
INTEGRATED STREAMBANK
PROTECTION GUIDELINES
ROUGHENED ROCK TOE
CONCEPTUAL DESIGN
FIGURE 6-27

Log Cribwalls
Structural Techniques

DESCRIPTION

Gravity retaining walls can be useful in stabilizing streambanks. One type of gravity retaining wall is built by constructing an elongated box out of logs and backfilling the box with soils and rock. Such retaining walls are referred to as "log cribwalls." The log box is positioned with its long sides running parallel with the channel centerline and its shorter sides perpendicular to the channel centerline. The long, parallel logs are referred to as "stretchers;" and the short, perpendicular logs are called "headers." Stretchers and headers are stacked alternately to create the cribwall. Once the log cribwall is backfilled, the gaps between the successive layers of logs can serve as planting sites to create a live cribwall. *Figure 6-28* (at the end of this technique discussion) shows various applications of log cribwalls throughout Washington State.

APPLICATION

Log cribwalls are typically applied as bank protection on steep slopes. They are often installed where: 1) floodplain encroachment has occurred, and 2) a near-vertical structure is required to protect an eroding streambank. As part of construction, the existing bank is usually excavated where the cribwall will be placed to minimize channel confinement at the site.

Log cribwalls can be useful in areas where toe erosion is the predominant mechanism of failure and where structural instability results from subsurface drainage or mass failure. Refer to the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of log cribwalls based on the mechanism of failure and causes of streambank erosion.

Log cribwalls can also be used as toe protection where a deformable channel boundary is desirable to promote long-term channel migration and to maintain geomorphic progression. However, it should be noted that log cribwalls, by their very nature, prevent deformation - an important process in maintaining stream equilibrium and contributing material for fish habitat. Since cribwalls can last for decades, this may have a considerable impact on the stream. Refer to the segment in this chapter addressing *Log Toes* for further information regarding this application.

It is important to understand the existing physical characteristics and geomorphic processes present at both the site and along the potential project's reach (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance). Log cribwalls are not recommended for use at sites where the mechanism of failure is an avulsion or local scour. Log cribwalls are also not recommended for use within aggrading or rapidly degrading reaches.

Emergency

Log cribwalls are not recommended for use as an emergency bank-protection technique because they require time to design, and construction is difficult and impractical during high-flow events.

EFFECTS

Log cribwalls can be very effective at controlling bank erosion and can provide relatively permanent protection. However, permanent protection eliminates a source of sediment supply and recruitment of large woody debris, which affects the natural balance of erosion and deposition within a channel. Also, cribwalls tend to arrest downstream meander migration, increasing bank erosion upstream and/or downstream from their placement. Because logs have a limited life span, this effect is not permanent, but it may go on for decades.

The reduced roughness characteristics of log cribwalls may also have a detrimental impact to adjacent spawning beds, cover and holding habitat. Roughness can be enhanced in the design of a log cribwall by densely planting the gaps in the cribwall and/or incorporating roughness elements such as rootwads into the cribwall's construction.

Log cribwalls also cause increased velocity and reduced complexity and diversity along the channel margin, thereby affecting habitat value, though considerably less so than riprap treatments do. The increased velocity may also cause the channel to deepen at the toe, concentrating the thalweg (deepest part of the channel) along the log cribwall bankline. These effects can be mitigated, to some degree, by incorporating rootwads or large woody debris in the treatment. The vertical nature of cribwalls make them somewhat comparable to bridge abutments, and studies have shown that vertical bridge abutments incur twice the scour that sloped abutments do. Additional scour is likely if rootwads are incorporated into a log-cribwall design due to exaggerated turbulence around them. Scour depth must be anticipated so that the log-cribwall treatment is installed deep enough not to be undermined. Therefore, scour must be accounted for in both the depth of the toe and in armoring the adjacent banks. For a more extensive discussion of the effects of log cribwalls on river morphology and aquatic habitat, see Appendix K, *Literature Review of Revetments*.

DESIGN

Design of log cribwalls includes geotechnical, structural and biological analysis. The integrity and safety of a log cribwall structure cannot be provided without specific geotechnical and structural analysis. For this reason, it is very important that qualified structural and geotechnical engineers be included as part of the design team. A conceptual design drawing is shown in *Figure 6-29*.

Geotechnical Considerations

Since a log cribwall functions as a gravity retaining wall, it should be designed in such a way as to resist sliding, overturning and bearing failure. Additional aspects that must be taken into consideration in design include: deep-seated shear, existing and proposed hydraulic conditions, transitions from the ends of the cribwall to the undisturbed streambank, backfill retention, structural integrity of the crib, plant establishment and design life. The following guidance will assist in taking these factors into account in the design phase; however, additional useful information can be found in Donald Coduto's book, *Foundation Design, Principles and Practices.*[1]

Designing *resistance to sliding* into the treatment involves calculating active and passive lateral earth pressures applied by adjacent soils and comparing them to the log cribwall's frictional resistance to sliding. The log cribwall's resistance to sliding may be improved by increasing its footprint, mass and/or inclining the log cribwall with a batter angle.

Resistance to overturning can be achieved by calculating movements applied by active and passive lateral earth pressures and comparing them to the log cribwall's ability to resist those moments. The log cribwall's ability to resist overturning may be increased by increasing its footprint and/or mass, and/or by inclining the log cribwall with a batter angle.

Underlying soils must be able to support the cribwall without settling. In other words, they must be able to *resist bearing failure*. A geotechnical analysis is suggested to determine the bearing capacity of the soil. If the soil has a low load-bearing capacity, the log cribwall's foundation soils should be replaced; a pile foundation should be driven to transmit the load to lower layers of soils, and/or its mass should be decreased.

Deep-seated shear failure refers to a rotational failure of soils behind and underneath the log cribwall. Deep-seated shear failure is a rare but catastrophic event. A geotechnical engineer will look at ways to resist deep-seated failure by first analyzing lateral earth pressures and the cribwall's resistance to sliding, overturning and bearing failure. He or she will then assess the likelihood of a global rotational failure or deep-seated shear failure. Log cribwalls are semi-flexible systems (compared to riprap, which is flexible, and concrete, which is inflexible), which may enable them to compensate for small movements behind the structure.

Hydraulic Conditions

Existing and proposed hydraulic conditions are discussed in the earlier section of this technique discussion under *Effects*. The designer should avoid the creation of channel constrictions when determining the placement for cribwalls. A scour analysis should be performed, and the log cribwall should be extended below the anticipated depth of scour. For further discussion on calculating scour, refer to Appendix E, *Hydraulics*.

Transition

Depending upon site and reach conditions, it may be necessary to create a smooth transition at the upstream and downstream ends of the log cribwall, especially if adjacent streambank soils are erodible. If a smooth transition is not created, turbulent eddies will result, and erosion may occur upstream or downstream of the cribwall. Installing a key into the banks may be necessary at the ends or the cribwall to resist flanking of the structure. For further information about keying treatments at the upstream and downstream end, refer to the discussion in this chapter regarding the technique, *Riprap*.

Backfill

A log cribwall must retain its backfill in order to maintain its integrity as a gravity retaining wall. Care must be taken to avoid loss of backfill through the gaps between logs comprising the cribwall. This may be accomplished by using a granular filter, where coarse backfill material spans the gaps along the structure's face and by using progressively finer material within the cribwall. The coarse backfill material at the structure's face should be of a quality suitable to serve as productive growing medium for live cribwalls.

Structural Integrity

The structural integrity of a log cribwall depends upon the size and strength of its log members and the method of fastening headers and stretchers together. To learn more about selecting the correct size of logs, review the American Institute of *Timber Construction's Timber Construction Manual; A Manual for Architects, Engineers, Contractors, Laminators, and Fabricators Concerned with Engineered Timber Buildings and Other Structures*.[2] Log cribwalls should be constructed using logs that retain their strength for an acceptable period of time and are resistant to rot. Cedar and spruce logs provide a relatively good resistance to rot, while soft wood, such as alder and pine, should be avoided. The use of galvanized fasteners, which include spikes and lag bolts, must be of a size large enough to withstand forces applied by internal cribwall stresses. For further information, refer to Appendix I, *Anchoring and Placement of Large Woody Debris.*

Vegetation

The greatest challenge for designing live cribwalls is providing a suitable growing medium. Cribwall backfill must be fine enough to retain moisture so that plants can grow. However, fine backfill is more likely to be washed through the gaps between cribwall members. A granular filter or biodegradable erosion-control fabrics may be used to reduce soil loss. Cribwall backfill must also have enough organic content to provide nutrients to plants placed within live cribwalls. Live cribwalls may require irrigation, and plant selection should be based upon the frequency and duration of inundation. See Appendix H, *Planting Considerations and Erosion-Control Fabrics* for more information. Woody plants placed in live cribwalls may extend the longevity of a log cribwall; as their root systems become more extensive, they can provide the stability that would otherwise be lost as log crib members rot over time.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Placing log cribwalls may require removal of existing riparian vegetation. Constructing a live cribwall serves as mitigation for this loss. Plant root structures can continue to provide bank stability after the log cribwall members decay. Additionally, planting a riparian buffer adjacent to the treatment will provide long-term erosion protection as the log cribwall eventually degrades.

Other requirements may include mitigation for lost-opportunity impacts and loss of cover, complexity and diversity. Construction impacts will also require mitigation.

Habitat loss can be partially mitigated by creating hydraulic roughness along a cribwall to provide more complex habitat. Embedding rootwads beneath or within log cribwalls can provide flow breaks and eddies that are used by fish. Rootwads can be placed beneath the cribwall with the root ball extended into the active channel. Another method to incorporate rootwads and enhanced roughness characteristics is to use them for headers in the cribwall, where root balls are extended into the active channel. For further information about design considerations for incorporation of large woody debris, refer to Appendix I. Refer to Chapter 4, *Considerations for a Solution* for further discussion of mitigation requirements and to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

A live cribwall may eventually provide shade to a stream, thus providing a water-quality benefit. Live cribwalls provide overhanging cover for enhanced fish habitat. Rootwads attached to the toe logs provide cover and interstitial flow breaks for holding habitat. Also, a log cribwall can serve as a temporary template structure for restoring natural channel processes. Log cribwalls provide interim soil stability to allow streambank vegetation to become established. Riparian vegetation provides stability after log cribwall members decay and allows natural meander migration processes to occur.

RISK

The log cribwall treatments themselves provide a relatively low risk and reliable approach to streambank protection. However, if rootwads are a component of the design, then their potential hazard to recreational users should be evaluated prior to implementation.

Habitat

A smooth cribwall may cause scour and bury spawning beds adjacent to and/or downstream of the site. Other potential risks include temporary loss of cover and holding habitat due to reduction of roughness characteristics.

Log cribwalls result in lost opportunity for sediment supply, recruitment of woody debris and off-channel spawning and rearing habitat by locking a streambank in place. Such lost opportunity will need to be mitigated. The duration of lost opportunity can be up to decades long, depending upon factors such as type of logs used in the cribwall, size of logs, duration of submersion and flow characteristics of the stream. For further discussion of lost opportunity, refer to Chapter 4.

Infrastructure

Log cribwalls depend on the strength of their wood members to reinforce soils and support steep slopes. The logs used to construct such cribwalls will eventually rot and lose their strength. Plants established within a live cribwall may or may not provide enough strength to reinforce soils as log crib members rot. For this reason, there is uncertain risk of damage to adjacent infrastructure where log cribwalls have been installed. The designer should compare the design life of the infrastructure to be protected with the anticipated design life of the log cribwall and eventual establishment of riparian vegetation. The design life of the log cribwall may be maximized by using logs that are resistant to rot, joining crib members with galvanized fasteners and planting woody vegetation within the log cribwall structure. In most cases, a properly designed log cribwall should outlast the design life of the infrastructure to be protected.

Reliability/Uncertainty of Technique

If vegetation becomes established, and rooting depth and density is sufficient to reinforce soils after log crib members rot, a live cribwall can become a semi-permanent structure. However, vegetation may die before it becomes established, or rooting depth and density may not become sufficient enough to reinforce soils before log crib members rot. This uncertainty can be minimized by planting vegetation densely and by providing it with adequate nutrients, sunlight and water. Monitoring vegetation through its establishment period is also important in minimizing uncertainty.

CONSTRUCTION CONSIDERATIONS

Materials Required

The market demand for wood products can provide challenges when trying to obtain logs for cribwalls. However, log cribwall structures do not generally require large-diameter logs; they can be constructed from logs ranging in diameter from six inches to 18 inches, depending upon strength of wood and stream hydraulics.

Sediment- and erosion-control materials, fasteners and backfill are also required for log cribwalls. Refer to Appendix I for further discussion of anchoring wood. Live cribwalls also need vegetation to be planted in them in order for them to be effective (see Appendix H). A common type of plant material used consists of riparian cuttings obtained from native, woody vegetation.

Timing Considerations

Cribwalls are best constructed during low flow, when dewatering is possible. Dewatering eases installation and prevents siltation of the stream during construction. This can be accomplished using a coffer dam during low-flow conditions.

Log cribwalls should be constructed to minimize instream disturbance. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Vegetation will have a better chance of surviving transplant to the live cribwall if cuttings are collected in the winter months when the vegetation is dormant. Typically, cribwalls are most successfully constructed in the summer months, so planning and acquisition of vegetation may need to be done well in advance of the actual construction. After the cuttings are collected, they must be kept dormant in cold storage until construction begins, or be sprouted and cared for in a nursery until they can be planted in the cribwall.

Cost

Construction of log cribwalls involves excavation, installation of the crib structure, backfilling and installation of vegetation. Typical costs range from $250 to $350 per foot of bank protected. Costs are greatly affected by availability of log materials, labor rates, and dewatering needs. Logs used for cribwall construction must be relatively straight and comparable in diameter. Refer to Appendix L, *Cost of Techniques* for further discussion of costs associated with materials acquisition and site dewatering.

MAINTENANCE

Maintenance may include repairing log members and anchors, or looking after the vegetation in the structure. Establishment of vegetation may require irrigation during the first-year growing season. Maintenance of live cribwalls should also include replacing dead vegetation if it is an integral part of the cribwall's structural integrity.

MONITORING

Monitoring of log cribwall treatments should include survey and inspection of the integrity of the log-cribwall structure and associated vegetation components. Monitoring should also include detailed, as-built surveying and photo documentation of the project area, and upstream and downstream reaches to evaluate design performance. Details on how to develop a monitoring plan are discussed in Appendix J, *Monitoring*.

Survey and visual inspection, as well as photo documentation, should focus on:

- scour at the toe of the cribwall structure,
- subsidence of backfilled soils,
- plant-growth progress,
- evidence of erosion adjacent to the log cribwall,
- potential weak points in the design (such as transitions between treated banks and undisturbed upstream and downstream banks),
- location and elevation of key log members at 50-foot intervals along the treatment and at upstream and downstream limits,
- sagging or movement of log members,
- loss of logs, and
- deterioration of logs.

Monitoring frequency should be annual for at least the first five years (or the anticipated design life of the structure if less than five years) and conducted during low flows when visual inspection of the toe of the structure is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J.

For a comprehensive review of habitat monitoring protocols, refer to Johnson, et al.[3] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

1 Coduto, D. P., 1994. Foundation Design, Principles and Practices. Englewood Cliffs, NJ. Prentice Hall, Inc., pp. 704-721.

2 American Institute of Timber Construction, Timber Construction Manual; A Manual for Architects, Engineers, Contractors, Laminators, and Fabricators Concerned with Engineered Timber Buildings and Other Structures, New York, Wiley, 1974.

3 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

a. Log Cribwall during construction. Columbia River.
Source: Inter-Fluve, Inc.

b. Log Cribwall. Fanno Creek, OR.
Source: Inter-Fluve, Inc.

Figure 6-28. Examples of log cribwalls throughout Washington State.

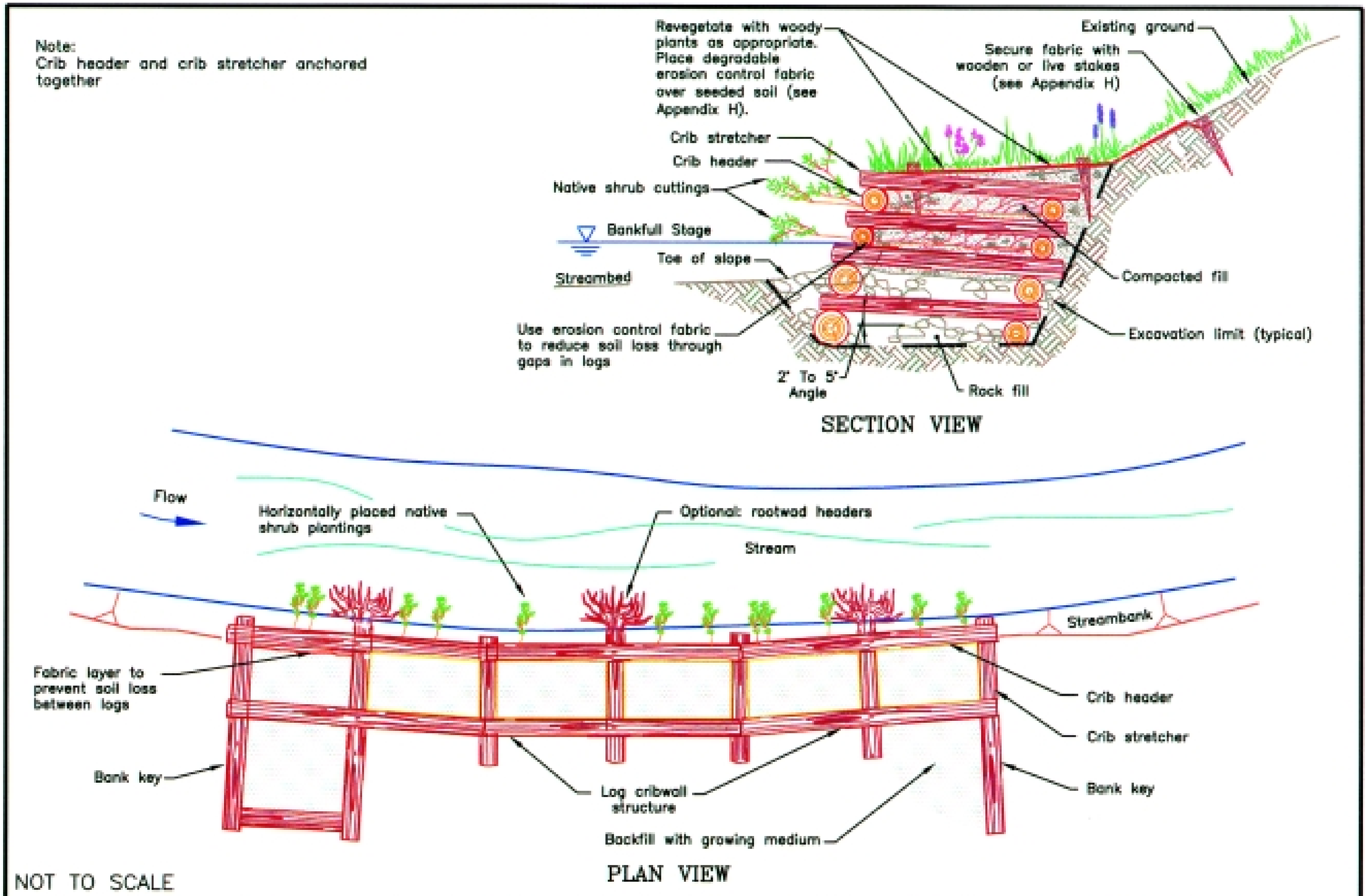


FIGURE 6–29

LOG CRIBWALL CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES
www.wa.gov/wdfw/hab/ahg/strmbank.htm

DESCRIPTION

Manufactured retention systems can be used to stabilize channel banks and beds. There are a large variety of systems available, with more appearing on the market each year. For the purposes of discussion, these retention systems are classified into two categories, based on material type: two-dimensional and three-dimensional. Two-dimensional retention systems provide relatively thin, skin-like protection to bank surfaces and include a variety of fabrics, reinforcement mats and geogrids. Three-dimensional retention systems provide a relatively thick, durable outer layer and include articulated concrete blocks, geocellular containment systems, concrete armor units and wire-mesh walls.[1] Systems within these categories (except wire-mesh walls, which will be discussed in future editions of these guidelines) are briefly described below (the Washington Department of Fish and Wildlife does not recommend or endorse any one product or trade name). *Figure 6-30* (at the end of this technique dicussion) shows applications of these systems.

Two-Dimensional Retention Systems

Fabrics and Reinforcement Mats

Fabrics and reinforcement mats are mainly used as temporary surface protection to lend tensile strength and shear resistance and to retain soil particles on the surfaces of streambanks and floodplain areas until vegetation gets established. These products come in biodegradable, nonbiodegradable and composite (semi-biodegradable) form. Biodegradable materials used in fabric and mat construction commonly include coir (coconut fiber), jute, straw and cotton mesh. Nonbiodegradable fabrics and mats are generally constructed of UV-stabilized synthetic fibers, such as polypropylene, Tensar or nylon.

The difference between fabrics and reinforcement mats can be subtle and somewhat subjective. Fabrics are woven materials of marginal thickness used as an outer "skin" atop the soil surface. Most fabrics are sufficiently porous to allow vegetation to readily establish through them. Reinforcement mats typically are thicker and more porous than fabrics and are usually not woven. Reinforcement mats are intended to become an integral component of the slope surface. In fact, soil is often installed on top of mats and worked into the voids within the mats to facilitate incorporation into the seeded turf.

Fabrics and reinforcement mats are available in a variety of materials, configurations, strengths and levels of biodegradability. Available products range from light-duty, completely biodegradable, erosion-control blankets of straw and cotton mesh to very-heavy-duty reinforcement mats constructed of nonbiodegradable, UV-stabilized polypropylene. The most durable of such products can be used as a long-lasting alternative to riprap. The least durable serve only as temporary protection against surface erosion caused by rainfall.

Geogrids

Geogrids are grids made of a UV-stable, high-strength, synthetic material. Originally developed for use as an internal-stabilization tool for embankments, geogrids are also used to impart tensile strength to the surface of constructed streambanks and other instream structures. To provide internal stabilization to embankments and streambanks, the geogrid is usually laid horizontally in the bank materials to protect against translational and rotational slope failure. As a surface treatment, geogrid is used to encapsulate soil and/or rock on the bank surface. Geogrid offers a very durable and high-strength skin to the constructed bank. Its porous construction also allows vegetation to establish itself. Because the holes in geogrid are relatively large, an inner layer of fabric or reinforcement mat should be used to prevent soil loss.

Three-Dimensional Retention Systems

Articulated Concrete Blocks

Articulated concrete blocks are precast concrete blocks held together by interlocking edges, steel or synthetic fiber cables, or a combination of the two. There are currently a variety of these products available that are well suited for a wide range of applications. The heavy-duty blocks are over nine inches thick, have no holes within the blocks for vegetation and are held together with steel or synthetic fiber cables. Lighter-duty blocks are also held together by cables, but have holes for inter-planting of vegetation. The lightest-duty blocks are held together solely by their interlocking edges and are available with or without holes for vegetation.

Articulated concrete blocks represent a flexible and very durable bank treatment similar to riprap. Like riprap, articulated concrete blocks generally require a filter layer of granular material, filter fabric or both, placed between the block layer and underlying native soil. As in the case of riprap, these blocks offer very little aquatic or terrestrial habitat, although holes in most types of blocks allow for the installation of soil and vegetation. Common locations where articulated concrete blocks have been used successfully are under bridges for slope protection to protect abutments.

Geocellular Containment Systems

Geocellular containment systems are honeycomb-like cellular materials that stabilize the upper layer of soil, while allowing installation of soil and vegetation. Usually manufactured of polyethylene or polyester strips, the thin-walled cells can be up to 20 centimeters (about eight inches) deep.[1] Because the walls of the geocellular "honeycomb" are relatively thin, vegetation and soil make up the vast majority of geocell volume.

Geocellular containment systems provide substantial structural support to the bank face, while allowing vegetation to establish almost unimpeded. On gently sloping banks, geocellular containment systems can be installed directly on the bank slope, at the same grade as the bank face. On steeper banks, the geocellular containment system can be installed in a stair-step fashion for greater stability. To further increase slope stability, an internal drain of granular material and filter fabric are often installed beneath the geocellular containment systems.

Concrete Armor Units

Concrete armor units include a wide variety of three-dimensional products constructed of reinforced concrete. They are typically installed as a layer on streambanks and around bridge abutments. Originally designed for use in coastal engineering, these structures have been used in river engineering to provide scour protection near structures, toe protection for banks, and barbs. Concrete armor units are available in a number of configurations under such product names as Doloes, Toskanes and A-Jacks®. They range in size from relatively small, hand-installed A-Jacks® to eight-ton Doloes. Some products, such as A-Jacks®, are available in a variety of sizes.

Reinforced Wire Wall

Manufactured retention systems can be used to stabilize channel banks and beds. There are a large variety of systems available, with more appearing on the market each year. For the purposes of discussion, these retention systems are classified into two categories, based on material type: two-dimensional and three-dimensional. Two-dimensional retention systems provide relatively thin, skin-like protection to bank surfaces and include a variety of fabrics, reinforcement mats and geogrids. Three-dimensional retention systems provide a relatively thick, durable outer layer and include articulated concrete blocks, geocellular containment systems, concrete armor units, and reinforced wire walls.[1] Systems within these categories are briefly described in the next section (the Washington Department of Fish and Wildlife does not recommend or endorse any one product or trade name). Reinforced wire walls are not described in this edition of the guidelines but will be in the next edition.

APPLICATION

Manufactured retention systems are appropriate for sites where the mechanism of failure is mass failure or subsurface entrainment. They are also appropriate for armoring against all types of scour if applied landward of the scour hole. Artificial materials and systems are not appropriate for sites where there exists the potential for an avulsion or for meander migration within the channel migration zone. They are also not appropriate for toe erosion caused by a reduced-vegetative bank structure or a smoothed channel.

Refer to Chapters 2, *Site Assessment* and 3, *Reach Assessment* for further discussion of site and reach limitations, and to Chapter 5, *Identify and Select Solutions* for further discussion of appropriate selection of protection techniques.

Fabrics and Reinforcement Mats

Fabrics and reinforcement mats are typically used where the stream flow is relatively low in energy and there is a good revegetation potential. Biodegradable materials typically provide temporary support for three to five years. Most stream and river banks (at least the upper portions) meet these criteria. Fabrics and reinforcement mats should not be used below the line of perennial vegetation nor anywhere that conditions such as hydraulic forces or shade are likely to preclude dense vegetation growth.

For more information on fabric and reinforcement mat installation, refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics*.

Geogrid

There are two common uses for geogrid in streambank construction. Geogrid is sometimes used like a fabric or reinforcement mat in lift construction (see the discussion in this chapter on *Soil Reinforcement*). Used as such, geogrid provides a highly durable, high tensile-strength outer layer that allows for vegetation growth. Geogrid is more widely used to provide internal stability to slopes and embankments. In this capacity, geogrid protects against translational and rotational slope failure.

Articulated Concrete Blocks

Articulated concrete blocks are usually used where stream flow is high-energy and where bank failure is not acceptable, such as under bridge abutments. Typically, blocks without holes are used below the line of perennial vegetation. Above that line, blocks with holes that allow planting are recommended. The articulated-concrete-block revetment system usually requires a filtering under layer to prevent fine bank material from migrating into the block layer, a situation that can threaten bank stability. Articulated-concrete-block revetment typically results in an extremely uniform bank surface, a factor that should be considered when habitat and aesthetic values are important. In addition, the smooth surface of revetment will result in relatively high velocities along the streambank.

Geocellular Containment Systems

Geocellular containment systems are suitable for use in low- to medium-energy-flow situations. On gently sloping streambanks, the cellular systems can be laid at the grade of the bank, staked and filled with soil, and seeded. On steeper banks, the cellular systems can be laid in the horizontal plane and stepped to produce a relatively steep bank. Including a fabric outer layer helps retain soil in the individual cells. Such stepped cellular systems have been used in conjunction with geogrid to stabilize relatively high, steep banks under rapid drawdown situations.

Concrete Armor Units

Concrete armor units have been successfully used to stabilize eroding banks, to counteract scour at bridge piers and abutments, and to construct barbs and groins. In addition, concrete armor units can be used to anchor log jams. As components of bank protection, concrete armor units create a large amount of void space, which may be useful as aquatic and terrestrial habitat. In addition, groins constructed of these units tend to be very effective collectors of woody debris.

For the majority of materials discussed in this section, vegetation provides some or all of the long-term strength. Vegetation stabilizes bank surfaces in a variety of ways: roots provide deep and shallow stability to the bank soil, protecting against surface erosion and slope failure; and stems and leaves provide roughness to protect the bank surface from runoff above the water line at low flows. At higher flows, stems and leaves also create a low-velocity boundary layer near the bank surface. Because dense vegetation is a desirable (and sometimes required) component of most manufactured retention systems, these systems are generally applicable only to the zone lying above the line of perennial vegetation growth. Exceptions to this generalization include articulated concrete blocks and concrete armor units, which do not rely on vegetation for their function.

Bank protection below the line of perennial-vegetation growth requires materials and techniques that retain their long-term viability independent of vegetation cover. This lower portion of the bank is typically referred to as the bank toe. Materials commonly used to construct the bank toe include rock; coir log; gravel-filled, reinforced lift; and wood. Less-common materials include articulated concrete blocks and concrete armor units. A common bank-treatment strategy involves combining a constructed bank toe with an upper bank that is reinforced with fabric, reinforcement mat, or similar materials. This strategy provides durable protection against scour at the bank toe, coupled with readily vegetated upper-bank surfaces.

VARIATIONS

All of the manufactured retention systems discussed in this section can be combined to address specific situations. For instance, a composite bank treatment might include an articulated-concrete-block bank toe, a midbank of stepped geocellular materials and an upper bank of fabric-encapsulated soil.

It is highly recommended that vegetation be incorporated into all bank revetment designs. Proven revegetation strategies include seeding, sod installation, willow cutting installation and planting of container-grown plants. Planted vegetation should always be native species.

EMERGENCY

With one exception, installation of the manufactured retention systems discussed in this section require dewatered conditions. Additionally, installation tends to be relatively labor-intensive and time-consuming. For these reasons, the manufactured retention systems discussed in this section are not particularly suitable for emergency installation. The exception, concrete armor units, can be installed under somewhat adverse conditions. However, unlike emergency bank-protection measures that do not require precision (such as riprap, which can simply be dumped into place), concrete armor units must be set in place one-by-one using a crane or excavator.

COMPONENTS

Manufactured retention systems typically contain some or all of the following components: outer layer, under layer, securing system and internal slope support. In addition, vegetation lends strength to some systems and habitat/aesthetic value to others.

Outer layer

Outer-layer materials include fabrics, retention mats, geogrid, geocellular containment systems, articulated concrete blocks or concrete armor units. The outer layer is in direct contact with the stream flow and is, therefore, subjected to direct hydraulic forces as well as vibration, abrasion and debris impact. In the case of fabrics, retention mats and geogrid, the tensile strength of the outer layer often contributes to slope stability. The outer layer should, therefore, be selected and designed to withstand all anticipated shear forces in accordance with the project-design criteria.

Under layer

Depending upon the nature of the outer layer, the under layer may provide filtration of fine particles, drainage or growth medium. Fabrics, retention mats and geogrid (when used as a surface treatment) typically require an under layer of soil to support vegetation growth. In geocellular containment systems, the soil can be considered to be an integral part of the outer layer.

Articulated concrete blocks and concrete armor units generally require a filtering under layer to prevent the migration of fine particles from the underlying streambank soil. If not properly addressed, this migration of fine particles can lead to the formation of voids in the underlying soil, which may destabilize the bank.

Streambanks that are relatively high, steep, composed of poorly draining soils or any combination therein often require a subsurface drainage system. Subsurface drains are typically composed of granular material such as crushed gravel, but can also be constructed of synthetic drain materials or a combination of natural and synthetic materials (see the discussion in this chapter addressing *Subsurface Drainage Systems* for additional information). The draining under layer relieves soil-pore pressure within the bank, improving bank stability. This is particularly important when banks are high, steep or subject to rapid drawdown. In practice, a draining under layer can usually be designed to serve as a filtering under layer as well.

Securing System

With the exception of concrete armor units, all materials described in this section must be secured to the bank surface. Since edges and joints between materials are potential weak points, proper design of the overlap and anchoring system is critical to revetment integrity.

Fabrics, retention mats, geogrid and geocellular containment systems are typically secured by staking. However, vegetation can provide additional anchoring strength. Often, 24-inch-long wood stakes are used in conjunction with key trenches to form a stronger anchor. Articulated concrete blocks are usually secured by trenching and cabling them to deadmen along the outer edge of the revetment.

Internal Slope Support

Occasionally, special precautions must be made to ensure internal stability of streambanks. As is the case for subsurface drainage systems, internal supports are generally needed for banks that are high, steep, poorly-drained, or any combination therein. Two commonly used methods of internal support include geogrid and geocellular containment systems. When used in a "stepped" configuration, geocellular containment systems lend support to the outer portion of the bank. Geogrid is commonly used to provide deeper internal slope support. Geogrid has become popular for use in the stabilization of hill slopes and embankments along highways.

Vegetation

Vegetation contributes habitat value, aesthetic appeal and strength to bank surfaces. Some retention systems, such as articulated concrete blocks and concrete armor units, employ vegetation strictly for habitat and aesthetic values. Other systems, such as geocellular containment systems and nonbiodegradable retention mats, employ vegetation to bolster long-term resistance to erosion. Systems constructed of biodegradable materials typically rely entirely on vegetation to provide long-term slope stability and resistance to erosion.

EFFECTS

Effects vary according to the combinations of manufactured retention systems employed and by the efforts taken to create aquatic and terrestrial habitat. Systems discussed in this section can be used to construct uniform banks offering little habitat value of any kind, more natural-looking streambanks that are heavily vegetated with native riparian plants or any variation in between.

Generally, biodegradable, two-dimensional systems offer the greatest potential for promoting habitat value and minimizing mitigation requirements. Deformable bank treatments generally incorporate these materials. Conversely, nondegradeable, three-dimensional materials eliminate the opportunity for sediment and large-woody-debris recruitment, will require significant mitigation and should, therefore, only be used where relatively permanent and nondeformable protection is needed.

DESIGN

Engineering analysis for streambank design requires examining hydraulic forces, slope stability and filtration and drainage concerns. Determination of hydraulic forces typically involves using Manning's equation (see Appendix D, *Hydrology*) to estimate parameters, such as channel depth, velocity and wetted perimeter. From these parameters, shear is calculated. Factors such as the increase in shear and velocity on the outside of bends should always be considered in the hydraulic analysis (see Appendix D and Appendix E, *Hydraulics*). Available design guidelines from manufacturers of retention materials should be consulted for specific design criteria.

The correct choice of manufactured retention systems depends upon the circumstances of the site and project, including :

- project objectives;
- acceptable risk of failure;
- acceptable types of materials (e.g., biodegradable vs. nonbiodegradable);
- magnitude of hydraulic forces at the site;
- soils and slope stability concerns; and
- potential for vegetation to establish.

The choice of materials, their grade or weight, and their securing system are typically based on anticipated velocity and shear. Most manufacturers of retention systems offer material testing results and durability information for use as design guidelines. When using these systems, the designer should consider the conditions under which the tests were performed. For instance, materials are often tested for shear resistance over relatively brief time periods, whereas the same materials in an actual bank revetment may be subjected to prolonged exposure to shear on a yearly basis. The designer should consider using a factor of safety of 1.5 to 2.5.

Filter

Methods for determining the need for and design of a filtering under layer are presented in most riprap-design manuals. Refer to the discussion in this chapter entitled, *Riprap* for additional information and sources of information about filter materials. In addition, most manufacturers of articulated concrete block units provide guidelines for filter-layer design.

Vegetation

In general it is recommended that manufactured retention systems be revegetated aggressively. In addition to providing critical strength to some retention systems, vegetation provides terrestrial habitat as well as shade, overhanging cover and nutrient input to the adjacent stream or river. Revegetation can be accomplished by installing seed, sod, cuttings and container-grown or transplanted plants. Refer to Appendix H for more information on revegetation and erosion control.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Application of manufactured retention can range from relatively barren, uniform streambanks to heavily vegetated, natural-looking streambanks. An aggressive revegetation effort is required for banks constructed of manufactured retention materials. If revegetation is thorough and successful, most of the materials and techniques presented in this section will result in banks requiring no mitigation for riparian habitat. However, any bank treatment constructed as nondeformable will likely require mitigation for lost opportunity, riparian function, cover, spawning, complexity and diversity, construction, and flood refuge.

The heavier bank treatments, which include articulated concrete blocks and concrete armor units, are the most likely to require mitigation for habitat loss and opportunity lost for sediment and large-woody-debris recruitment. On-site mitigation strategies such as extensive planting (including installation of cuttings amongst concrete armor units) can be used to hide these concrete treatments from view and provide terrestrial habitat. In addition, large woody debris can be added to these treatments (see Appendix I, *Anchoring and Placement of Large Woody Debris*). Due to the limitations of on-site mitigation for articulated-concrete-block and concrete-armor-unit revetments, off-site mitigation may be required. Refer to Chapter 4, *Considerations for a Solution* for further discussion of mitigation requirements and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

No mitigation benefits are provided by these techniques.

RISK

Habitat

With proper application, manufactured retention systems can provide terrestrial habitat in the region of the banks lying above the line of perennial vegetation. However, risks to habitat are present. For instance, a uniform bank toe offers poor aquatic habitat and increases velocities, which, in turn, limits spawning potential. Additionally, inadequate or unsuccessful revegetation efforts can result in poor upper-bank habitat; this is particularly likely with articulated-concrete-block or concrete-armor-unit revetments.

The risk to aquatic habitat along the bank toe can be minimized by installation of large woody debris as a component of the bank toe (see Appendix I). The risk of creating inadequate upper-bank habitat can be minimized by a well-planned and well-carried-out revegetation plan, by replanting as necessary and by avoiding the use of articulated concrete blocks and concrete armor units as upper-bank treatment wherever possible.

Infrastructure

The improper use of manufactured retention systems, or their use at an inappropriate location, could lead to bank failure that results in damage to infrastructure. However, the application of harder, three-dimensional treatments can reduce risk to adjacent infrastructure.

Reliability/Uncertainty of Technique

In general, the application of manufactured retention materials and systems carries a higher level of uncertainty than traditional bank treatments like riprap. This is primarily due to the relative complexity of the systems, uncertainties regarding in-situ material strength and longevity, and the reliance of many systems on relatively rapid and dense vegetation establishment. Nonetheless, when used properly, manufactured retention materials and systems have been effective.

CONSTRUCTION CONSIDERATIONS

Materials Required

The various materials and applications presented within the category of *Manufactured Retention Systems* will require a respective variety of construction considerations. However, installation of all of these materials and systems will require consideration of access to the site for equipment and materials. Further information on access and dewatering is provided in Appendix M, *Construction Considerations*.

Timing Considerations

Timing is an important factor in the installation of manufactured retention systems. Installation is generally a labor- and time-intensive process requiring favorable weather conditions. Because some of these methods are installed below the water line and may require excavation and turbidity control, dewatering will be required. Manufactured retention systems are best constructed during low-flow conditions, when dewatering is possible and when resident and anadromous fish are less likely to be impacted by construction activities. In order to install materials to the depth of scour, excavation within the channel bed will be necessary, which will also require temporary dewatering. Dewatering allows for ease of installation and prevents siltation of the stream during construction. This can be accomplished with a coffer dam during low-flow conditions.

Critical periods in salmonid life cycles, such as spawning or migration, should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can be found in Appendix M.

In addition, planting success can be highly dependent upon the time of the year that the seed, cuttings or rooted-plant stock is installed. For this reason, installation of cuttings or rooted plants may need to be delayed until the most favorable planting season.

Cost

The cost of these techniques and systems is highly variable and depends upon the materials selected, bank height, dewatering methods selected and site-specific construction factors. Artificial streambank-protection systems, however, are usually selected over other techniques when the cost of more traditional techniques and materials are too high (due to availability or accessibility limitations), or when site limitations dictate alternative methods and materials. Furthermore, manufactured retention systems normally require considerably greater labor to install. As such, the cost of these techniques is typically much greater than more traditional techniques and often exceeds $100 per foot of bank protected.

For further discussion of construction costs, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

Maintenance requirements of manufactured systems depend upon the type of materials selected and the form of protection they provide. Monitoring will reveal maintenance needs, which may include repair or replacement of materials members or retention systems. As many of these systems have integrated members, loss or movement of a single unit may substantially jeopardize integrity of other units or members.

MONITORING

Monitoring Manufactured retention systems should involve survey and visual inspection, including periodic photo documentation. Monitoring should include detailed as-built surveying and photo documentation of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Details on development of a monitoring plan are discussed in Appendix J, *Monitoring*.

Monitoring activities should focus on potential weak points in the design, such as transitions between treated banks and undisturbed upstream and downstream banks. Surveying should measure displacement of materials, particularly those connected to other materials. Monitoring frequency should be annual for a minimum of five years, or the anticipated design life of the structure, and conducted during low flows, when visual inspection of the toe of the bank is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[2] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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1 Grey, D. H. and Sotir, R. B. 1996. Biotechnical and Soil Bioengineering Slope Stabilization. John Wiley & Sons. New York.

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a. Manufactured Retention System. Salmon Creek, Tributary to Columbia River. 2002.

b. Temporary Manufactured Retention System using fabric mat. Salmon Creek, Tributary to the Columbia River. Source: Clark County Public Utilities.

Figure 6-30. Applications of manufactured retention systems.

Woody Plantings

Biotechnical Techniques

DESCRIPTION

The placement of woody plantings is a bank-stabilization technique that relies on installed trees and shrubs to stabilize eroding banks, provide habitat benefits and improve aesthetics. The most commonly used type of woody plantings are live cuttings, especially those from willows, because of their ability to root well from locally collected, dormant cuttings and to colonize bare, alluvial deposits. Other woody plant materials, including containerized plants, bare-root stock and salvaged plants, are also commonly used. Ball-and-burlap materials are of limited use on streambanks; but, if budget allows, they can be useful on less frequently flooded upper floodplains. *Figure 6-31* shows various applications of woody plantings (at the end of this technique discussion).

This technique makes use of strong, relatively deep roots (up to several feet) that provide excellent soil-reinforcement capabilities, especially when plants are mature. Above-ground shoots and stems also help prevent surface erosion, encourage deposition and provide overhanging vegetation cover along streambanks. The varied heights of vegetation within a mixed-species riparian zone provides a variety of wildlife habitat in terms of cover and food sources and ultimately will provide large, woody material for recruitment.

Woody plantings are also referred to as pole plantings, willow plantings, tree plantings, shrub plantings and riparian revegetation.

APPLICATION

Woody plantings can be effectively applied on a reach of degraded streambank characterized by toe erosion, marginal vegetative cover, and a relatively wide and shallow channel cross section. A woody-planting treatment may involve minor regrading or bank reshaping, but the bulk of the work is accomplished by planting suitable, native, woody species on the streambanks. With the proper techniques, woody plantings can be applied to banks with 2:1 slopes or shallower.[1,2]

Woody plantings are also a suitable treatment for controlling meander migration within a migration zone and at the edge of a migration zone, as long as toe erosion is the mechanism of failure. Aggrading reaches are also good candidates for woody plantings because of the colonizing ability of willows and other desirable, native riparian trees and shrubs. Woody plantings, especially in the case of low-growing willows, form dense stands of vegetation that reduce local velocities and offer root reinforcement, so they can also be used on floodplains to reduce the potential for channel avulsion (see the mechanism-of-failure discussion in Chapter 2, *Site Assessment*).

Although limited data are available on the erosion resistance of woody plantings, H. M. Sheicthl and R. Stern report that dense willow plantings (three to four years after planting) can provide erosion protection equivalent to that provided by riprap comprised of "large quarry stone."[3] While such data need to be viewed cautiously, they do suggest the potential of woody plantings as successful erosion-control mechanisms.

Refer to Chapter 2 and Chapter 3, *Reach Assessment* for further discussion of site and reach limitations and to Chapter 5, *Identify and Select Solutions* for information about how to select the most suitable bank-protection techniques.

As a stand-alone method of bank protection, woody plantings can provide excellent long-term benefits, on a streambank that has a relatively stable toe but has poor vegetative cover and possibly some surficial erosion or modest reach-based aggradation. Unless they are integrated with toe protection such as rock, log or coir-log toes, woody plantings are not appropriate where toe erosion is occurring. However, if used in combination with other bank-protection and erosion-control techniques, such as toe protection, herbaceous plantings and/or erosion-control fabric, woody plantings can provide immediate protection against surface erosion and toe scour.

Woody plantings are generally not the best choice of treatment in systems that are degrading because vegetation cannot control channel incision or downcutting (see Chapter 3).

Variations

Woody plantings include a wide variety of tree and shrub species, plant-material types, plant-material sizes and planting configurations. The length, diameter and age of live cuttings used in woody-planting bank treatment may vary extensively. Rows of cuttings may be oriented parallel or perpendicular to stream flow, placed horizontally or vertically, planted in clumps or on linear planting grids, and planted at shallow or deep depths.

Woody plantings may be used in conjunction with toe-stabilization techniques such as a roughened-rock toe or coir-log. Riparian shrubs and trees can also be incorporated into riprap, fabric-covered slopes and other forms of bank protection, and they are a major component of bioengineered techniques such as soil reinforcement. Several traditional types of bioengineered bank protection that are common variations of live cuttings are briefly described below. For a more thorough discussion of these and other bioengineering techniques, refer to the following texts: Biotechnical Slope Protection and Erosion Control;[4] Guidelines for Bank Stabilization Projects in the Riverine Environments of King County;[5] Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection;[3] and Streambank and Shoreline Protection, NRCS Engineering Field Manual.[2]

Live Stakes. Live staking, also called sprigging or willow staking, involves the insertion and tamping of live, unrooted vegetative cuttings into the ground.[2] Live stakes are a quick, inexpensive and effective means of securing a vegetative cover for control of soil erosion and shallow.[4] They can also be used to stake down and enhance the performance of erosion-control fabric and other soil-bioengineering techniques (e.g., fascines or brush mattresses) or to stabilize bare sections of slope between other soil-bioengineering techniques.[2] 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.[2] Note that, when live stakes are used alone, these desired effects do not commence until after vegetation establishment (at least one growing season).[3] Live stakes can be interplanted with rooted stock.

Cuttings used for live-stake applications should be unbranched, one- to several-year-old shoots of shrub and tree species.[6] Willow and cottonwood species are most commonly used, but other species may be suitable.[7] Cuttings for live stakes must be from a species with large, sturdy stems that can root readily and easily in a field setting. One- to two-inch-diameter cuttings are recommended,[5] but cuttings as small as 1/2 inch diameter may be used if cutting stock is sturdy enough to be pushed or driven into the soil without damage. Species with long, straight stems are much easier to cut and drive than those with crooked stems.[4] Recommended cutting length varies with site conditions. Cuttings two to three feet in length are commonly used at sites where the soil is moist. Longer cuttings are required at sites where the soil is dry in order to reach deep water tables. Longer cuttings may also be preferable when live stakes are being used to secure another bioengineering treatment to the bank. Side branches should be cleanly removed and the basal ends of cuttings should be pointed to facilitate driving them into the ground.

Live stakes can be pushed into the bank by hand or driven into the bank with a dead-blow hammer (i.e., a hammer with the head filled with shot or sand). In dense soil, it may be necessary to prepare pilot planting holes with a metal rod (such as rebar), auger or other specialized device, some of which are described in this section under *Construction Considerations*. The diameter of the pilot hole should be slightly smaller than the cutting to ensure a snug fit between the cutting and the soil. Cuttings should be placed in a random pattern at a density of two to five cuttings per square yard.[2, 3, 5] It is recommended that cuttings protrude above ground a maximum of one-fifth to one-fourth of their length to minimize water loss due to transpiration and to lessen the problem of root breakage caused by relative movement between the cutting and the ground.[2, 3, 4] Refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for additional information.

"Joint planting" is the term commonly used when live stakes are driven into joints or openings in rock revetments. The vegetation works in conjunction with rock to provide benefits to the bank and stream offered by both forms of bank treatment. Root systems provided by live stakes bind or reinforce the soil and prevent washout of fines between and below the rock.[4] They also improve drainage on the slope by removing soil moisture. Above-ground portions of the plants offer shade and cover and dissipate some of the energy along the streambank. However, the addition of vegetation to the riprap matrix does not mitigate for all the negative impacts that the use of rock imparts to the stream.

Cuttings used in joint-planting treatments often need to be longer than those planted in unarmored banks; the minimum length depends on the thickness of the riprap. The basal ends of cuttings must extend into the backfill or undisturbed soil behind the riprap. Burying 4/5 of the length of the stake is optimal;[5] no less than 1/2 of the length is recommended. To prevent desiccation, it is important not to have a long length of stake exposed. Joint planting is more labor-intensive than ordinary live staking; and plant survival may be less than other planting techniques, especially in thick, riprap-revetment applications. Tools such as the *stinger* (described in this technique discussion under *Construction Considerations*) can make planting in riprap easier.

Cutting survival may be low in thick riprap unless soil is incorporated into the riprap matrix. Prior to cutting installation, dirty, pit-run gravel or soil with substantial clay content can be machine-placed over rock and pressed into the rock with a backhoe or excavator bucket. Clay soil is less likely to scour during high flows and holds moisture better than a sandy or silty soil. Following cutting installation (but prior to placement of seed or mulch), a tanker truck with a hose can be used to wash soil into the crevices and voids of the riprap to ensure good soil-to-cutting contact. Some engineers have expressed concern that inclusion of soil in riprap or the loss of vegetation that has been incorporated in riprap can reduce the structural integrity of the riprap. Engineers in British Columbia addressed this concern on the banks of the Frasier River by creating designated planting areas within the revetment. These planting areas consist of rebar frames in the shape of long tubes approximately 18 inches in diameter that extend from the riprap surface into the underlying soil. Each tube was lined with filter fabric and filled with soil suitable for plant growth. Cuttings were then planted inside each tube, with their basal ends extending deep into the underlying soil.

Brush Layering. This technique, also known as "branch packing," consists of dense rows of live cuttings, branches and/or rooted stock between layers of compacted soil. Individual layers are generally aligned horizontally or along the contour of the slope. Cuttings extend back into the bank and protrude slightly from the soil surface. As such, they immediately provide shallow soil reinforcement and protection from surface erosion, and they rapidly establish a vegetated streambank.[2, 3, 5] Bank stabilization is achieved by breaking up the bank into a series of smaller, vegetated slopes that dissipate energy, physically bind the soil within the root zone and promote the entrapment of sediment and debris. As cuttings are deeply covered in soil, there is little chance of them being uprooted during flood flows.[3]

Brush layers are particularly applicable in bank-protection projects that require fill. They are less commonly used on eroded slopes where excavation is required to install the cuttings. Brush layers can be used as a rehabilitation measure for seriously eroded and barren slopes and where patches of streambank have been scoured out or have slumped leaving a void. However, they are typically not effective in slump areas greater than four feet deep or four feet high. They are most effective once the stress causing the slump has been reduced or eliminated.[2]

Individual brush layers should be four to six inches thick and be comprised of rooted stock, branches, or cuttings 1/2 to two inches in diameter, and three feet minimum in length. Cuttings should be 20- to 25-percent longer than the depth of the terrace onto which they are placed. Place them in a random, crisscross pattern (not parallel to each other) to maximize their contact with soil and, thus, their rooting capability.[4] Recommended planting density varies from two[4] to six[3] branches per linear foot. As long as there is a sufficient percentage of live cuttings capable of propagation spread uniformly throughout the treatment, dead branches may be incorporated into the brush layers.[3] Recommended vertical spacing between brush layers ranges from three to eight feet, depending upon the erosion potential of the slope (i.e., soil type, rainfall, stream velocities, and length and slope of the bank).[4] A minimum spacing of one foot is recommended on fill slopes.[5] On long slopes, spacing should be closer at the bottom and increase as one moves up the slope. Fill used between layers of branches must be able to support plant growth. Individual layers are typically angled back into the slope at a minimum, 10-degree angle from horizontal. On drier sites, especially those requiring fill, this angle of inclination can be increased, and longer cuttings can be used in order for cuttings to reach deep water tables.

This method requires a relatively large number of live branches compared to live staking. However, on slopes subject to surface erosion, it offers an advantage over live stakes by providing immediate, shallow soil reinforcement and surface-erosion control. If plant material is inexpensive and abundant, the additional cost of brush layering over live staking will be minimal.

If the layers of soil are wrapped with erosion-control fabric, brush layering works in a fashion similar to the soil-reinforcement technique (see the discussion on this technique in this chapter). The addition of fabric to this technique adds relatively little to the cost, but greatly improves the erosional resistance, especially during the plant-establishment period.

Fascines. Also called wattles or contour wattles, fascines are long bundles of live cuttings that are bound together and secured to the streambank or floodplain with live and dead stakes. They are placed on the bank in one or more rows of shallow trenches that typically run parallel to the stream. Fascines work well to stabilize shallow gully sites and areas of general scour where the banks can be sloped back to 1:1 or flatter.[4] Fascines can serve to facilitate drainage on wet slopes if installed at a slight angle.[2] They work particularly well in straight reaches and on the inside bends of streams where erosion forces are low. Fascines help protect banks from shallow slides (one to two feet deep) and offer immediate protection from surface erosion. Bank stabilization is achieved by breaking up the bank into a series of smaller, vegetated slopes that dissipate energy, physically bind the soil within the root zone and promote the entrapment of sediment and debris. Installing erosion-control fabric between fascines can enhance the initial erosion-control capabilities of the system.

Plant materials for fascines should be 1/2 to two inches in diameter and at least three feet in length (the longer the better). The completed fascine should be eight to 10 inches in diameter and tapered at each end. For ease of handling, bundle length typically varies from 10 to 30 feet. The recommended spacing between fascines varies with the slope and erosion resistance of the soil. Fascines are not recommended as a stand-alone treatment on banks steeper than a 3:1 slope that are comprised of fill or erosive soils.[2]

Because fascines are oriented parallel to the soil surface, they are unable to reach deep water tables. Consequently, mortality can be high in all but the most consistently moist streambank sites. This method also requires a relatively large amount of live plant material and a larger work force compared to live-stake treatments. However, it does offer the advantage of providing immediate surface-erosion control.

Brush Mattresses. This variation, also known as "brush matting," consists of a thick layer (mattress) of overlapping live cuttings or branches placed on the surface of a streambank and secured with a combination of twine, wire, and live and dead stakes. Individual cuttings are either oriented perpendicular to stream flow so that their basal ends lie down slope,[2,3,5] or they are placed in a shingle-like manner, with basal ends angled upstream.[4,5] The bottom edge of the mattress is often anchored with a fascine. Brush mattresses function as mulch to immediately protect the bank from surface erosion, and it rapidly establishes dense vegetation.[5] The added roughness they provide reduces local velocities and promotes the entrapment of sediment and debris during flooding conditions. These effects increase with the age of the system as the vegetation becomes established. If there is a shortage of cuttings capable of propagation, a combination of live and dead branches can be used instead.[3]

The recommended maximum slope of a bank for both material survival and ease of installation is 3:1.[2] Though the treatment has been successfully applied to slopes up to 1.5:1,[4,5] applications on slopes steeper than 3:1 are recommended only if necessary and on cohesive soils. Mattresses will collect sediment and may collapse if constructed on too steep a bank. Branch layers should range from four to 18 inches thick, with the thicker mattresses being applied to streams that are larger or carry higher quantities of ice and bed load.[4,5] Cuttings should be six to nine feet long and approximately one inch in diameter.[2,3,4] 5 to 15 branches or stems should be placed per linear foot of stream to make up the desired thickness. To facilitate rooting, it is essential that the branches be in contact with the soil. Branches should lie flat against the bank and be covered with thin layers of topsoil, leaving the top surface of the mattress and the fascine slightly exposed.

This technique is most appropriate in moist sites where shallow or surface placement of cuttings will not be too dry for vegetation establishment. The relatively large quantity of plant materials needed and the labor-intensive nature of the treatment make brush mattresses best suited to short segments of streambank and on sites where both inexpensive material and volunteer hand labor are abundant. They should not be used on slopes that are experiencing mass movement or other slope instability.[8]

Emergency

Woody plantings are not effective in emergency situations because of the time required for establishment and root colonization of streambank soils. In addition, installation of woody plant materials requires advance planning, and installation can be slow and labor-intensive.

EFFECTS

The effect of woody plantings as bank protection is limited in the first growing season, though it rapidly increases in subsequent years after roots and above-ground shoots and stems increase in size and coverage. On relatively undisturbed streambanks, woody plants provide stabilization to depths of two to three feet by physically binding soil particles and adding tensile strength to potential shear layers in the soil.[9] Above-ground shoots and stems may provide some protection against surface erosion, but usually less than continuous mats of herbaceous vegetation. Woody plantings add structural habitat diversity to banks and floodplains and can provide overhanging cover for fish, eventually contributing woody material to channels. Deposition of sediment may also be encouraged by the increase in hydraulic roughness created by dense stands of woody vegetation.

DESIGN

The following is a short summary of some design considerations for woody plantings. are the best option for your situation. Please refer to Appendix H for a more detailed description of the bulleted items below. Also, an understanding of fluvial and riparian processes will greatly improve the chances of success of any woody-plantings project. Conceptual design drawings are shown in *Figure 6-32*.

- Develop design criteria. Design criteria are detailed guidelines that will identify specific requirements related to plant performance, including acceptable plant-establishment period, size of plants, growth characteristics and species diversity.
- Conduct a site review of the project and reference sites. Identify existing plant species, their abundance and distribution, the lower limit of perennial vegetation, the depth to groundwater, the types of soil, the availability of light, hydrology and geographic characteristics, and land use. Choose an active reference site, preferably in the same or nearby watershed with similar site conditions to aid in the design of a planting plan for the project site.
- Identify site constraints. Site constraints are site-specific factors that may limit the success of the bank-treatment design. They include biological, physical, economic and construction-sequencing issues.
- Select plant materials for the project. This may include unrooted live cuttings, rooted cuttings, bare-root stock, containerized plants and, in some cases, ball-and-burlap stock. If you decide to seed the streambank, the seed should be placed under erosion-control fabric to reduce the chance of seeds washing away during flood flows (this is true of all seeding projects). The type of plant material selected depends upon the project scope, design criteria and the overall budget.
- Select plants. For each plant-material type, select plant species based on your design criteria, the species' compatibility with site conditions and their availability. Consult your reference site to identify plants with the highest likelihood of survival. Plant species native to the project area should be used, and using a broad variety of species will improve the likelihood of project success.
- Within each hydrology-based planting zone, determine planting density and layout for all plant materials and each species based on design criteria and cost.
- Determine site-preparation requirements, timing of installation and the proper planting techniques for all plant materials.
- Consider the need for maintenance such as irrigation, weed control and the control of animal browsing. Monitoring data will help determine maintenance activities needed to maintain healthy plant growth.

Site conditions that may inhibit woody-planting success are numerous. Consequently, the design and planning of revegetation efforts requires knowledge in horticulture or plant biology, with a specific emphasis on riparian ecology. Success is dependent on proper selection, handling, storage and installation of plant material. Poor success may result if, for example, soils are not compatible with selected vegetation, cuttings fail to reach the summer water table, beavers destroy installed plants or plants are not installed in the proper hydrologic zone. More details on revegetation considerations are discussed in Appendix H.

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BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

No mitigation is needed for this technique.

Mitigation Benefits Provided by the Technique

Woody plantings, if properly designed and implemented, can provide overhanging cover for fish, structural diversity for birds and wildlife, detritus for aquatic invertebrates and long-term recruitment of large, woody material. Consequently, this technique avoids impacts that may degrade habitat, and it can be used to compensate for habitat impacts created by other streambank treatment activities such as loss of riparian function, cover, complexity and flood refuge.

Please refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for additional information on biological and mitigation considerations.

RISK

Habitat

Except for the time that may be required for woody plantings to establish and mature, properly designed woody plantings are excellent from a habitat perspective.

Infrastructure

Woody plantings are typically compatible with adjacent infrastructure only in cases where they are a component of more resilient bank-stabilization techniques, such as a rock toes, soil-reinforced banks or log cribwalls, which provide stable transitions into infrastructure.

Reliability/Uncertainty of Technique

Woody-planting success can vary significantly from site to site. In general, western Washington is a very hospitable climate in which to establish vegetation due to the long growing season and plentiful moisture. Establishing woody plants in eastern Washington can be much more challenging, requires more careful planning and generally needs more intensive maintenance.[10] Common causes of failure include incorrect planting locations, inability of plant material to reach the summer water table, damage by wildlife and livestock and inability of installed plants to compete with naturally establishing riparian vegetation.

CONSTRUCTION CONSIDERATIONS

Materials Required

Several types of materials may be beneficial to use during woody-plant installation, including general backfill, topsoil, compost and slow-release fertilizers. These are discussed in more detail in Appendix H.

The project's scope and site conditions will determine the types of tools required for the installation of woody plants. Where soils are fine-textured, moist and not over-compacted, woody plants can be effectively installed with hand tools. Often, however, it is more effective to use some type of mechanized planters to create planting holes, especially if long cuttings are being installed or if soil is coarse-textured and over-compacted. Conventional earthwork equipment, such as Bobcats, backhoes, augers, excavators and tree spades can be useful for woody plantings. Additionally, restoration practitioners have developed planting devices specifically for woody plantings. Some examples include the stinger, which is used for inter-planting riprap; the ripper, which is used to plant cemented floodplain soils; and the water-jet stinger,[1, 12] which uses pressurized water to create a deep hole for planting long willows in fine-textured soils. These tools are described briefly below.

Stinger Method

The stinger method makes it easier to plant cuttings in compacted streambank soils and riprap revetments. As an attachment to a backhoe or excavator, the stinger can push three- to four-inch-diameter cuttings into the soil to depths of up to approximately six feet.[2, 12] The Janicki stinger was developed in 1995 for the Washington Department of Fish and Wildlife to attach to the bucket of an excavator. It consists of a solid steel rod, approximately three to four inches in diameter, that creates a pilot hole through coarse or rocky layers of streambank or riprap and stops when it reaches the softer, native soil underneath (subsoil). The finer subsoil serves as a rooting zone for installed willow or cottonwood pole cuttings. Cuttings are inserted into the pilot holes by hand and pushed down to the required depth with the heel of the bucket. Care is required to ensure that cuttings are footed in moist subsoil and that there is a continuous tight fit between the cutting and the soil. The cutting should make its own hole through the native subsoil. No more than one-half of the cutting should protrude above the soil; six inches is recommended. This system has been used across western Washington with great success and eases planting in difficult conditions such as floodplains where water tables are as much as six feet beneath the ground surface or in streambanks with riprap layers up to five feet thick. The Janicki stinger can plant 40 to 50 cuttings per hour on average. Because the Janicki stinger can push the cuttings in only as far as the riprap surface, cutting survival may be low in thick layers of riprap, unless soil has been incorporated into the riprap matrix.

A planting device similar in purpose to the Janicki stinger is the "expandable stinger," which consists of a pair of eight-foot-long, elongated probes, with an internal plant receptacle. The bottom tips of the probes can be closed to hold the plant within the plant receptacle and opened to release the plant into the ground. Like the Janicki stinger, the expandable stinger also attaches to an excavator bucket. The cutting is placed inside the probe's plant receptacle, and the excavator drives the probe into the ground. Once the probe has reached the proper depth in the soil or riprap, the operator opens the probe (it operates hydraulically from the cab of the excavator), and the cutting is released. The probe is then removed from the hole; the probes are closed; a new cutting is inserted, and the process is repeated. The advantages of the expandable stinger over the Janicki stinger include:

- The cutting is protected at all times (leading to potentially higher survival rates) rather than being pounded into place.
- Smaller-diameter cuttings can be used. The probe can accommodate 1/2-inch- to four-inch-diameter cuttings that are up to four feet in length. Larger cuttings may be held in the tip of the probe and driven into the soil.
- The "shear wall," a compacted wall in the planting hole created when planting tools are inserted into the soil, is minimized or eliminated. The probe tip of the expandable stinger has longitudinal ribs that break up the compacted soil around the walls of the planting hole as the probe is removed and allows the now-loosened soil to fill the hole. Without this feature, shear walls can be created, hampering the proper dispersal of roots and often resulting in poor or unsuccessful growth.
- Field crews remain relatively safe on the top of the bank rather than having to climb along the banks in close proximity to heavy equipment operation.

The expandable stinger is capable of planting in streambanks, floodplains and through riprap up to four feet thick. It has been used to plant 30 to 250 cuttings per hour, depending upon site conditions.

A variation on the expandable stinger is capable of planting three-inch-diameter rooted-plant plugs into unarmored streambanks at a rate of up to three hundred per hour.

Ripper Method

The ripper was also developed to facilitate revegetation efforts in cemented floodplain soils with deep water tables. It consists of a five-foot-long shank pulled behind a D-8 Caterpillar bulldozer or equivalent. The shank creates a narrow trench in the soil. Up to four workers drop cuttings into the trench from a platform on the tool bar of the ripper as it moves along. The ground may collapse under its own weight back onto the cuttings. More often, however, to ensure good soil contact with the cuttings, the operator must ride over soil mounded up to one side of the trench with the outside of the bulldozer track. The minimum width between trenches is the width of the bulldozer track, approximately four to five feet. Trenches are normally placed perpendicular to the stream or at a downstream angle. Advantages of the ripper include that it loosens the soil around the cutting to promote good root development, and the trenches of relatively uncompacted material can help to draw water from the stream to recharge the aquifer. Disadvantages include that it can only be used on large-scale projects, and the ground is left in a roughened state that may not be acceptable if immediate aesthetics are of concern. The ripper has been used to plant an average of 1,000 cuttings (up to six inches in diameter) per hour into cemented floodplain soils.

Water Jet Stinger Method

Another method to create a deep, narrow hole for long willow or cottonwood pole cuttings is the water jet method.[1,11] Unlike the stinger, this method is designed for sites with fine-textured soils, a low rock or gravel content, and relatively deep water tables. This planting system consists of a gas-powered pump that forces water from the nearby stream through a long rod with a special nozzle. The nozzle creates a pressurized flow capable of creating a six-foot-deep hole in approximately 20 seconds (in good conditions). The length of rod depends on the length necessary to reach the summer water table, but typically ranges from three to 10 feet. If the willow cuttings are promptly placed in the scoured holes, the slurry of saturated sediments within the hole will form a tight fit between the cutting and the soil, which increases cutting survival.

Timing Considerations

The optimum time to plant depends on the specific type of woody plantings under consideration, the availability of water or the potential for irrigation, and project scheduling. Unrooted cuttings should be harvested and planted during the spring or during the fall dormant season. Bare-root plants should be planted during the late winter/early spring. Containerized plants and salvaged plants have a wider planting window. They can be installed almost any time of year, provided they will receive adequate water, but best results occur with spring or fall plantings. All work on the streambank should be timed to coincide with flows that are low enough for crews to reach planting zones.

Cost

Some approximate costs for installed woody plant material types are as follows:

- three-foot-long willow cutting–$2.00;
- six-inch-diameter willow post–$25.00;
- ten-cubic-inch shrub tubeling–$2.00;
- one-gallon containerized shrub–$8.00;
- locally salvaged willow clump–$25.00;
- two-foot-diameter, bare-root shrub–$1.00; and
- 1.5-inch caliper ball-and-burlap tree–$200.

More information on the cost of woody plantings and how to calculate the total number of plants required per acre is provided in Appendix L, *Cost of Techniques.* Costs for use of the stinger and water-jet method depend upon equipment costs, site conditions and the scale of the job.

MAINTENANCE

General maintenance needs for installed woody vegetation may include, but are not limited to irrigation, browse control (beaver, livestock, deer and small mammal), pruning, weed control and fertilization. Some of these topics are discussed in greater detail in Appendix H. Maintenance should be initiated based on predetermined success criteria and monitoring findings.

MONITORING

Woody-plant monitoring is critical to project success and should be linked to maintenance activities, such as irrigation, browse or beaver control and, if needed, replanting. Monitoring should be conducted monthly during the first full growing season after installation and can be reduced to a single, annual visit in subsequent years. In the first year after planting, it is easy to measure survival of all installed plants by a physical count; but, with increased density as vegetation fills in, it may be necessary to use cover rather than count of individual plantings as a measure of plant survival. Another consideration, specifically related to riparian zones, is that any survival monitoring criteria should anticipate that deposition of alluvial material on banks or floodplains may limit survival of installed plant material. However, these conditions are conducive to the natural establishment of other desirable riparian species. More information on monitoring is provided in Appendix J, *Monitoring*.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[13] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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a. Live Stakes planted through Coir Fabric.
Source: Inter-Fluve, Inc.

c. Rows of Woody Plantings. Cedar River Levee.

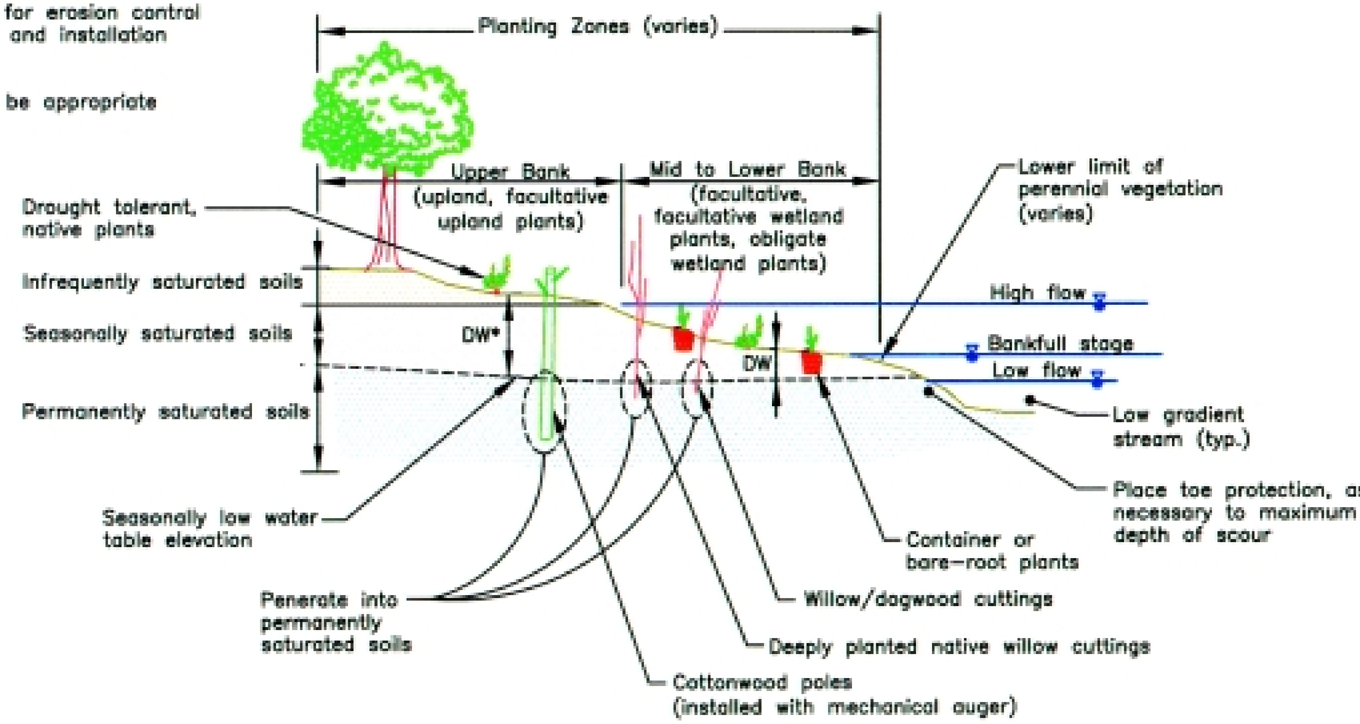
b. Woody plantings with tube protector to protect from being girdled by rodents. Tucannon River.

d. Woody Plantings with fencing to protect from animal browsing, especially beaver. Nooksack River.

Figure 6-31. Various applications of woody plantings.

Notes:

1. Planting zones provided are approximate. Appropriate plant species and distribution vary with each individual site and plant species characteristics. See Appendix H for additional planting guidelines.
2. Use of erosion control fabric is site dependent. See Appendix H for erosion control fabric application, selection, and installation guidelines
3. Herbaceous plantings might be appropriate with woody plantings



HYDROLOGY-BASED PLANTING ZONES AND TYPICAL WOODY PLANTING BANK TREATMENT

SECTION VIEW

* Depth to low water table (varies)

NOT TO SCALE

FIGURE 6–32	WOODY PLANTINGS CONCEPTUAL DESIGN	INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

Herbaceous Cover
Biotechnical Techniques

DESCRIPTION

Herbaceous cover is a bank-stabilization technique that consists of planted or installed herbaceous vegetation. This technique is used to improve bank stability, fish and wildlife habitat, and site aesthetics. Herbaceous vegetation consists of grass and grass-like wetland plants and includes rushes, sedges, ferns, legumes, forbes and wildflowers. In contrast to woody vegetation, herbaceous vegetation tends to have roots that are shallow, fine and dense. Above-ground shoots tend to form a more continuous mat across the soil surface than typically observed in woody plants. *Figure 6-33* (at the end of this technique discussion) shows various applications of herbaceous cover.

Herbaceous vegetation is usually planted as seed, but other widely used riparian herbaceous planting materials include containerized plugs, bare-root seedlings, rhizomes and tubers. Herbaceous plantings might also be referred to as seeding, groundcover, sprigging, plugging, hydromulching, drill seeding or broadcast seeding. Refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for a more detailed description of different planting material types.

APPLICATION

Herbaceous cover is an upper-bank treatment. It can be used as a stand-alone treatment or in conjunction with other treatments.

A typical application of herbaceous cover as a stand-alone treatment is on a streambank that has a relatively stable toe but has poor vegetative cover and possibly some surficial erosion or modest, reach-based aggradation. Herbaceous cover may also be an excellent choice as ground cover in parks and urban areas where flood conveyance and ease of maintenance is important. For example, on low-gradient streams where uniform coverage of the floodplain surface can be ensured, herbaceous cover may be used to protect an otherwise bare soil surface from stream channel avulsions. As summarized in Matrices 1 and 2 in Chapter 5, *Identify and Select Solutions*, under no circumstances should herbaceous cover be used as the primary method to control major bank-erosion problems, but this approach can provide an important component of a composite solution.

Herbaceous cover is not an appropriate stand-alone bank treatment for sites where undercutting or mass failure occurs because it does not address the mechanism of failure (see Chapter 2, *Site Assessment* and Matrices 1 and 2 in Chapter 5). Only when used in combination with toe protection and erosion-control fabric is herbaceous cover an acceptable treatment for banks affected by local scour. Due to the relatively shallow rooting depths of grasses and grass-like plants, this treatment should not be used on reaches where degradation and channel downcutting is widespread. The only exception to this limitation is erosion caused by an extreme event that is not likely to occur again in the near future and when damage from such an event is expected to be limited.

Variations

Variations of this treatment include the use of erosion-control fabric and different plant types. Erosion-control fabric should be used with seeding placement unless the risk of seed washing away is minimal. Erosion-control fabric is seldom required for the protection of rooted stock because plants are physically attached to the soil surface. An excellent, low-cost type of herbaceous cover, frequently used in streambank reconstruction projects, is sod salvaged from the project site and placed over subsoil. The dense root/soil mass of a sod mat is relatively resistant to washing away during flood flows and the well-developed root masses have the potential to quickly establish with minimal maintenance. Another interesting type of herbaceous plant material is a prevegetated coconut mat that resembles conventional turf sod. Available from some Washington native-plant nurseries, these products can be an effective, low-risk (but expensive) means to quickly establish herbaceous cover.

Emergency

Herbaceous cover is not appropriate for emergency situations, due to the length of time required for establishment of a dense stand of vegetation.

EFFECTS

Herbaceous cover is effective once vegetation matures and establishes uniform coverage of the soil surface. Roots, especially of highly desirable streambank species such as sedges or rushes, physically bind soil particles together in a cohesive unit. Meanwhile, above-ground shoots and stems form a continuous soil cover that reduces velocities and erosional forces at the soil/water interface. Due to maximum rooting depths of one to two feet, herbaceous cover can provide excellent erosion resistance on small streams where streambanks are less than two feet in height. On taller streambanks, herbaceous plants are best used in combination with other bank-protection treatments because their roots may be too shallow to resist the long-term hydraulic forces of flowing water on their own. Dense, herbaceous cover can also provide good weed control and aesthetic benefit.

DESIGN

Design of an herbaceous-cover treatment must consider site conditions and specific planting issues as summarized below. Conceptual design drawings are shown in *Figure 6-34*. The following list of sequential steps provides general design guidance given the number of plant types that may be used and variability from site to site (see Appendix H for more information on these items):

- Develop design criteria. Design criteria are detailed guidelines that identify specific treatment requirements related to acceptable plant-establishment periods, desired size of plants and species diversity.
- Conduct a site review of the project and reference site. Choose a functional reference site with similar soil, light and moisture characteristics, preferably in the same or nearby watershed with similar site conditions, to aid in the design of a planting plan for the project site. Identify existing plant species, abundance, distribution and the lower limit of perennial vegetation. These characteristics can be replicated from the reference site to the project site.

- Identify site constraints. Site constraints are factors specific to the proposed site that could limit the success of the bank-treatment design. They include biological, physical, economic and construction-sequencing issues that may affect the timing of plant installation.
- Select herbaceous plant types for the project. The type of plant(s) selected depends upon the project scope, design criteria and overall budget.
- Select plant species. Select plant species based on design criteria, compatibility with site conditions and availability. Consult the reference site to identify plants with the highest likelihood of survival. In most cases, native species should be used. A diversity of species is encouraged to improve the likelihood of project success.
- Determine planting density (including seed rate) and layout within each hydrology-based planting zone for all plants based on design and cost criteria.
- Determine site-preparation requirements, timing of installation and the most appropriate planting techniques for all plants.
- Consider the need for maintenance, such as mowing, irrigation and weed control. Monitoring data will help determine maintenance requirements.

For additional information on developing seed mixes, see Appendix H and the *Soil Rehabilitation Guidebook*.[1]

Erosion Resistance

A limited amount of literature is available on the erosion resistance of mature, herbaceous cover and is based, in part, on research generated from studies on grass-lined channels in dam spillways. These findings are incorporated into HEC-15 (1988),[2] a standard hydraulic engineering reference, but should be used cautiously. Depending upon the soil type, grass species and condition of the stand of grass, the erosional resistance of mature stands of tested grasses ranges from 0.4 to 3.3 lbs. per square foot (comparable to a range of approximately one- to six-inch diameter gravel/rock bank protection).

Along most streambanks, installation of seed is done in conjunction with erosion-control fabric to reduce the risk of seed washing away during flood events. This is especially important along the lower banks and outside bends of streams. In some cases (e.g., along inside bends, upper banks and low-gradient creeks), seed may be less prone to washout during flood flows, but a decision not to use erosion-control fabric on seeded streambanks should be made by an experienced stream specialist. Rooted, herbaceous plants, compared to seed, are less likely to be washed away by flood flows and are a better choice as a stand-alone technique in erosive sites.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

No mitigation is required for this technique. For additional information on mitigation considerations, refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5.

Mitigation Benefits Provided by the Technique

Herbaceous cover can provide mitigation value for riparian and aquatic habitat loss. As mitigation, herbaceous cover can provide near-bank cover (especially when grasses are tall), detritus for aquatic invertebrates and structural diversity for birds and wildlife. As a result, this technique avoids impacts that may degrade habitat and can be used to compensate for habitat impacts such as loss of riparian function, cover, complexity and flood refuge. Chapter 4 and Matrix 3 in Chapter 5 provide additional information on biological and mitigation considerations for herbaceous cover.

RISK

Habitat

No risk to habitat is caused by this treatment.

Infrastructure

This technique is not appropriate for bank protection where infrastructure is at risk, unless it is part of a well-designed biotechnical treatment.

Reliability/Uncertainty of Technique

In western Washington, the climate and associated growing season make herbaceous cover much easier to successfully implement than in other parts of the state. In those parts of the state where drought, poor soils and shorter growing seasons occur, irrigation may be necessary for successful propagation of a herbaceous cover. Troubles with seeding can often be linked to poor soil-to-seed contact (insufficient compaction), over-compaction, improper timing and/or drought. Rooted, herbaceous plants may fail if the hydrologic regime is inappropriate, or if planting conditions and associated soil moisture are inadequate during the critical establishment phase.

CONSTRUCTION CONSIDERATIONS

Materials Required

Materials required to implement herbaceous cover along a streambank include the specified plants and, if required, imported or salvaged topsoil, soil amendments and erosion-control fabric. Surficial mulches are not used along streambanks because they are subject to being washed out during high flows. Similarly, conventional chemical fertilizers are not recommended as they can contribute excessive nutrients to the adjacent waterway.

The equipment necessary to install herbaceous cover depends upon the scale of the project. For example, on relatively small jobs, landscaping equipment may be sufficient to scarify compacted soils or incorporate soil amendments and topsoil into the rooting zone. But on large jobs, a variety of farm equipment and heavy earthwork machinery may be more cost effective. Application of seed also depends upon site conditions and the scale of work and can range from mechanical hand seeders on narrow, hard-to-reach streambanks to mechanized drill seeders or hydromulching equipment on more accessible adjacent floodplains. Light compaction of seeded areas, which is recommended after seed application, may be undertaken with excavator buckets, excavator tracks and/or conventional vibrating or roller compactors. Hand tools are generally the best equipment to use for installing most rooted forms of herbaceous cover.

Timing Considerations

The timing for planting herbaceous cover along streambanks must be based on a number of site and regional factors, including seasonal moisture and temperature patterns, timing of flood flows, and the timing of any streambank-construction activities. Since there is a wide range of climates in Washington, timing of plantings will need to be tailored to the specific site. Nonetheless, as a very general guideline, spring and fall are good times to install most herbaceous plants, but mid-summer and early fall should be avoided unless supplemental irrigation is provided. For further discussion of timing considerations, refer to Appendix M, *Construction Considerations*.

Cost

The cost to revegetated a streambank with herbaceous cover alone may range from $1 to $3 per foot of bank. Costs can range up $6 per foot if topsoil and erosion-control fabric are required. An approximate cost for native seed is $10 per pound but varies by species and the volume ordered. Costs to hand broadcast seed along a bank-stabilization project are approximately $750 per acre. Hydroseeding costs depend upon acreage, but can range from $1,000 to $2,000 per acre. Installed, 10-cubic-inch, containerized herbaceous plugs are about $1 to $4 each. Native, bare-root herbaceous plants (typically wetland species) can be purchased and installed for about $1 to $2 each. Refer to Appendix L, *Cost of Techniques* for additional information on cost and to Appendix H for conversion of planting densities to total number of plants required per acre.

MAINTENANCE

Herbaceous cover requires little maintenance, if any, and is relatively self-sustaining once established. In some cases, irrigation and weed control may be required and should be undertaken if monitoring indicates a need. During the establishment phase, it is also important to limit foot traffic and livestock access. Livestock access following the establishment phase should be limited and carefully monitored to prevent damage to vegetation and soils.

MONITORING

Monitoring herbaceous cover should include success criteria established as part of the design process and the identification of indicators for initiating maintenance activities (if needed). Monitoring should consist of inspecting for any signs of erosion, including surficial and toe of bank erosion, and for loss of soil or damage to erosion-control fabric. Important monitoring parameters include uniformity of coverage and weed coverage. Uniformity of coverage and the presence of weeds can be determined through casual visual survey, or by establishing specific criteria for measuring coverage and weed density. Full, herbaceous cover can generally be accomplished during the first growing season with minimal weed competition. Even so, survival criteria should anticipate the deposition of alluvial material on planted banks and floodplains that may limit the survival of installed cover but may also create conditions conducive to the natural establishment of other desirable riparian species. Consequently, success criteria should address maintenance activities associated with deposition of fine materials.

Monitoring should be conducted monthly during the first full growing season after installation (and perhaps linked to flood events) and can be reduced to a single, annual visit in subsequent years. For further discussion of monitoring methods, refer to Appendix J, *Monitoring*. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[3] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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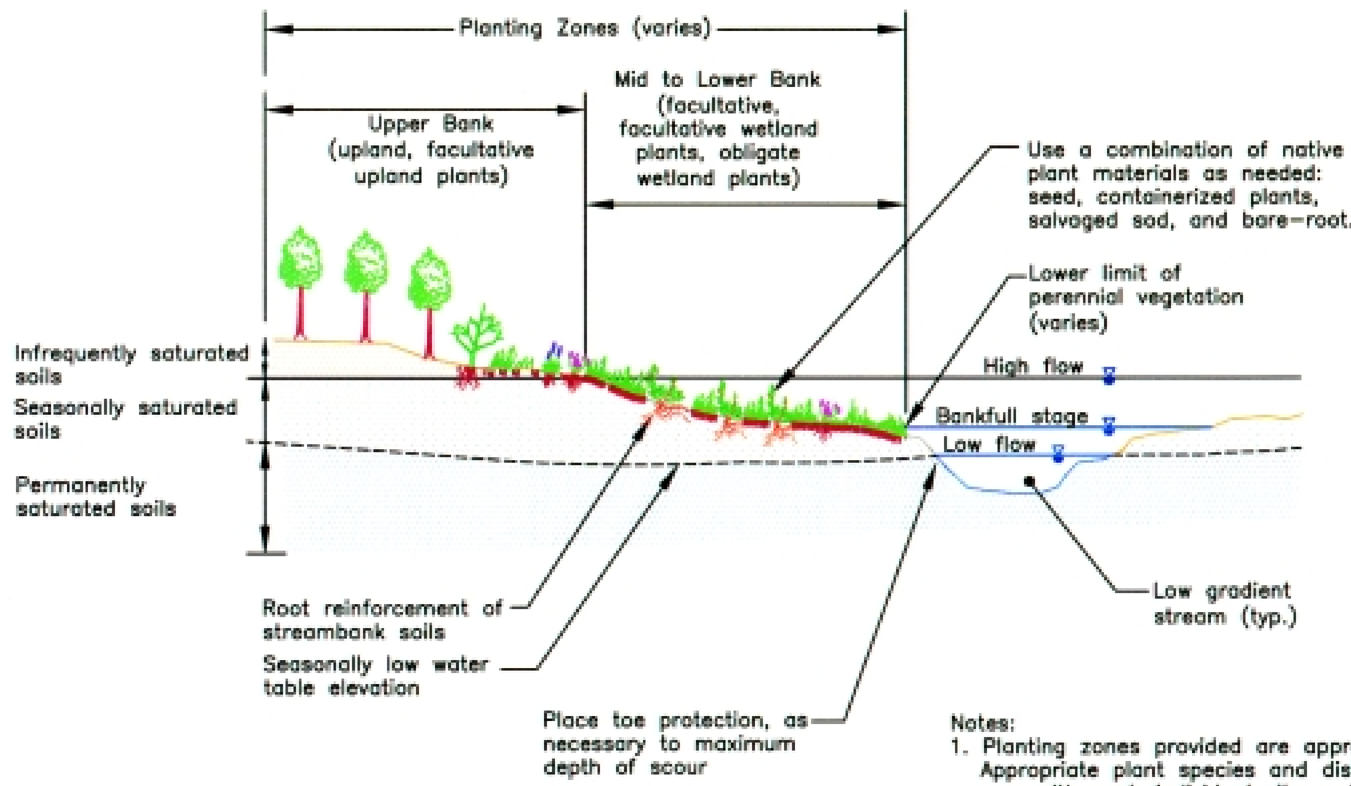
a. Wind River.

b. Sauk River.

Figure 6-33. Applications of herbaceous cover.



Notes:
1. Planting zones provided are approximate. Appropriate plant species and distribution vary with each individual site and plant species characteristics. See Appendix H for additional planting guidelines.
2. Use of erosion control fabric is site dependent. See ISPG Appendix for erosion control fabric application, selection, and installation guidelines.
3. Woody plantings might be appropriate with herbaceous plantings, especially on upper bank.

NOT TO SCALE

FIGURE 6–34	HERBACEOUS COVER CONCEPTUAL DESIGN	INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

DESCRIPTION

Soil reinforcement refers to a system of soil layers or lifts encapsulated or otherwise reinforced with a combination of natural or synthetic materials and vegetation. Most often, the lifts are oriented along the face of a bank in a series of stepped terraces. When used with degradable fabrics, the fabric will provide one- to four-year erosion protection, giving installed vegetation the time it needs to become well established for long-term bank stabilization. In situations where increased fabric strength and longevity are needed, synthetic fabrics can be used to provide both short- and long-term structural integrity. Nearly all applications of this approach are integrated with toe protection below the lower limit of vegetation. *Figure 6-35* (at the end of this technique discussion) shows various applications of soil reinforcement throughout Washington State.

These systems are also known as fabric-encapsulated soil, fabric-wrapped soil, soil burritos, vegetated geogrids or soil pillows. This technique is included in the biotechnical section of these guidelines, but it could also be considered a structural measure when designed with geotechnical components. Soil reinforcement is included among biotechnical measures because of the short lifespan of some fabric components and the importance of long-term vegetative reinforcement.

APPLICATION

Soil reinforcement is a frequently used approach to stabilizing or reconstructing eroding banks on small creeks and large rivers where a resilient and proven bioengineered or biotechnical treatment is needed. It is suitable for use where a wide range of bank-failure mechanisms occur, including toe erosion, mass wasting and scour. (See Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for information on the mechanism and causes of bank failure). The stepped configuration of a series of lifts lends itself to a variety of slopes ranging from 1:1 to flatter than 3:1 making them useful where slopes cannot be cut back. If used in a series of terraces, lifts can be fit to bank heights of a few feet to more than 30 feet.[1]

A structural toe technique (see *Roughened-Rock Toes* and *Log Toes* techniques in this chapter) can be combined with a fabric-covered soil, providing a considerably higher level of protection against bank erosion than vegetation alone. When used in such combination, fabric-encapsulated soil lifts built with degradable fabrics can conservatively withstand bank tractive forces of one pound per square foot.[2] The use of synthetic fabrics can further increase shear-stress resistance to match the performance of many traditional rock methods. This type of system provides immediate protection from surface erosion and structural bank failure because soil is not exposed.

The screening matrices in Chapter 5, *Identify and Select Solutions* provide additional guidance on the applicability of soil reinforcement based on the mechanism of streambank failure and causes of streambank erosion.

This technique tends to form relatively uniform and smooth streambank edges that may not provide immediate roughness and cover that is desired from a fish habitat perspective. While it is expected that large roots of trees and shrubs would eventually colonize the soil lifts and create desired roughness and bank diversity, such benefits take many years to come to fruition. Consequently, unless incorporated with a roughened toe (with associated large woody debris), this technique is not recommended if a project requires immediate bank roughness for fish habitat.

While soil reinforcement is an acceptable treatment on aggrading reaches (see Chapter 3), the use of an associated structural toe may not be necessary. Along degrading reaches, reinforced soils are suitable in combination with grade-control structures.
A geotechnical evaluation may be required in over-steep, highly erosive project sites to ensure that slope configuration, fabric types and internal soil drainage are adequate to meet the need.

Variations

The soil-reinforcement technique can be applied using a variety of fabrics and structural components. Numerous types of woven, nonwoven, degradable and nondegradable fabrics can be used alone or in combination. Different fabrics provide varying levels of protection and longevity. Additionally, incorporation of geogrids and other geosynthetic materials within lifts can provide significant structural integrity to steep banks and areas of mass wasting. Soil reinforcement used in combination with gravel filters and drains create a workable solution where drawdown and other drainage problems are prevalent or where they are the mechanism of failure. Refer to the discussion in this chapter on *Subsurface Drainage Systems* for more detailed information about drains.

A number of configurations can also be used for the toe foundation. Natural Resources Conservation Service guidelines[3] specify that a fabric-wrapped toe can be created that resembles the upper lifts in appearance, but it incorporates coarse alluvial substrate. D. E. Miller describes a more traditional toe foundation made of unwrapped stone.[4] In addition, soil reinforcement is one of the few techniques that can function as a deformable bank. In areas of low risk, deformable-bank treatments allow restoration of the channel's natural migration to take place, regulated by bank vegetation, just as it is in natural settings. A deformable bank uses somewhat undersized toe material (may be mobile at two- or five-year recurrence flows) that is wrapped in coir fabric to provide short-term stability and long-term deformability.[5] Another style of bank toe that functions as a deformable bank, though on a different time scale, is a log toe, which is described separately in this chapter and in the *Log Toe and Revetments* section of the Natural Resources Conservation Service guidelines.[3]

Emergency

This technique is not recommended for use in emergency situations.

EFFECTS

If well-designed and constructed, this technique provides immediate and long-lasting streambank protection. Within several growing seasons, these treatments can support a diverse plant community; and, as vegetation matures, overhanging stream cover and undercut, root-reinforced banks may develop. Shrub plantings can provide roughness in flood flows, and trees will provide a long-term source of large woody debris.

Reinforced soil protection can be designed and constructed as either deformable or nondeformable treatments, which may result in lost-opportunity impacts and effects on the stream, depending upon the application.

DESIGN

Soil reinforcement typically employs four components:

1. toe protection,
2. an internal gravel drain,
3. soil reinforced lifts, and
4. revegetation.[2]

The toe foundation generally consists of rock, creating a stable base for the bioengineered bank to resist channel bed scour. However, deformable-toe alternatives, previously described under *Variations*, may also apply. The bottom elevation of the toe should extend to the maximum estimated depth of scour. The top elevation of the toe should be set high enough that the fabric-wrapped lifts resting on the toe will support the growth of perennial vegetation. An internal, gravel-filter drain is often included to provide subsurface drainage during rapid draw-down conditions following high-flow events.[6] A conceptual design drawing of soil reinforcement is shown in *Figure 6-36*.

Design Flow

The design of all components for a reinforced-soil project should be based on selected flow levels. P. B. Skidmore and K. F. Boyd describe various flow-based design criteria for deformable reinforced soil banks.[7] Selection of a toe-foundation treatment, fabric types, vegetation types, and bank slope will depend upon the design flows selected. Different bank components can be designed for different flows. For example, a deformable-toe treatment can be designed to withstand forces associated with a 50-year flow for the first five years and to be deformable thereafter, whereas the upper bank can be designed to withstand lesser flows. Similarly, all bank components can be designed to withstand the 100-year flow until vegetation becomes established, at which point stability will depend on the qualities of the established vegetation.

Fabric

Individual soil lifts, typically 0.5 to 1.5 feet tall, can be placed to create bank slopes ranging from 1:1 to flatter than 3:1. Lifts can be laid in horizontally or at a 10- to 15-degree backslope. They are frequently filled with fine-grained soils that will support the growth of vegetation. Bank treatments longer than the width of the fabric are constructed by overlapping adjacent strips of fabric by a minimum of three feet. The upstream fabric ends of fabric rolls should overlap downstream fabric ends like roof shingles to prevent the edges from being pulled up during flood events. The bottom and top edges of fabric lifts should be buried (embedded) a minimum of three feet. Fabric can be tensioned and secured using 18- to 24-inch-long, wedge-shaped wooden stakes, placed on three-foot centers along the upper edge and sides of a fabric wrapped lift.

Upstream and downstream ends of a treatment must be well-transitioned into nontreated banks and may consist of treatment ends that are keyed into the bank, covered with soil-filled riprap, or fabricated into carefully folded fabric corners. Transitions are discussed in more detail in the discussion on *Riprap* in this chapter.

Fabric used to build these lifts can be degradable, nondegradable, or a combination of both (see Appendix H, *Planting Considerations and Erosion-Control Fabric*). A fully degradable system can be created using two layers of degradable coir (coconut-husk fiber) fabric to encapsulate the soil lifts.[8] An outer layer commonly used is a heavy, 700-g/m^2, woven-coir, erosion-control fabric. This layer provides structural integrity to each lift and the bank itself. The use of an inner fabric prevents piping of fine material through the coarser outer fabric. The inner fabric is typically nonwoven coir, although burlap fabric or straw can also be used if more inexpensive, temporary materials are desired and seed establishment is expected to be rapid.

The entire structure should be designed to withstand bank shear forces during the establishment of vegetation. The anticipated lifetime of the coir fabric advertised by suppliers is five to seven years, although recent data suggesting a shorter life span should be considered.[8] A variety of nondegradable fabrics can also be used if vegetation establishment is uncertain or if erosional forces exceed the resistance provided by degradable fabrics.[9]

Plant Materials

A wide variety of plant materials can be used to ensure that vegetation successfully reinforces the soil lifts by the time any degradable fabric weakens. Typically, native grass seed is used because it is easily and inexpensively installed during construction and can provide both short and long-term bank reinforcement. It is recommended that cuttings of native willows or perhaps dogwood or cottonwood be placed (horizontally) between lifts during construction. Cuttings can also be planted into vertical or horizontal surfaces of lifts after construction (during the dormant season), but this tends to be more labor-intensive, as willows have to be physically pounded into the compacted soil lifts. Native herbaceous and woody plants grown in containers can also be planted into the exposed horizontal surfaces of lifts, although care should be taken to minimize the number of fabric strands cut to install plants. As with any revegetation effort, plant-species selection should be based on the site hydrologic regime, soil type, and rooting and establishment patterns.

The following is a summary of revegetation suggestions for this technique:

Seeding under erosion control fabric:

- Use a native seed mix with at least one quick-establishing species.
- After seed placement, ensure that seed is lightly compacted with a compactor, excavator bucket or the equivalent.

Planting horizontal cuttings:

- Cuttings are inexpensive and easily installed if placed horizontally between lifts during construction.
- Use cuttings that are three to five feet long (up to 15 feet long if necessary) and have a minimum diameter of 0.5 inches. Butt ends of cuttings should touch the back of the excavated trench and protrude only slightly from the lifts. Both diameter and species should be varied.
- Space cuttings no more than two feet apart; two to five cuttings planted per linear foot is about right.
- Orient cuttings perpendicular to stream flow, or at a slightly downstream angle.
- Place each cutting such that 75 percent of its stem is covered by the lift.
- Place one to three inches of soil around the rooting zone of the cuttings (optional).
- For better cutting survival during late-summer construction, consider using rooted cuttings grown in a biodegradable burlap sleeve.[10]

For additional information on revegetation considerations and planting methodology, refer to Appendix H.

CONSTRUCTION CONSIDERATIONS

An important consideration when using this treatment is that it requires great attention to detail during the design and construction phase. Failure to adequately consider the importance of seams, fabric overlaps, staking patterns and transitions between other treatments can lead to weak points and potential failures. Disturbance of existing riparian trees and shrubs should be kept to an absolute minimum during construction.

A greatly simplified, eight-step construction sequence for this technique is as follows:

1. Dewater the site as necessary to construct and install the toe foundation.
2. Excavate the subgrade.
3. Place the specified toe material from the depth of scour to an elevation consistent with the lower limit of perennial vegetation.
4. On the surface of the toe, place the selected fabric parallel to the stream and backfill with the selected fill material.
5. Compact the soil fill and place the seed. Lightly compact the soil around the seed.
6. Wrap the fabric over the compacted soil, tension the fabric and stake it.
7. Place the horizontal cuttings on the surface of the completed lift as described previously.
8. Repeat steps four through seven for each subsequent lift to create a terraced bank at a specified slope.[3,4]

Materials Required

Materials required for constructing a fabric-reinforced, soil-lift treatment may include, but are not limited to, the following (note - varying types of soil reinforcement will use varying types of fabric):

- rocks, logs or other toe protection;
- a gravel filter (as needed) to allow for internal soil drainage (refer to the discussion in this chapter on *Subsurface Drainage Systems*);
- three- to four-meter-wide, seamless, woven, erosion-control fabric for use as the outer layer;
- nonwoven or finely woven inner fabric to prevent soil piping through outer fabric layer;
- imported or native, loamy, soil fill, which will serve as a good growing medium;
- angled, 18- to -24-inch-long wooden stakes cut diagonally from 2 x 4s;
- herbaceous seed to be placed on the soil surface and beneath the erosion-control fabric; and
- rooted or unrooted willow or other cuttings for horizontal placement between lifts.

Construction generally requires the following equipment and labor:

- a crew of two to five laborers,
- an experienced construction supervisor,
- an excavator or bobcat to place and compact soil in the lifts,
- a compactor (hand-operated "bullwhacker" or the equivalent),
- construction forms (optional - see *Figure 6-36*), and
- a loader to haul and place soil and other materials.

For additional design and construction details on soil reinforcement refer to Natural Resources Conservation Service guidelines[3] and *Degradation Rates of Woven Coir Fabric Under Field Conditions*.[2] An article by the same author entitled, *An Innovative Method of Rooting Hardwood Cuttings for Use in Bioengineered Streambanks,*[10] describes an approach for propagating and installing horizontal willows that are designed specifically for soil reinforcement, and *Designing with Geosynthetics*[6] is an excellent reference for the design and placement of erosion-control fabrics in such applications.

Timing Considerations

Soil-reinforced banks must be constructed during low flow when dewatering is possible and when resident and anadromous fish are less likely to be impacted by construction activities. In order to install rock or log toe materials to the depth of scour, excavation within the channel bed will be necessary and, consequently, will require temporary dewatering systems. Dewatering allows for ease of installation and prevents siltation of the stream during construction. This can be accomplished with a coffer dam during low water.

Critical periods in salmonid life cycles such as spawning or migration should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion on construction timing and dewatering can also be found in Appendix M, *Construction Considerations.*

It is by far more desirable to construct this type of bank during the plants' dormant season than in their growing season so that installed seed and cuttings will successfully germinate at the onset of the subsequent growing season. If this is not possible, certain adjustments regarding planting may be required. For example, during late-summer construction, it may be necessary to use rooted cuttings instead of other planting materials to get vegetation established quickly, and these and other plant materials may require irrigation.

Cost

Costs for installing soil-reinforcement treatments can range considerably due to the myriad of factors involved. Soil reinforcement requires a large amount of imported soil, rock, fabric, plantings and other materials; and it requires dewatering, excavation, materials management, equipment access and considerable hand labor. Fabric-encapsulated soil lifts range from $12 to $30 per linear foot for a single, one-foot-tall lift. Fabrics can cost from $0.50 to $3.00 per square yard for nonwoven material, uninstalled. For additional information about fabric costs, refer to Appendix H and Appendix L, *Cost of Techniques*. To learn more about the costs of other techniques used in concert with soil reinforcement, such as roughened-rock toes, log toes, subsurface drains, woody plantings and herbaceous cover, refer to the sections in this chapter that address them specifically.

In terms of time required, the typical construction pace for a fully completed single lift of fabric-encapsulated soil can range from 200 to 1,200 feet per day, depending upon site access, equipment, size and skill of labor crew, and many other factors.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Soil reinforcement can be designed and constructed to be either deformable or nondeformable. Nondeformable treatments will result in long-term lost opportunities for spawning and rearing habitat, gravel recruitment and recruitment of large woody debris, which must be mitigated. Deformable treatments result in short-term lost opportunity impacts caused by construction activities; these also must be mitigated. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for additional guidance concerning mitigation.

Mitigation Benefits Provided by the Technique

One of the main benefits of deformable, soil-reinforcement bank protection is that bank stability and erosion control are provided while also creating conditions conducive to the establishment of dense native vegetative cover. By itself, this technique does not provide any mitigation benefit.

RISK

Habitat

Because this technique requires considerable earthwork and excavation, temporary impacts during construction can be considerable, but it should be emphasized that these impacts are generally only short-term. To reduce habitat risks associated with construction activities, restrictions are placed on the allowable construction period. Best-management practices for sediment and erosion control must be implemented.

Infrastructure

This technique has been successfully implemented in streambank-protection projects to protect infrastructure. Success is dependent upon using this technique in combination with other biotechnical techniques and, in some cases, toe protection.

Reliability/Uncertainty of Technique

This technique can be highly successful if designed and implemented by experienced designers and qualified contractors. Properly applied design criteria and careful engineering of all project components can result in a high level of certainty for project success and long-term bank protection.

MAINTENANCE

Soil-reinforcement treatments generally require little maintenance when subjected to flows less than or equal to their design flow. However, maintenance needs may include some of the following: temporary irrigation and reseeding or replanting of woody-plant materials.

MONITORING

Monitoring soil-reinforcement treatments should involve survey and visual inspection - including regular photo documentation of the integrity of the reinforced soil structure and associated vegetative components. Monitoring should focus on looking for potential weak points in the design, such as scour at the toe of the structure, plant growth, fabric integrity, transitions between treatment methods and transitions between treated banks and undisturbed upstream and downstream banks.

Monitoring frequency should be annual for a minimum of five years, or the anticipated design life of the structure and should be conducted during low flows when visual inspection of the toe of the structure is possible. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring-plan development and monitoring methods, refer to Appendix J, *Monitoring*.

Impacts to the channel and to habitat must be carefully monitored. Changes to available habitat should be documented on a schedule dictated by fish life cycles. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[11] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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a. Soil Reinforcement lifts with barbs and rock toe. Salmon Creek, Tributary to Columbia River. 1997.

c. Soil Reinforcement lifts with rock toe. Touchet River. 2000.

b. Soil Reinforcement lifts with log and rock toe. Salmon Creek, Tributary to Columbia River. 1997.

d. Soil Reinforcement lifts with woody plantings. Cedar River side channel.

Figure 6-35. Various applications of soil reinforcement throughout Washington State.

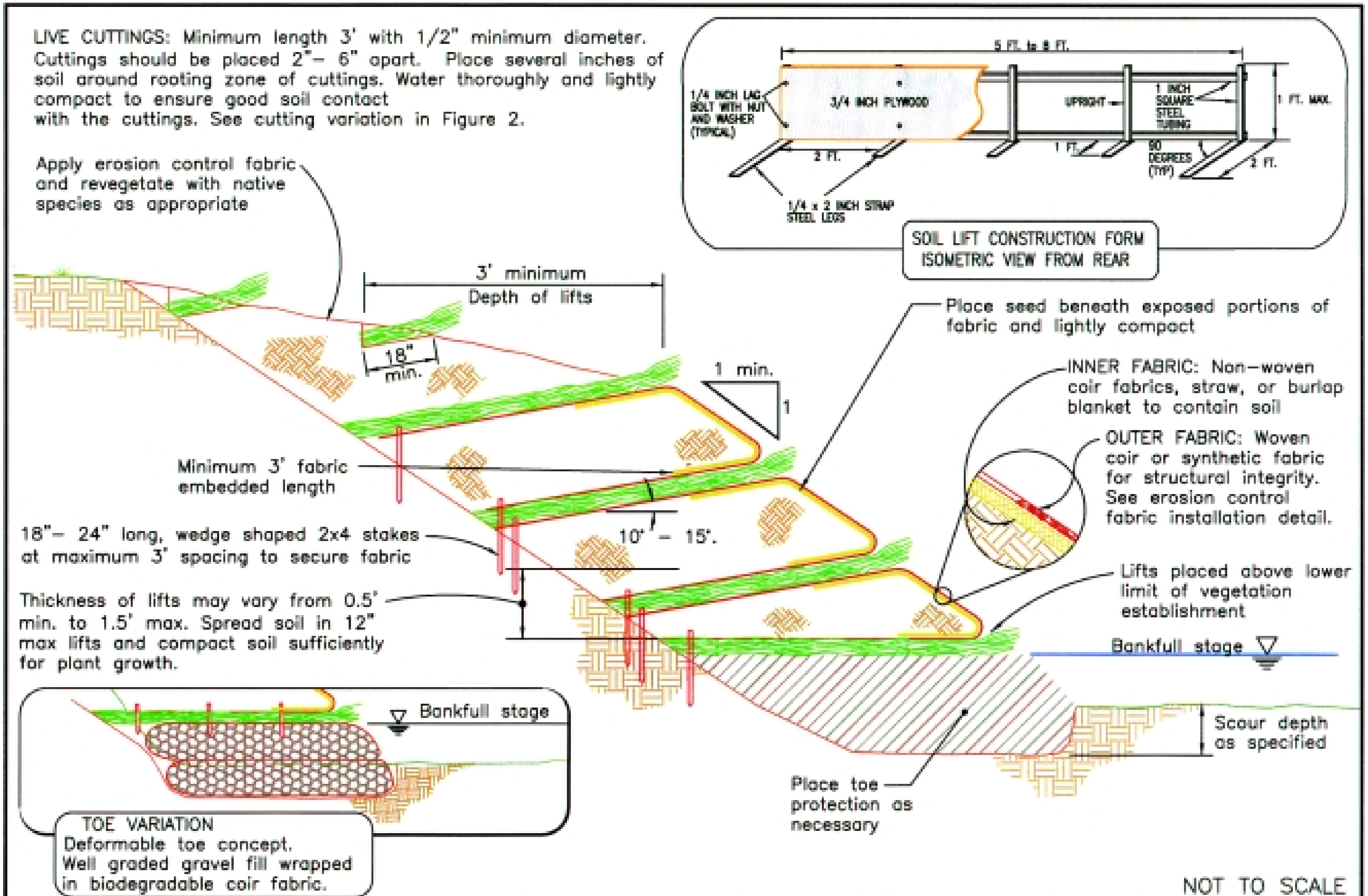

FIGURE 6–36 | SOIL REINFORCEMENT CONCEPTUAL DESIGN | INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

DESCRIPTION

Coir logs are long, sausage-shaped bundles of coir (coconut fiber), bound together with additional coir or synthetic netting. Typically planted with riparian vegetation, coir logs provide biodegradable stabilization to streambanks. The coconut fiber core has a high tensile strength, relatively slow decomposition rate (seven to 12 years) and good moisture-retention properties. When used in streambank construction, coir logs can trap stream sediments during overbank flows, which further enhances their function as a growth medium for streamside plants. *Figure 6-37* (at the end of this technique discussion) shows an application of coir logs.

Coir logs are known by several trade names, including Biologs®, Koirlogs® and BioD-Roll®.

APPLICATION

Coir logs are commonly used as a temporary measure to stabilize the bank toe while riparian vegetation develops to provide bank support. They are typically staked in a single row at the base of low (one- to three-foot-high) streambanks on small streams. However, in limited circumstances, successful applications of coir logs have been made on much higher banks of large streams. Once the coir log is in place, the bank behind the log can be reshaped to a stable configuration and planted with native riparian vegetation. In this configuration, the logs provide protection against hydraulic forces at the toe of the bank. Properly installed, coir logs may also provide a good growth medium for riparian plants and are usually planted with herbaceous or woody vegetation.

The most appropriate application of coir logs without supplemental toe protection is at the base of streambanks of relatively shallow, low-energy and possibly braided streams, where toe erosion is observed (see Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for more information on the mechanisms and causes of bank failure). Examples include streams with low seasonal variation in stage, such as spring-fed or wetland-dominated streams and those with very small or low-elevation watersheds. This application is particularly appropriate where channels have become over-wide due to grazing or other sedimentation impacts, and it can be used to create channel-margin wetlands.

If coir logs are used on higher-energy streams, it is recommended that they be used in combination with toe protection below the coir log. The choice of toe protection will vary with the degree of durability required at the site and the estimated shear stress to which it will be subjected. On high-energy streams, a hard toe made of stone or similar material is often used. On low-energy streams, a second coir log, dead-brush layer or other type of soft toe may be sufficient to prevent undercutting of the treatment. The toe should extend down to the estimated depth of scour.

An advantage of coir logs over some other bank treatments is that they can be transported to the site and installed without the use of heavy equipment, making them a valuable tool where site access is limited.

As with any technique that relies on vegetation to provide long-term bank stabilization, coir logs should only be used in areas that can support vegetation and where vegetation, in combination with any toe protection, will provide all necessary long-term bank strength. Coir logs are not appropriate under bridges, areas subjected to heavy foot and animal traffic, or in areas where poor water or soil quality will inhibit plant growth. The top of the coir log should be placed at or above the lower limit of perennial vegetation.

There are several inherent site limitations to coir-log treatments placed without supplemental toe protection. As a single log installed at the base of a streambank, the log will provide a degree of protection to the base of the bank, but may offer little to no protection against undercutting by scour. A stream with even a moderate amount of erosive potential could readily scour under the logs and destabilize the bank. This will often rule out the use of coir logs as a stand-alone treatment on high or unstable banks and in high-energy situations.

On the other hand, coir logs in combination with bank-toe protection is a possibility where the mechanism of bank failure is scour. However, before a hard toe is used with a coir-log treatment, preparations to adequately stake and secure coir logs must be made; staking into rock toes is often difficult, if not impossible.

On stream treatments where bank failure can be attributed to mass failure or avulsion, coir logs, with or without supplemental scour protection, are not an appropriate bank-protection technique. The screening matrices in Chapter 5, *Identify and Select Solutions* provide more guidance on the applicability of coir logs based on the specific mechanism of failure and causes of streambank erosion.

Another potential site limitation of this technique is that coir logs tend to form relatively uniform and smooth streambank edges and may not provide the immediate roughness and cover that is desired from a hydraulic or fish-habitat perspective. This trait may also limit its application where smooth banks are already creating excessive, low-flow velocities. Eventually large, woody roots of trees and shrubs would be expected to colonize the coir log and bank, thus creating the desired roughness and bank diversity, but such benefits take many years to manifest. Consequently, this technique is recommended where immediate bank roughness is required only if it is used in conjunction with a roughened toe.

While planting into coir logs is recommended and generally very successful, it should be noted that the water-holding capacity of coir logs is not as good, for example, as a comparable volume of loamy soil. Thus, establishment of riparian plants in coir logs can be difficult on mid to upper banks of droughty streambank sites, especially in eastern Washington.

Variations

Log Terraces

When used as a buttress at the toe of streambanks, an edge of coir fabric can be anchored under a coir log or laced to the log using strong coir or synthetic twine. Soil is then placed landward of the log, and fabric is wrapped over the fill material and staked in place to provide erosion protection for backfilled soils until vegetation establishes. Another excellent application of coir logs is to install them at intervals up a sloping bank surface to create steps or terraces to control surface erosion and aid plant growth. Another variation is to stack rows of coir logs upon one another to form a tall bank face. When stacking coir logs, the upper log should be placed above and behind the first log and the two logs should be laced together with stout coir or synthetic twine, laced every six inches and knotted at a minimum of every three linear feet to prevent separation of the logs.

Sediment Control

Coir logs can be used as sediment-control devices at the toe of stable, but nonvegetated streambanks on small and low-energy streams. While the logs can trap sediment running off of the bank, coir logs provide no protection from sediment inputs to the stream during high-flow events when the log is over-topped.

Alternatives

Straw Bales and Straw Logs

Low-cost alternatives to coir logs are hay or straw bales. Straw will tend to biodegrade more rapidly than coir, and this factor should be taken into account when considering using it. Unless applied in low-gradient, spring-fed creek environments, bales should be wrapped in coir fabric for added integrity. Straw logs are somewhat similar in appearance to coir logs, but they provide surface sediment control and are considered a biodegradable replacement for silt fences. Straw logs are not recommended for streambank applications.

Emergency

Coir logs are generally not applicable in emergency situations.

EFFECTS

Coir logs, if properly applied, provide deformable streambank protection and sediment retention. Within several growing seasons, these treatments can support a functional floodplain that, in turn, supports a diverse plant community and overhanging stream cover. Shrub plantings behind or within coir logs can provide roughness in flood flows and installed or colonizing trees will provide a long-term source of large woody debris. If used to narrow the cross section of an over-widened stream, sediment transport within the channel and sediment retention in the floodplain bench may be improved. This may make stream gravels more suitable for spawning.

If biodegradable coir logs are used, there are no long-term negative impacts from their installation. However, if coir logs with synthetic materials are installed, the breakdown time of the synthetic components may be on the order of decades.

DESIGN

A conceptual design of a typical coir log is shown in *Figure 6-38*. Because coir logs do not provide long-term bank stabilization, they should only be used in situations where vegetation will provide all necessary long-term bank strength.

Most manufacturers supply guidelines regarding maximum velocity and/or shear that their products can withstand. When considering such information, the designer should keep these observations in mind:

- tests conducted by manufacturers are generally short-term and do not reflect natural conditions including long flood durations and product degradation over time; and
- coir logs may withstand higher hydraulic forces than laboratory tests suggest by securing systems and surrounding in situ bed and bank materials.

Installing and Securing Coir Logs

Like many bank-revetment systems, weak points in coir-log revetments lie at the transitions between the logs and the securing system. The following are eight design/installation guidelines, based in part on Natural Resources Conservation Service recommendations[1] (note that the following procedures do not take into account supplemental bank-toe protection):

1. As with any bank-protection treatment, the coir-log technique should start and end in a stable reach.
2. Excavate a shallow trench for the log at the toe of the bank slope. The bottom of the trench should be slightly lower than the streambed level.
3. Inspect all coir logs for breaks in the netting, and repair all breaks with natural or synthetic rope prior to log installation. Place the logs in the trench such that the ends are butted firmly together. The logs should be laced together, end-to-end, with coir or synthetic rope to create a continuous length. End-to-end lacing may be completed either before or after placement in the stream, whichever is easiest. The upstream and downstream ends of the continuous length of coir logs tend to be weak spots and should therefore be buried three to five feet laterally into the bank to protect against erosive forces.
4. When properly installed, the upper surface of the roll should be parallel to the water surface at or above the ordinary high-water line and within the zone of perennial vegetation. Cut-and-fill adjustments can be made as needed, using only hand tools wherever possible, to seat the roll so that it lies smoothly at the correct elevation.
5. Secure the coir log in the trench by driving stakes (2 x 2 x 36 inches) between the binding twine and the inner log material on either side of the log. Pairs of stakes (one stake on each side of the log) should be installed at intervals of one to four feet along the length of the log, depending upon anticipated hydraulic forces. The tops of the stakes should not extend above the top of the log. All stakes should have notches that prevent laced twine from sliding off the ends of stakes.
6. In areas that will experience wave or ice action, 16-gauge wire should be used to secure the log. To install the wire, notch the outside faces of each pair of stakes slightly below the top of the log and install the wire through the notch.

7. Once the logs are secured, soil should be backfilled on the bank side of the log, and the bank should be reshaped as necessary. Planned surface treatments and plantings should then be installed on the bank. Care should be taken to disturb as little soil as possible outside the work area and to avoid damaging any existing trees and shrubs on or near the bank.
8. Rooted herbaceous plantings should be installed into the top or sides of the coir log. Alternatively, live cuttings can be installed through the log into the underlying substrate if a means to mechanically pierce the logs is available.

Planting in Coir Logs

Planting vegetation into coir logs can be difficult because of the tight fabric strands and the high density of the coir filling. Some manufacturers have responded to this problem by offering logs with three- to four-inch-deep, premade holes that make insertion of plant materials into the logs easier. Similarly, insertion of stakes through the logs can be much more difficult than might be expected (this partially explains why stakes are placed along the edges of coir logs); however, if a mechanical device is used to punch holes through the dense fill of coir logs, stout willows can be planted through the log for use as both staking and woody-plant cover. Other bioengineering techniques can also be used with coir-log applications, including brush layers and fascines. See the discussion in this chapter addressing *Woody Plantings* and Appendix H, *Planting Considerations and Erosion-Control Fabric* for more information.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

There may be some mitigation concerns for this type of treatment, since limiting channel migration can result in loss of overhanging banks and gravel sources. However, because coir logs are biodegradable and deformable, these effects tend to be short-term, as long as any toe protection that is added is also deformable.

Additionally, there may be impacts to fish habitat in terms of sedimentation during installation of coir logs; but, because impacts also tend to be temporary, mitigation is generally not required. Since coir logs can be installed using hand tools and because they trap sediment, they are less impacting in terms of sediment than many other types of streambank protection. To reduce habitat risks associated with construction activities, restrictions are placed on the allowable construction period. Best management practices for sediment and erosion control are also required. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Coir-log installation avoids mitigation needs for long-term impacts. A benefit of this technique is that bank stability and erosion control are provided while also creating conditions conducive to the establishment of dense, native-vegetative cover. Coir logs can be used to narrow the cross section of small, over-widened creeks, creating a functional floodplain and potentially improving the quality of spawning gravels. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this technique.

RISK

Habitat

The use of coir logs poses no long-term risk to habitat. When used to create low banks in relatively low-energy systems, coir logs produce a bank very similar in appearance and function to natural banks, once vegetation is established. This treatment can be used to transition into zones of existing adjacent vegetation.

Infrastructure

Coir logs pose no risk to infrastructure unless they are used incorrectly, which could result in continuing bank failure. It may be difficult to safely transition coir-log bank treatments into adjacent infrastructure such as bridges and culverts.

Reliability/Uncertainty of Technique

There is uncertainty in all treatments that rely on vegetation for long-term strength. An advantage coir logs have over other biodegradable products such as erosion-control fabric is that, because of their bulk and thickness, they tend to biodegrade relatively slowly. However, it is essential that coir logs be used at sites and within specific elevation ranges where aggressive plantings will succeed. Poorly executed site selection, log placement or revegetation techniques may leave a coir-log treatment inadequately vegetated and vulnerable to erosion as the coir log degrades.

Successful implementation requires a substrate suitable for installation of wooden stakes as well. Bedrock and substrate with a large amount of rock, such as a rock toe, may limit or prevent staking and securing of coir logs.

CONSTRUCTION CONSIDERATIONS

Materials Required

Depending upon the manufacturer, coir logs are available in a range of diameters, between six and 20 inches, and a range of densities, between six and nine lbs/ft^3. Commonly available lengths are 10 and 20 feet. The type of netting used to bind the coir logs can be either coir or synthetic (wire or twine). Higher-density coir logs provide greater stability and longer life than logs packed with lower densities of material. Synthetic netting is recommended over coir netting for banks subject to higher levels of shear stress and where conditions are such that the growth of vegetation will be limited in the first growing season. The range of conditions appropriate for each product should be based on the manufacturer's guidelines and the professional experience of the treatment designer and installer.

Simple coir-log installation requires the logs themselves, wooden stakes, biodegradable or synthetic rope, and rooted vegetation or cuttings. As mentioned above, wire or twine may be required as an added measure to secure logs in areas subjected to wave or ice action. Often, coir logs can be installed by hand, but heavy equipment such as an excavator may be useful on larger applications.

Timing

Coir-log installation should be undertaken when water levels are low. Ideally, this can also coincide with the riparian-plant dormant season to maximize the success of planted vegetation. When this timing is not possible, vegetation should be installed during the first planting season after bank construction. Coir logs can often be installed without dewatering in low flow conditions; however, dewatering may be required if excavation for supplemental toe protection is necessary. For further discussion of construction timing, refer to Appendix M, *Construction Considerations*.

Cost

The cost of coir logs is between $6 and $12 per linear foot, depending upon their diameter and density. Installed coir-log toe treatments with plantings cost about $26 per linear foot.[2] A similar treatment with the addition of erosion-control fabric and willow bundles runs about $43 per linear foot.[2] The cost will vary tremendously depending on what is done for bank-toe treatments under the logs and for upper-bank treatments.

Costs for implementing this treatment may also include gaining access to the site, dewatering, excavation, importing fill, and materials and installation of any additional toe materials and upper-bank treatments. For additional information on the costs associated with this technique, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

Because the long-term integrity of this bank-stabilization technique relies on the roots and shoots of vegetation, installed plantings may require irrigation, weed control and/or protection from grazing. The anchoring system may also need maintenance or replacement, with special attention paid to the wire or twine laced between stakes and over the logs.

MONITORING

Monitoring is an essential tool to evaluate project success, to ensure that project objectives are met and to determine if maintenance is needed. Monitoring activities should focus on potential weak points in the design, such as at transitions between undisturbed and treated banks and between different bank treatments. Monitoring should include regular photo documentation. Additionally, monitoring coir logs should be coordinated with monitoring associated bank-protection techniques, which may include upper-bank revegetation and other bank-toe treatment.

Monitoring should include detailed as-built surveying and photo documentation of the project area, as well as upstream and downstream reaches to evaluate performance relative to design. Details on developing a monitoring plan are discussed in Appendix J, *Monitoring.*

The monitoring plan for coir-log treatments should be designed to evaluate the integrity of the securing system, the integrity of the coir material over time and the success of the vegetative component incorporated into the coir log toe. Monitor the physical integrity of installed logs and securing systems in response to the first few high-flow events to which the bank treatment may be exposed. At a minimum, coir logs should be inspected for movement (indicating loose installation) or loosened securing components after flow events equivalent to the one-year flow for the first three years.

It is also important to monitor vegetation success. As with most biotechnical bank treatments, monitoring should be most intensive during the first year after installation and can be scaled back to a single, annual monitoring event in subsequent years. For further discussion of monitoring methods, see Appendix J.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[3] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

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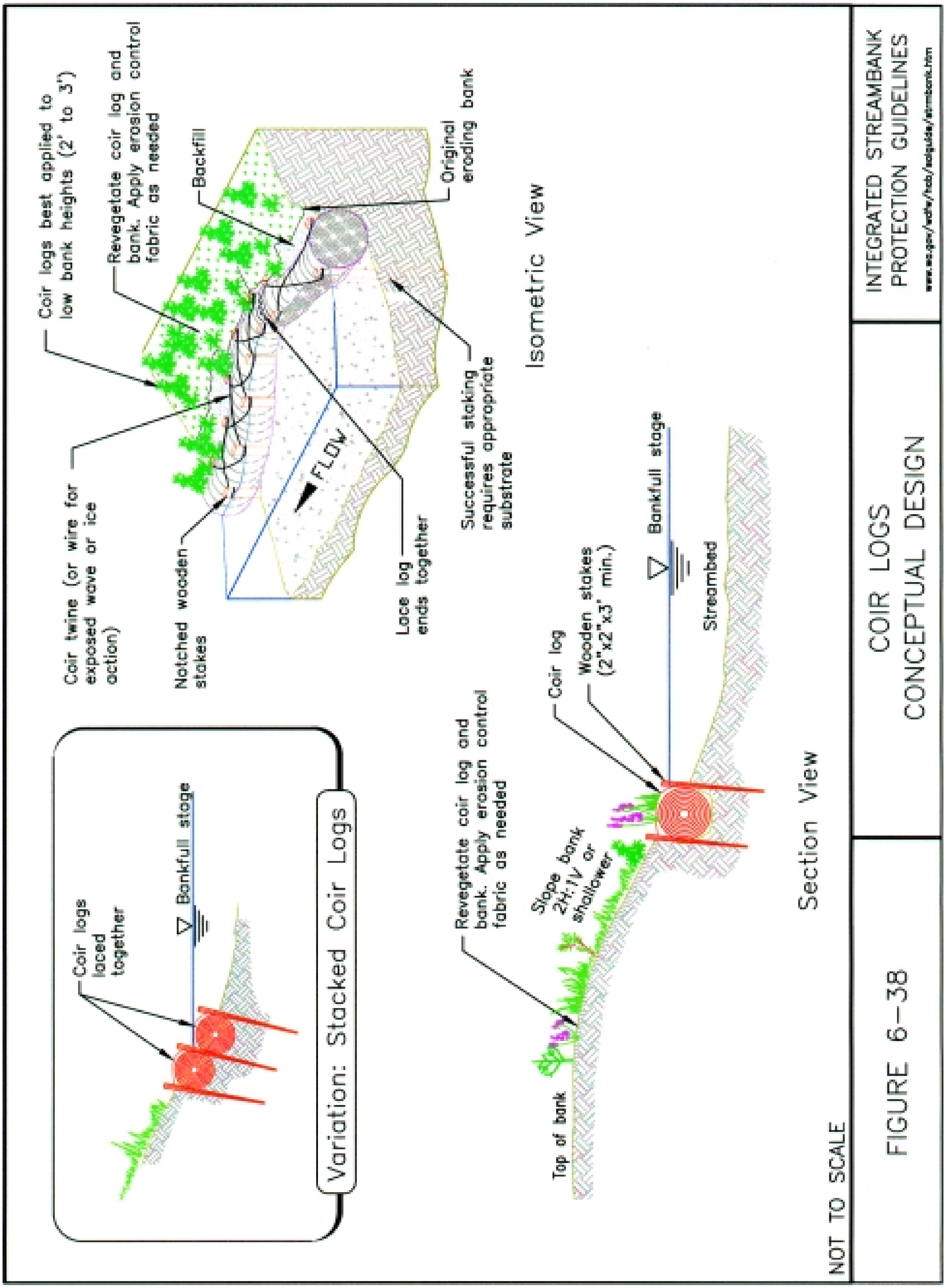
Figure 6-37. Coir Logs. Zaccuse Creek, Tributary to Lake Sammamish. 2000. Source: King County Department of Natural Resources.



Coir logs best applied to low bank heights (2' to 3')
Revegetate coir log and bank. Apply erosion control fabric as needed
Backfill
Original eroding bank
Coir twine (or wire for exposed wave or ice action)
Notched wooden stakes
FLOW
Lace log ends together
Successful staking requires appropriate substrate
Isometric View
Coir logs laced together
Bankfull stage
Variation: Stacked Coir Logs
Revegetate coir log and bank. Apply erosion control fabric as needed
Slope bank 2H:1V or shallower
Coir log
Wooden stakes (2"x2"x3' min.)
Bankfull stage
Streambed
Top of bank
Section View
NOT TO SCALE
FIGURE 6—38
COIR LOGS
CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES

DESCRIPTION

Bank reshaping stabilizes an eroding streambank by reducing the angle of its slope, without changing the location of its toe. Excavating the bank to reshape it changes the cross-sectional geometry for that segment of the stream. Bank reshaping is usually done in conjunction with other bank-protection treatments, including revegetation of the excavated bank and installation of toe protection and erosion-control fabric. *Figure 6-39* shows various applications of bank reshaping throughout Washington State.

APPLICATION

This technique is commonly applied along streambanks that are vertical, eroding and positioned in the outside bends of a stream, where they have been undercut and are failing in cohesive masses due either to toe erosion or to mass failure. Because bank reshaping provides greater cross-sectional area in a channel and it accommodates revegetation well, it is also a useful bank-protection technique for use in aggrading reaches. The ability to reshape banks may be limited where access is difficult for heavy equipment, and it may be unsuitable where mature riparian vegetation or infrastructure (such as roads, housing or bridges along the upper bank) stand in the way.

Bank reshaping is an effective way of addressing over-steepened banks resulting from virtually any mechanism of failure, but it generally requires that other treatments be incorporated as well. Bank reshaping can be especially effective when used in combination with some form of temporary or permanent toe hardening. Bank reshaping should not be applied at a reach level to prevent avulsion because it does not address the actual mechanism of failure. The problem would simply continue to occur.

Additional guidance on the applicability and limitations of bank reshaping based on both the site mechanism of failure and reach conditions can be found in Matrices 1 and 2 in Chapter 5, *Identify and Select Solutions*. Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* provides information on the application of assessing the causes of erosion.

Emergency

Attempting to reshape banks during a flood is not recommended because of the exposure of saturated and unprotected soil to the floodwaters.

EFFECTS

By definition, bank reshaping consists of changes to channel bank slope and cross-section configuration. It generally results in increased channel cross-sectional area (see Appendix F, *Fluvial Geomorphology*). Bank reshaping is a necessary component of some of the biotechnical practices and structural remedies described in these guidelines. In addition, it provides a number of benefits to the stream system. First, making the slope shallower adds stability and reduces the banks susceptibility to failure. Second, the additional bank surface area effectively creates more roughness in the cross section and dampens the effects of secondary currents in river bends. The added roughness and cross-sectional area decreases average and local velocities, slows erosion and increases the likelihood of sediment deposition. Third, modifying the channel bank slope makes it easier for vegetation to take hold, and a shallower slope facilitates planting and long-term maintenance. Fourth, reducing vertical bank slopes that have excessive drainage improves soil moisture conditions. Fifth, bank sloping may improve recreational access to the river, and it reduces safety hazards. Bank sloping often results in an initial loss of undercut banks, which provide good fish habitat; however, undercut banks can be integrated into bank-toe design or may occur naturally once vegetation is well established.

DESIGN

Designs associated with bank reshaping are site-dependent. On small creeks, or where infrastructure is not at risk, reshaped banks may be accomplished with relatively simple design and planning. In other instances, bank reshaping may require extensive analysis, design and preparation of complete plans and specifications. Principal components of bank-reshaping design may include revegetation, surface soil-erosion control and toe protection. A conceptual design drawing is shown in *Figure 6-40*.

Bank reshaping has several components, including excavation of over-steepened bank materials, placement or transport of excavated materials, and the recontouring or reshaping of excavated streambanks. Often, recontouring is the most difficult of these phases because it requires the combination of an understanding of fluvial processes, a skilled excavator operator and subtle grade breaks. A reshaped bank must transition well from adjacent treated or untreated banks so that the erosive forces of flowing water will not be concentrated on a specific area.

During the design and construction phase, be sure to minimize the removal or root disturbance of existing riparian trees and shrubs. They play many important roles in stabilizing banks and providing fish habitat, and they need to be protected.

Slope Grading

The actual grading or slope configuration related to this technique varies. At the simplest, banks can be graded to a stable slope and planted with tree shrubs and native seed (see Appendix H, *Planting Considerations and Erosion-Control Fabrics*).

The constructed slope of the bank may also vary, depending upon the height of the bank, soils strata, seasonal groundwater conditions and seepage from the bank, revegetation needs for soil and moisture conditions, and availability of land. Soils, vegetation and hydrologic conditions should be clearly understood for the site, and appropriate expertise should be consulted on the subjects.

To mimic natural banks, the slope should be varied along the length of a stream reach so that a constant slope is avoided. One approach to add variability to both habitat complexity and slope is to use large woody debris in the toe of a resloped bank. Where width allows, it may also be possible to incorporate a nearly horizontal bench or terrace into the reconfigured slope. Another variation is to create shallow swales or depressions on the upper surface of a resloped streambank to create micro-sites that will support diverse vegetation types.

Revegetation and Soil-Erosion-Control Fabric

On small streams, placement of salvaged sod or other types of herbaceous and woody vegetation on the reshaped bank may be sufficient to prevent surface erosion and to establish vegetative cover. However, there is always the risk that bare soils will erode as a result of either rainfall or high flows before vegetation becomes established. At more severe sites, a recontoured bank may need to be covered with erosion-control fabric or other forms of bioengineered bank protection. In general, the need for erosion-control fabric on reshaped banks should be based on the scale of the project, a thorough understanding of the mechanisms of failure at work and the risk of erosion should vegetation not become established. Topsoil may have to be placed over the cut bank to improve revegetation conditions. Topsoil might be placed over the entire area to be planted or in zones for specific vegetation types. See Appendix H for further discussion of these topics.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Replanting vegetation on the reshaped banks may be the primary habitat mitigation needed. Additionally, if a nondeformable bank-toe treatment is used in combination with reshaping, then the lost opportunity for recruitment of gravel and large woody debris will require mitigation.

Because this technique requires considerable earthwork and excavation, temporary impacts during construction can be considerable. To reduce habitat risks associated with construction activities, restrictions are placed on the allowable construction period. Best management practices for sediment and erosion control must also be implemented.

Considerable volumes of excavated soil can be generated by a bank reshaping project. The proper disposal of those soils should be planned for so they do not jeopardize other habitats.

Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

This technique will reduce sediment input to a stream once banks become revegetated. Stable, low-gradient banks enable the re-establishment of native, riparian plant communities to occur more quickly than if left alone and may improve bankline habitat complexity.

RISK

Infrastructure

Bank reshaping has no impact on infastructure.

Reliability/Uncertainty of Technique

Like many other streambank treatments, the reliability of this technique depends upon the quality of its design and implementation. If modes of bank failure are not addressed and reshaped bank surfaces not adequately protected, the site will likely continue to erode. And, if transitions between treated areas and untreated areas are not dealt with properly, this technique is prone to failure.

CONSTRUCTION CONSIDERATIONS

Materials Required

Bank reshaping, at a minimum, requires an excavator or equivalent piece of heavy machinery for earthwork. If excavated material needs to be moved a farther distance than the reach of an excavator, additional equipment such as loaders, dozers or dump trucks may be needed to haul or move material. The only imported materials required may be topsoil or soil amendments, seed and locally harvested or salvaged plant materials. On more complex projects, materials for use in toe reinforcement, erosion control and planting of nursery-grown vegetation may also be needed. Careful consideration should be given to the potential for soil eroding from the bank before vegetation has a chance to become established. For further discussion of construction considerations, see Appendix M, *Construction Considerations.*

Timing Considerations

In most regions of Washington, fall is the best time for this type of work; flow levels are low; soils are generally dry, and most plant materials can be safely installed. The survival of plantings may require a spring construction period and/or an extended construction period to appropriate planting seasons. Any instream work will depend upon resident and anadromous fish presence and may require dewatering. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). For further discussion of timing considerations, see Appendix M.

Cost

In its simplest form, bank reshaping is one of the least expensive types of bank-reconstruction techniques. Bank reshaping costs typically vary between $10 and $45 per foot of streambank treated. Revegetation costs for reshaped banks may vary between $1,000 and $5,000 an acre, depending upon plant materials and soil amendments applied. Topsoil added may cost between $10 and $15 per cubic yard. Site-specific factors such as site access, quantity and haul distance of excavated material, and the degree to which erosion-control products and natural, wood materials are integrated into the reconstructed bank will result in site-specific and wide-ranging costs. If dewatering is necessary, costs will increase considerably. For further discussion of costs, see Appendix L, *Cost of Techniques*.

MAINTENANCE

Maintenance requirements for reshaped banks are relatively minimal, since this type of treatment is generally self-sustaining. Maintenance may involve care of vegetation, including irrigation, weed control, mowing, plant replacement and protection of vegetation from beaver damage, depending upon the site.

MONITORING

Monitoring is an essential tool to evaluate project success, to ensure that project objectives are met and to determine if maintenance is needed. Monitoring activities should focus on potential weak points in the design, such as transitions between undisturbed and treated banks and between different bank treatments. Periodic photo documentation should be included. The long-term success of bank-reshaping treatments will ultimately depend upon revegetation efforts and, if toe protection is incorporated, the integrity of toe-protection methods.

Monitoring should include detailed as-built surveying and photo documentation of the project area, including upstream and downstream reaches, to allow for evaluation of performance relative to design. Details on developing a monitoring plan are discussed in Appendix J, *Monitoring*.

Monitoring should involve inspecting for any signs of erosion, including at the toe of the bank, and should include photo documentation at each monitoring interval. Vegetation coverage and survival, weed establishment and response of the stream to the modified configuration should also be monitored relative to revegetation success criteria. Monitoring should include structural and functional evaluation of any habitat mitigation required.

Monitoring frequency should be most intensive (monthly) during the first few seasons following construction but may be reduced to annual monitoring in subsequent years. Additionally, monitoring should be conducted following any events that equal or exceed the one-year flow during the first three years following construction. For further discussion of monitoring methods, refer to Appendix J. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[1] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

REFERENCES

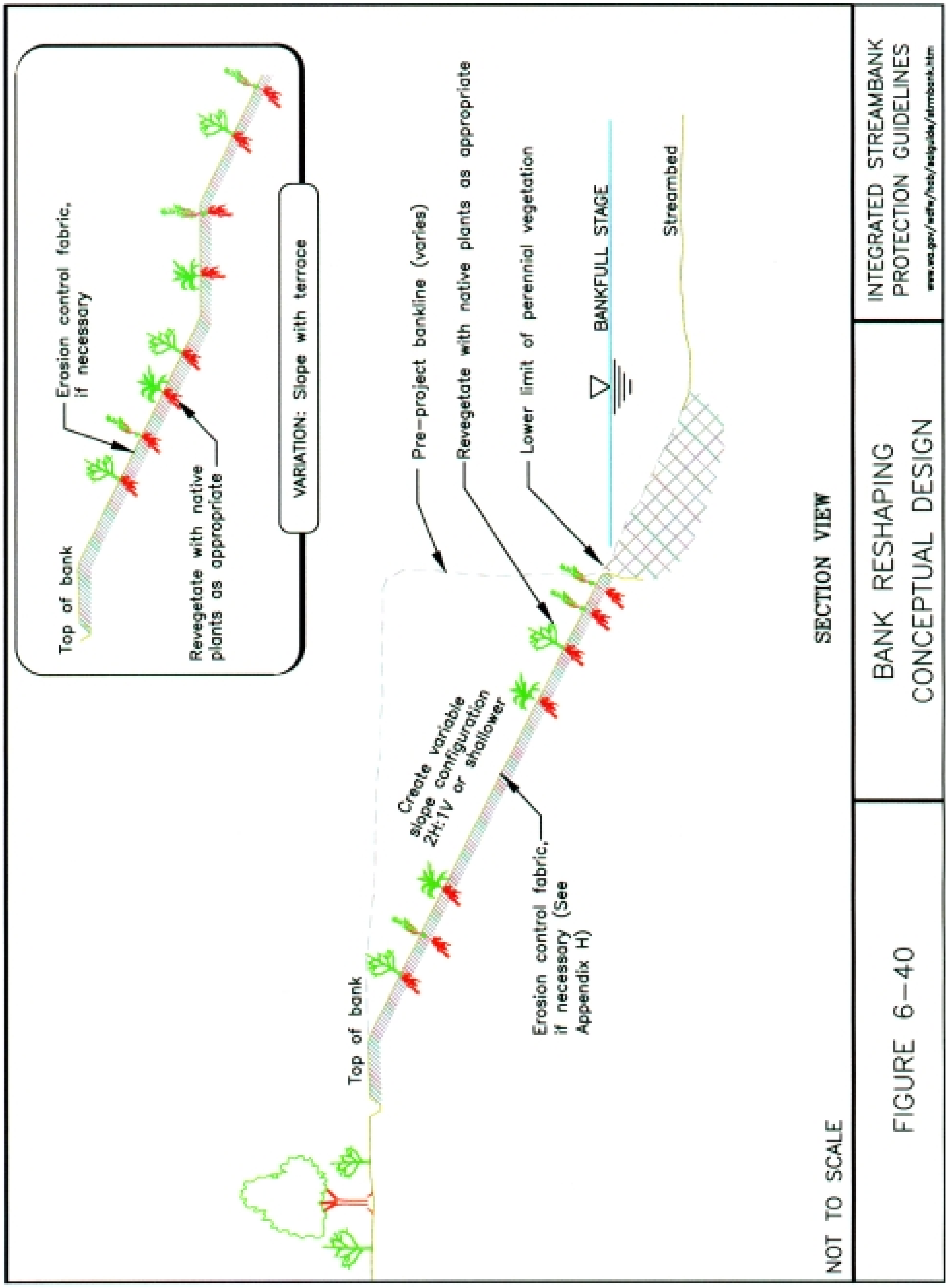
1 Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife, Olympia, WA.

a. Bank reshaping. Unidentified creek in Montana.
Source: Inter-Fluve, Inc.

b. Bank Reshaping. Chimacum Creek, Tributary to Admiralty Inlet, Puget Sound. 1996.

c. Bank Reshaping. Touchet River.

Figure 6-35. Various applications of bank reshaping throughout Washington State.



Top of bank
Revegetate with native plants as appropriate
Erosion control fabric, if necessary
VARIATION: Slope with terrace
Pre–project bankline (varies)
Revegetate with native plants as appropriate
Lower limit of perennial vegetation
BANKFULL STAGE
Streambed
Top of bank
Create variable slope configuration 2H:1V or shallower
Erosion control fabric, if necessary (See Appendix H)
SECTION VIEW
NOT TO SCALE
FIGURE 6–40
BANK RESHAPING CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES

Subsurface Drainage Systems
Internal Bank-Drainage Techniques

DESCRIPTION

Subsurface drainage systems, installed under or behind surface bank treatments, such as riprap or soil reinforcement, alleviate saturated soil problems in streambanks, side slopes and embankments. Subsurface drainage systems increase slope stability by decreasing soil-pore pressure. Subsurface drainage systems can be installed in a variety of configurations, including chimney drains, collection drains and gravel seams. These may include gravity or pumped systems.

APPLICATION

Subsurface drains are rarely installed as a stand-alone treatment, but they can be useful when used in combination with other treatments if any or all of the following conditions exist:

- rapid drawdown situations;
- high banks;
- steep banks;
- signs of slumping, seeps or soil creep; or
- poorly-draining soils.

Subsurface drains are often appropriate on eroding banks where the mechanism of failure is subsurface entrainment, which may be caused by poorly draining soils, rapid drawdown or excessive groundwater seepage. See Chapter 2, *Site Assessment* for more information about subsurface entrainment. See Chapter 3, *Reach Assessment* and the screening matrices in Chapter 5, *Identify and Select Solutions* for more guidance on the applicability of subsurface drains based on the mechanism of failure and causes of streambank erosion.

Variations

The purpose of subsurface drains in slopes is to provide an efficient and effective way for water contained in the slope to drain. This, in turn, reduces soil-pore pressure and enhances slope stability. Any mechanism that serves this purpose can be considered a subsurface drain. Characteristics that make a particular internal drainage system suitable for use in streambanks include:

- ease of installation,
- resistance to clogging,
- availability of construction materials, and
- unlikelihood of acting as a failure plane and precipitating slope failure.

Low potential for becoming clogged is important for streambank drainage systems because of the high volume of water they must convey. Unlike drains in the typical hill slope setting, streambank drainage systems must perform under rapid drawdown conditions, which produce high rates of seepage flow in bank materials. Such high rates will tend to clog poorly designed drains quickly. Subsurface drains constructed of natural materials are desirable in situations where erosion may otherwise expose and carry away portions of the drain, such as when streambanks are designed to allow a degree of natural deformation.

It is important that subsurface drains not become a failure plane. Many of the commercially produced drainage materials are designed for placement against retaining walls and foundations. When these materials are placed within the unsupported soil of a streambank, they can act as a failure plane.

Gravel seams and sloped sheet drains slope back into the bank at an *angle*. These drains typically underlie the treatment that is applied to the bank face (e.g., stepped geocellular system or fabric encapsulated soil). They form a planar surface that separates the native bank material (or fill) from the surface bank treatment. In this application, they can double as filter material for rock-toe and riprap treatments (see the discussions in this chapter addressing the techniques, *Rock Toes* and *Riprap,* for additional information). Seepage enters the drain from the overlying bank face and the underlying native bank material and is transmitted downward into a collection drain or porous bank toe.

Chimney drains are vertical drains that typically feed into a collection drain at their base. Chimney drains can be constructed of natural granular, sheet drain or high-profile drain materials. Chimney drains function in a manner similar to gravel seams and sloped sheet drains. Used primarily in conjunction with building foundations and retaining walls, chimney drains are commonly installed directly against a supportive structure. In bank construction, chimney drains may be installed on the back side of supportive structures such as cribwalls.

Collection drains lie along the base of gravel seams, sloped sheet drains and chimney drains. They collect discharge from these overlying drains and discharge it into the adjacent stream or river. Collection drains can be constructed of natural granular materials, synthetic materials, perforated pipe or any combination of these materials. Often, gravel seams, sloped sheet drains and chimney drains connect directly to a bank toe constructed of stone or similar porous material. In this case, the bank toe acts as a collection drain.

Emergency

Subsurface drainage systems are generally not practical for emergency applications.

EFFECTS

Subsurface drains generally improve bank stability and can increase the integrity of structural bank-protection techniques. However, the necessity of major excavation for installation results in a significant impact to riparian and bank vegetation and roots. Furthermore, drains may result in dry soils along streambanks, jeopardizing the survival of moisture-dependent riparian plants.

DESIGN

Generally, subsurface drainage is worthy of consideration in cases where streambanks are steep or high, or where other factors are present that bring slope stability into question. In such cases, a geotechnical engineer should be employed to assess bank stability under all expected conditions and to assist in subsurface drain design. Consult geotechnical manuals or manufacturer specifications for design drawings.

Design Criteria

Subsurface drains should be designed to meet the following design criteria:

- the drain should have adequate capacity to rapidly dewater the streambank,
- the drain must not allow soil particles to clog the filter surface or core,
- the drain must not act as a failure plane within the bank (sheet drains and filter fabric may be more likely to do this than natural granular materials),
- the drain should extend high enough and low enough within the bank to intercept seepage from highly permeable layers in the bank soil profile (it should adequately drain all components of a bank-treatment system that require such drainage), and
- the drain system should discharge through the bank toe.

Most geotechnical design manuals include information on subsurface drainage-design. These manuals are also a good source for finding drawings and pictures of subsurface drainage systems. In addition, riprap-design methods generally include procedures for gravel-filter design that are also appropriate for gravel-seam design (refer to the discussion on *Riprap* in this chapter).

Gravel Seams

Methods for granular-filter design are included in most riprap design manuals (see discussion about the use of *Riprap* in this chapter). A typical gravel seam drain is eight to 12 inches thick and composed of gravel whose size has been selected to bar the entry of native soil particles. Occasionally, particularly if the native bank material is very fine-grained, a layered filter composed of progressively finer granular materials is required. Alternatively, geotextile filter fabric is sometimes used as an outer layer for gravel drains in fine-grained soils.

In most cases, if a gravel seam of evenly-graded gravel is installed at a 2:1 slope or flatter, it will not be prone to acting as a failure plane. Steeper seams and seams placed in a bank with an inherently unstable soil profile should be analyzed by a geotechnical engineer before installation is attempted.

Gravel is often used as a filter layer under riprap and articulated concrete blocks. When used in this capacity, the gravel also serves as a subsurface drain.

The outlet for a gravel seam is typically the bank toe (generally constructed of stone or similar porous material). Connectivity must be maintained between the gravel seam and the porous toe material to allow free flow of water. Alternatively, a collection drain can be used to receive seepage from the gravel seam and transmit it to the bank toe.

Sloped Sheet Drains

Manufactured sheet drains can be oriented such that they angle back into the bank like gravel seams. They have the potential of acting as a failure plane if installed too steeply or if bank materials are prone to sliding or rotational failure, so it is important that a geotechnical engineer be involved in the design of them.

Chimney Drains

Like sheet drains, chimney drains have the potential of acting as failure planes in streambanks. For supported banks, such as banks faced by cribwalls, chimney drains are typically installed directly behind the supporting structure. Under these conditions, structural design should consider the effects of chimney drains on the behavior of the bank soil retained behind the supporting structure.

Horizontal Collection Drains

Collection drains are linear structures oriented parallel to the bank face at the bank toe. Typically, the horizontal and vertical extent of collection drains within the bank cross section is not extensive. Thus, by themselves, collection drains hold less potential for acting as failure planes than do the other types of drains previously discussed.

Whether collection drains are constructed of gravel, perforated pipe, high profile drains or a combination of these materials, there are several general guidelines for their design. Like other types of drains, a collection drain must have adequate conveyance capacity to efficiently dispose of all collected water. Collection drains must also be designed so as not to clog with particles from the surrounding soil. Finally, collection drains must include a means of efficiently discharging collected water into the stream. This discharge is most easily accomplished by routing the collection drain into the back of a bank toe constructed of stone or similar porous material. Alternatively, collection drains can discharge into a stone-and-gravel filled sump at the toe of the bank. The sump design should recognize the dominant stream-sediment processes at the proposed site.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Subsurface drains are often installed associated with a surface bank treatment, and the mitigation requirements depends mostly upon the mitigation requirements of the associated surface treatment. Refer to Chapter 4, *Considerations for a Solution* for further discussion of mitigation. Depending upon drain configuration, the inclusion of a drain in association with a surface bank treatment generally will not increase the impacts of the surface treatment appreciably. Significant, additional excavation may be required to accommodate a drain, in which case the impacts will typically be in the form of disturbance to riparian vegetation. In such instances, action such as replanting should be undertaken to mitigate for this disturbance. Refer to Chapter 4 and Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

There are no mitigation benefits provided by this technique, though it may reduce the amount of instream work.

RISK

In general, drains will decrease risk to property and infrastructure behind the banks by enhancing bank stability. However, an improperly designed or constructed drain may have the potential to serve as a plane for bank failure.

Risk to habitat will be dictated by the bank-protection technique constructed in association with the drains.

Drains may result in decreased water availability to riparian plant species.

Reliability/Uncertainty of Technique

If properly designed, subsurface drains can serve reliably for many years.

CONSTRUCTION CONSIDERATIONS

Disturbance of Vegetation

Subsurface drains require complete excavation for installation. Consequently there will be a significant impact to existing vegetation and roots. Removal or root disturbance of riparian trees and shrubs should be minimized on all bank-treatment projects, though complete removal of these plants should be anticipated and mitigated (see Appendix H, *Planting Considerations and Erosion-Control Fabrics*).

Materials Required

Typical subsurface drainage materials include natural, granular materials (such as gravel and sand) and manufactured soil-drainage products (such as sheet drains, high-profile drains, synthetic filter fabric and perforated pipe).

Natural, granular materials have the advantages of being locally available and relatively inexpensive, easy to install, aesthetically appealing and biologically inert if exposed by erosion. Additionally, they are not particularly prone to acting as a failure plane.

Sheet drains are composed of synthetic materials configured such that water is filtered by the outer layer of the drain and conveyed efficiently by the inner layer. Sheet drains are easy to install and can be oriented vertically within a supported bank (e.g., behind a log cribwall or similar supportive structure). Caution should be used when using sheet drains in unsupported banks as they may act as a failure plane.

High-profile drains are similar to sheet drains, but are narrower and flatter than sheet drains. High-profile drains are often used as collection drains at the base of sheet drains.

Synthetic filter fabric can be useful as a component of composite drains. For instance, crushed gravel is often wrapped in filter fabric to form subsurface drains. In this configuration the filter fabric prevents fine soil particles from entering the gravel, while the gravel provides a highly porous conduit for water to exit the bank.

Perforated pipe is also generally used as a component of composite drains. It is often laid in a trench and surrounded by gravel or sand. As water passes through the surrounding granular materials towards the pipe, fine soil particles are filtered out. The filtered water that enters the pipe is then efficiently conveyed out of the bank.

Timing Considerations

Because subsurface drains usually underlie a surface bank treatment, they are often the first component to be installed in bank treatments. Drains should be installed during low flow, when dewatering is possible, and when resident and anadromous fish are less likely to be impacted by construction activities. Dewatering allows for ease of installation and prevents siltation of the stream during construction. This can be accomplished with a coffer dam during low water.

Critical periods in salmonid life cycles such as spawning or migration should be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Cost

The cost of subsurface drains will include the materials selected, excavation, labor and equipment needed. Costs will be influenced by availability, transport and site access. Costs tend to vary significantly from site to site due to the wide range of materials and approaches available. For the most part, prices also fluctuate greatly both geographically and over time. Prices for gravel filter drains have remained fairly stable, however, and typically range from $30 to $160 per cubic yard.

For further discussion of costs, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

Subsurface drains cannot be accessed once installed, nor can they be easily monitored, except by examining the banks in which they are installed. When pipe is used to construct drains, cleanouts should be conducted at all junctions and at intervals of 100 feet. Pipes should be cleaned twice per year and at least once soon after any high flows.

MONITORING

Subsurface drains cannot be reasonably monitored independent of their associated bank treatment. Normal monitoring protocol established for the associated bank treatment should be sufficient for the subsurface drains. The effectiveness of subsurface drains in dewatering the bank can, however, be monitored indirectly by examining for signs of seepage at the bank surface or slumping/sliding of the bank surface. Refer to the monitoring discussion for the associated bank protection techniques described in this chapter and to Appendix J, *Monitoring*, for further details on monitoring protocol.

Floodplain Roughness
Avulsion-Prevention Techniques

DESCRIPTION

Floodplain roughness is a preventative technique used to decrease overbank flow velocity and related shear stress when there is a potential for a channel avulsion or chute cutoff to form. An increase in roughness is affected by the presence of live trees and shrubs, and large woody debris in the floodplain. This technique is also referred to as floodplain tree/large woody debris rows, live siltation fences, brush traverses, brush rows and live brush sills.[1] *Figure 6-41* shows various examples of natural floodplain roughness.

APPLICATION

Floodplain roughness elements are used in areas where the floodplain is either newly constructed or where land-management practices have left little natural roughness, leaving the stream susceptible to avulsion. A channel may also be prone to an avulsion or chute cutoff if the basin hydrology is flashy (rapid changes in discharge levels and water-surface elevation associated with storm events) or if the channel is aggrading, resulting in frequent overbank flow events. Refer to Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for further discussion of site-related and reach-related causes of an avulsion or chute cutoff. Typical implementation of floodplain roughness includes placing large woody debris perpendicular to the predicted overbank flow direction at the locations where an avulsion or cutoff is likely to form. If shear stresses are high during flood flows, large woody debris can be anchored to the floodplain. Live trees or dense rows of live cuttings may also be planted in rows roughly perpendicular to the channel.[1]

Floodplain-roughness approaches are generally appropriate when there is potential for an avulsion or chute-cutoff to occur. Refer to matrices in Chapter 5, *Identify and Select Solutions* for assistance regarding the proper selection and application of the most suitable technique for the circumstances in question. Floodplain roughness elements may be inappropriate in floodplains naturally devoid of woody vegetation (e.g., low-gradient, meadow-stream systems). In such instances, the risk and consequences of an avulsion forming are generally low.

Emergency

Floodplain-roughness elements are used as a preventative measure and have little utility in an emergency situation where the channel is in imminent danger of forming an avulsion or chute cutoff. However, it may be possible to install roughness structures (e.g., ecology blocks, large woody material) across the floodplain during an emergency overbank situation where flows are concentrated, with active headcutting.

EFFECTS

Floodplain roughness elements slow overland flow velocity during flood events by increasing roughness which slows floodplain flow velocity and dissipates energy. The net result is that the stream is less likely to abandon its current channel and create a new one.

Floodplain roughness may also increase depth of flow in the floodplain by reducing velocity during overbank flow events. In situations with strict floodplain- and flood-management regulations, the potential effect of increased flow depth should be evaluated with respect to allowable increases in flood-level flow elevations.

DESIGN

Flow velocity, depth and shear stress in the floodplain from overbank flows are modeled using hydraulic models, such as HEC-RAS.[2] The results from these models are then used to design a treatment that reduces floodplain shear stress and the risk of an avulsion or chute cutoff. Refer to the Appendix E, *Hydraulics* for further discussion of calculating shear. A conceptual design drawing is shown in *Figure 6-42*.

Large woody debris or vegetative roughness elements are placed on the floodplain approximately perpendicular to the down-valley slope on either side of vulnerable locations, such as at tight bends.[1] A combination of riparian plantings, live brush rows and large woody debris can be used individually or in combination. Native riparian plantings are densely planted in a random pattern on the floodplain. It is recommended that various configurations of live cuttings be oriented into multiple rows (live brush rows).[1] Multistemmed shrubs are preferable over single-stemmed trees, since they tend to disperse flood flows and encourage sediment deposition. The use of live cuttings is preferable over container or bare-root plants since they can be planted deep enough to reach the water table and are less prone to washout during flood flows. For guidance on planting, see the discussion in this chapter addressing the technique, *Woody Plantings*, and to Appendix H, *Planting and Erosion-Control Fabrics*.

Large woody debris may need to be anchored to the floodplain if high shear stresses are anticipated during design flood flows (see Appendix I, *Anchoring and Placement of Large Woody Debris* for additional information). Large woody debris with intact branches is preferable, since the branches provide greater roughness than a bare tree trunk does. If this is not available, an alternative is to cable multiple bare logs together into a matrix configuration to simulate a tree with intact branches. The design should not result in substantial reduction in floodplain flow conveyance.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

No mitigation is required for implementing this technique. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for additional guidance concerning mitigation.

Mitigation Benefits Provided by the Technique

Adding large woody debris or live plants to the floodplain, in most instances, increases biologic diversity for terrestrial plants and animals and roughness and complexity to the floodplain.

This technique provides protection for the maintenance and integrity of the floodplain or other elements at risk. If the risk of avulsion that is being managed is created or exacerbated by man-made conditions, there may be a biological benefit to controlling the induced avulsion. Conditions that might warrant protection from an avulsion include increased sediment or peak flood events specifically due to human land-use activities.

RISK

Habitat

There is little risk to either aquatic or terrestrial habitat from this technique.

Infrastructure

This technique may decrease the risk to infrastructure on the banks and in the floodplain.

Reliability/Uncertainty of Technique

Reliability of the technique is based upon being able to predict where an avulsion might occur and placing roughness elements in that location. Roughness elements can inadvertently concentrate flows in other areas of the floodplain, thereby increasing the potential for an avulsion or chute cutoff to occur in those areas. In instances where live vegetation is planted for the purpose of roughness, success will depend on plant survival.

CONSTRUCTION CONSIDERATIONS

Materials Required

Appropriate woody-debris materials include rootwads, logs or whole trees. Likely candidates for live trees and shrubs include alder, cottonwood and willow. The application of erosion-control fabric that is both biodegradable and erodable on a constructed floodplain surface may be appropriate to provide protection while vegetation becomes established. During emergency situations, ecology blocks can be applied as a temporary measure.

Timing Considerations

Placement of woody debris is desirable before periods when higher flows are expected. Planting of live trees and shrubs may occur either in early spring or late fall to facilitate their survival. For additional information, refer to the discussion in this chapter addressing *Woody Plantings* and to Appendix H). Floodplain roughness should not require working the active stream channel and so is not affected by instream construction windows.

Cost

The cost of installing floodplain roughness elements can be minimal if locally available large woody debris is used. Costs increase substantially when using live plantings and varies according to the maturity of the plants. Seedling plantings can be acquired and planted relatively inexpensively, but they do not provide immediate protection or benefit. Larger, potted, plant stock is more expensive than seed, and the labor costs are higher to install. But these more mature plants will provide benefits sooner. For further discussion of materials costs, particularly for vegetation, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

Roughness elements consisting of large woody debris do not require regular maintenance. However, maintenance may be needed following large flood events. For instance, woody debris may need to be re-anchored or replaced. Live plantings may require considerable maintenance and possibly irrigation during the first year. Additional live trees and shrubs may be needed to replace trees lost to mortality.

In the event that monitoring indicates development of scour or a floodplain channel following an overbank flow, maintenance of existing treatment, or application of other avulsion-prevention techniques may be appropriate. Refer to the discussions in this chapter addressing *Floodplain Flow Spreader and Floodplain Grade Control* for additional information regarding other avulsion- and chute-cutoff-prevention techniques.

MONITORING

All roughness elements installed should be mapped at the time of installation, and photo points should be established that are clearly identified on base maps. Monitoring will be qualitative for the most part. It should consist of visual observation and photo documentation from established photo points. Any roughness elements lost during overbank flow events can be indicated on base maps. Monitoring should be conducted following all overbank flows to observe any scour development or channel development on the floodplain in addition to any debris deposited by large flood events. Additionally, monitoring should include documentation of plant growth on the floodplain. Refer to Appendix J *Monitoring* for additional guidance on monitoring-plan development and monitoring methods.

REFERENCES

1 Sheicthl, H. M. and R. Stern. 1994. Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection. Blackwell Sciences, London, UK. 189 pp.

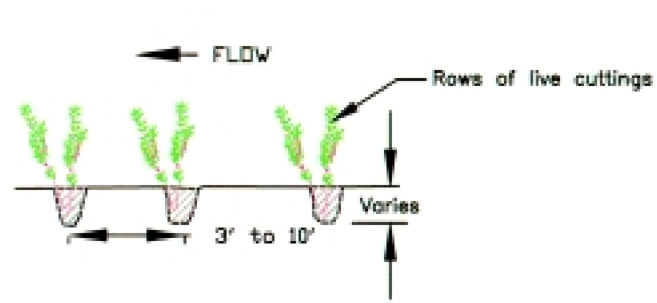
2 U. S. Army Corps of Engineers. 1997. HEC-RAS, River Analysis System, Version 2.0. Hydrologic Engineering Center, Davis, CA.

a. Floodplain Roughness using large woody debris. Clearbranch Creek, OR.
Source: Inter-Fluve, Inc.

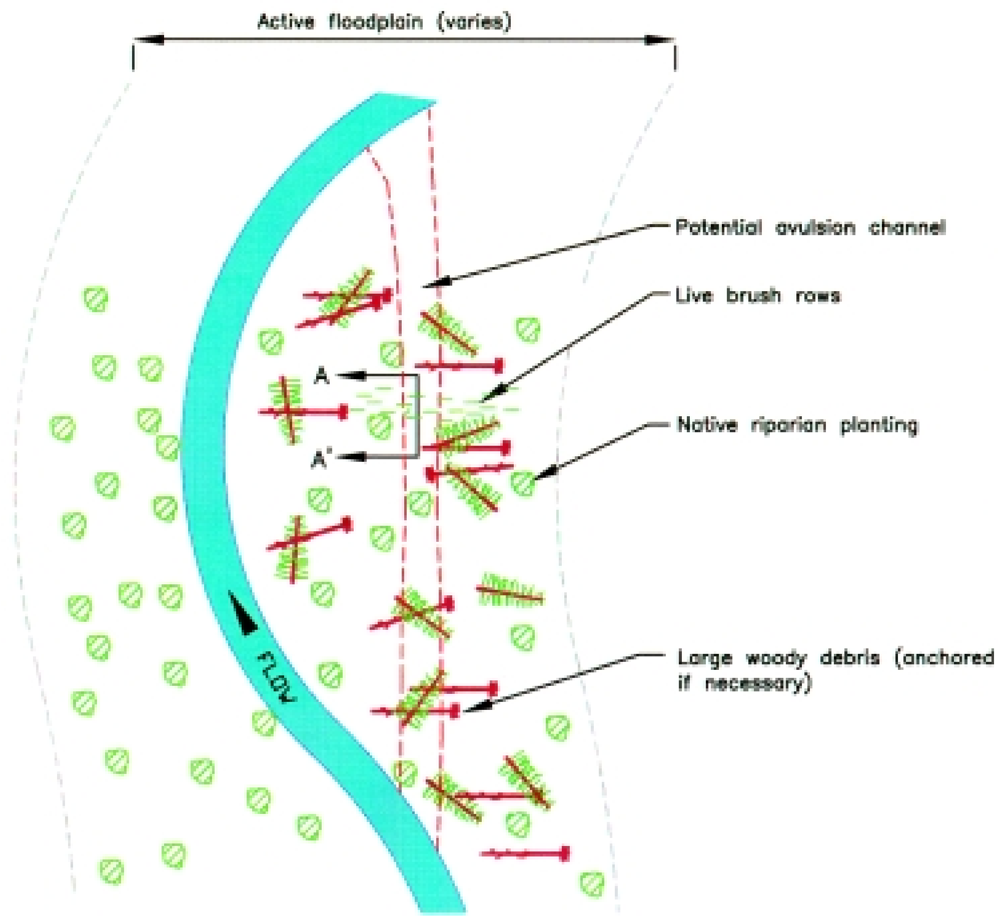
b. Floodplain Roughness. Woody plantings planted on floodplain for roughness. Salmon Creek, Tributary to Columbia River.
Source: Inter-Fluve, Inc.

c. Floodplain Roughness. Tree rows planted in floodplain for roughness. 1997.

Figure 6-41. Various examples of floodplain roughness.



Section A–A': Live brush rows



Notes:

1. Riparian plantings, live brush rows and LWD can be used individually or in combination to increase roughness and sediment deposition.
2. Flexible, multi–stemmed shrubs may be better choices on floodplain plantings compared to single–stemmed trees; they tend to better disperse flood flows, and encourage sediment deposition.
3. In riparian plantings and live brush rows the use of live cuttings may be better than containers or bare–root plants because they can be planted deep enough to reach water tables, are well suited to course floodplain soils, and are less prone to wash–out during flood flows.
4. LWD may need to be anchored based on design flood flows.

NOT TO SCALE

FIGURE 6–42	FLOODPLAIN ROUGHNESS CONCEPTUAL DESIGN	INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

Floodplain Grade Control
Avulsion-Prevention Techniques

DESCRIPTION

Floodplain grade-control structures prevent avulsion or chute cutoff. They are made of erosion-resistant material, such as large rock or logs, and they work on the subsurface level of the floodplain to prevent overland flow from forming a new channel where public safety or property may be threatened. These structures are placed in the floodplain, perpendicular to the down-valley direction, to prevent flood flow from scouring and headcutting a new channel into the floodplain (see *Figure 6-43* for an example of headcutting).

APPLICATION

Typical Application

Floodplain grade-control structures are typically used where there is potential for an avulsion or chute cutoff to develop. Floodplain grade control is used in areas where the floodplain is susceptible to an avulsion of a chute cutoff, either because it is newly constructed or it has little natural roughness due to land management practices. A channel may also be prone to an avulsion or chute cutoff if the channel is aggrading or if the basin hydrology is flashy (experiences rapid changes in flow level). Refer to Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for further discussion of site and reach based causes and mechanisms of an avulsion chute cutoff. The screening matrices in Chapter 5, *Identify and Select Solutions* contain additional guidance on the applicability of floodplain grade controls based on site- and reach-based mechanisms and causes of failure.

Variations

Floodplain grade-control structures can be used in conjunction with floodplain-roughness elements such as large woody debris and live trees to promote or direct flow within the channel and channel margin (see the section in this chapter that addresses *Floodplain Roughness* for more information). These floodplain-roughness elements are the "surface" component of headcut or avulsion preventionn. Floodplain grade-control structures are the "subsurface" component of headcut or avulsion prevention.

It may be appropriate to add woody or herbaceous plantings to floodplain grade controls to improve the biological value and aesthetics of these structures. See the technique discussions in this chapter addressing *Woody Plantings* and Appendix H, *Planting Considerations and Erosion-Control Fabrics* for more information.

Emergency

Grade-control structures can be installed following the onset of headcut development after flood water have receded. Once a new channel is formed, the channel adapts to fit the newly avulsed location and any attempt to direct the stream back into the original channel would be a channel-realignment project rather than an avulsion-prevention measure.

EFFECTS

Grade-control structures prevent headcutting by resisting the erosive forces of flood flows impinging on the floodplain. This resistance does not allow overbank flood flows to cut a new channel through the floodplain. While this may be desirable in terms of protecting property, the opportunity for new habitat to develop due to channel migration and side-channel development will be lost. Conceptual design drawings are shown in *Figure 6-44* and *Figure 6-45.*

DESIGN

The use of grade-control structures to prevent avulsion and chute cutoff is an untested method, so any design guidance that is currently available is only conceptual and preliminary. Once the method has been applied and tested, additional design guidance will become more refined.

It is possible to determine overbank (floodplain) flow velocity, depth and shear using backwater hydraulics models such as HEC-RAS or at-a-station modeling. Refer to Appendix E, *Hydraulics* for further discussion on how to calculate shear. Incipient-motion analysis can be used to determine the rock size needed to resist headcutting and preserve the integrity of the floodplain.

Once the median rock size (D_{50}) needed to resist entrainment is known, a gradation can be developed to determine the D_{15}, D_{90} and the relative amounts of all three sizes to be used in the construction of the grade-control structure. Federal Highway Administration and U.S. Army Corps of Engineers publications[1,2] provide guidance for determining gradations using standard riprap gradation methods. Rock should be placed to a depth of 1 to 1.5 times the expected scour depth, according to best engineering judgement. The grade-control structure should be positioned roughly perpendicular to the down-valley direction and span the area where erosive shear stresses are expected or predicted by hydraulic modeling.

Grade-control structures are installed with their top elevation flush with the channel-bed elevation or the swale elevation in which they are installed. They may be covered or left uncovered. The structure should extend across the entire channel or swale and be tied into the margins of the channel to prevent scour at the ends of the structure. Tie-in portions should be sloped upward (in an across-valley direction) at an angle of at least 5:1 or to match the existing ground contours to prevent flows from eroding around the margins of the structure.

If floodplain shear stresses are moderate, logs can be used in the floodplain as grade-control structures. The correct size for logs to be used can be determined by a summation of forces analysis using an appropriate density value for the wood used. Logs should be placed to a depth twice the log diameter and securely anchored. See Appendix I, *Anchoring and Placement of Large Woody Debris* for more information about anchoring large woody debris.

To any extent possible, vegetation should be incorporated into grade controls. Vegetation within a grade-control structure may act as a flow spreader to further reduce the avulsion or chute-cutoff risk (see the discussion in this chapter addressing the technique, *Floodplain Flow Spreaders,* for additional information). This may require the use of erosion-control fabric to hold soils in place while vegetation becomes established. Refer to Appendix H for further information on both planting and appropriate erosion-control materials for vegetated grade controls.

Location

In instances where a headcut exists, the grade control should be located at the head of the headcut, with consideration to scour at the toe of the structure. Where a headcut does not exist, but is likely to develop, a grade-control structure should be placed near the anticipated origin of the headcut. This will generally be near the downstream end of an existing overflow channel or swale. To avoid impacts to the downstream channel and the riparian area that may contribute to habitat and/or avulsion protection, structures should be place upstream from the point where the headcut channel will re-enter the main channel.

A series of grade-control structures can be built in the alignment of an avulsion or chute cutoff if the total head differential is greater than what can be dissipated successfully by a single structure.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Grade-control structures interfere with natural stream processes by halting natural avulsion or chute-cutoff processes that may occur during flood events. Consequently, mitigation for lost opportunity will be required. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for additional guidance concerning mitigation.

Mitigation Benefits Provided by the Technique

No immediate mitigation benefit is realized from installing grade-control structures. This technique simply provides protection for the maintenance and integrity of the floodplain or other elements at risk. If the risk of avulsion or chute cutoff is created or exacerbated by man-made conditions, there may be a biological benefit to controlling the induced avulsion. Conditions that might warrant protection from an avulsion include increased sediment or peak flood events specifically caused by human land-use activities.

RISK

Habitat

There is little risk to existing aquatic or terrestrial habitat from this technique if properly installed. However, there may be significant lost opportunity for riparian and off-channel aquatic habitat associated with preventing channel avulsion.

Infrastructure

This technique may decrease the risk to infrastructure on the banks and in the floodplain.

Reliability/Uncertainty of Technique

Reliability of the technique depends on being able to predict where a headcut might occur. The greatest uncertainty in the structural success of the technique is in calculating the flow and head differential across the structure and, therefore, its scour potential.

CONSTRUCTION CONSIDERATIONS

Materials Required

Required materials include graded rock or logs, or other material used to form the structure. Angular rock with a minimum density of 150 lbs/ft^3 is desirable for the construction of floodplain grade control structures. For further description of materials for grade controls, refer to the technique discussion in this chapter addressing *Drop Structures*.

Timing Considerations

Construction of floodplain grade-control structures is best timed after runoff, but early in the growing season so that a full growing season is provided for the vegetation overlying the structure prior to subsequent overbank flows. Floodplain grade-control drop structures should not require work in the active strean channel and so are not affected by instream construction windows.

Cost

The primary cost of installing grade-control structures is the purchase of graded rock, logs or other material used to form the structures and the equipment required to install the materials, including that used for excavation and for hauling and placement. For further discussion of costs of materials, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

Grade-control structures do not require regular maintenance. However, maintenance may be needed in the aftermath of a large flood event. Maintenance may involve repositioning and/or addition of materials following flood events. In the event that materials are added to these structures, some level of maintenance may be required.

MONITORING

Monitoring of floodplain grade control structures should be conducted following any overbank flows to determine whether headcuts have developed and, if they have developed, whether they are moving toward the grade-control structure or have reached it. Visual inspection is sufficient to determine success and maintenance requirements. Any plantings should also include monitoring. Refer to Appendix J, *Monitoring* for additional guidance on monitoring-plan development and monitoring methods.

REFERENCES

1 U. S. Department of Transportation, Federal Highway Administration. 1989. Design of Riprap Revetment. Hydraulic Engineering Circular No. 11.

2 U. S. Army Corps of Engineers. 1994. Hydraulic Design of Flood Control Channels. Engineer Manual 1110-2-1601.

Figure 6-43. Headcut in floodplain. Site of future floodplain grade control structure at nickpoint of headcut. Teanaway River. 1996.

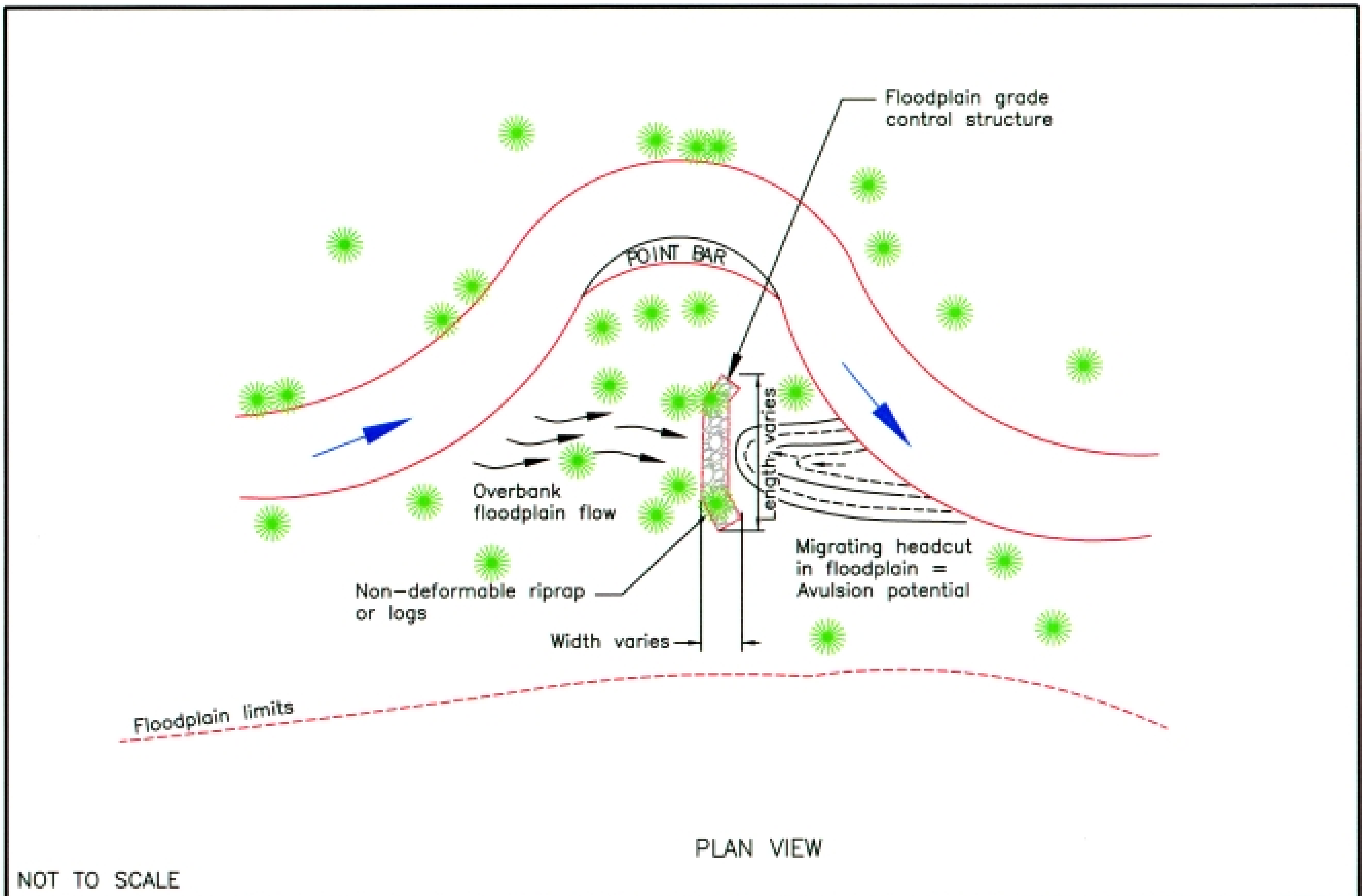
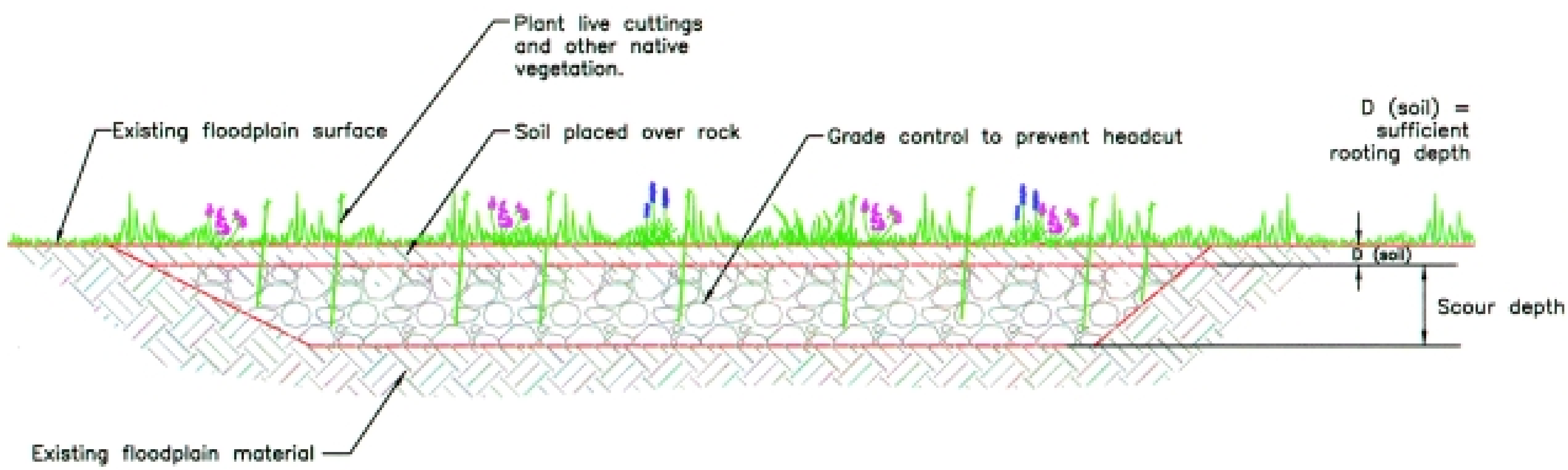


FIGURE 6-44 FLOODPLAIN GRADE CONTROL CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES



SECTION VIEW

NOT TO SCALE

FIGURE 6–45	FLOODPLAIN GRADE CONTROL CONCEPTUAL DESIGN	INTEGRATED STREAMBANK PROTECTION GUIDELINES www.wa.gov/wdfw/hab/ahg/strmbank.htm

Floodplain Flow Spreaders

Avulsion-Prevention Techniques

DESCRIPTION

Floodplain flow spreaders are designed to spread overbank flood flow across the floodplain. By eliminating concentrations of flow and high velocities in the floodplain, the potential for an avulsion or chute-cutoff is reduced. The intent of flow spreaders is to restore the natural roughness of a floodplain that has been removed by land clearing and grading.

Flow spreaders can consist of a row or several rows of planted trees. The spreading of flow is done by the roughness of the vegetation and by an accumulation of debris that may be placed against the trees, or it may come from the floodplain or from the channel and be delivered by a flood. The debris will collect where most of the water moves. As it collects, the flow is shunted to other portions of the flow spreader. Flow spreaders can also be nondeformable and constructed of compacted soil or rock (and be used in combination with planted trees, if suitable). Such flow spreaders are designed to remain stable during high flows. *Figure 6-46* shows various examples of natural and constructed floodplain flow spreaders.

APPLICATION

Typical Application

A floodplain flow spreader is used to prevent an avulsion or chute cutoff from occurring. The spreader evenly distributes overbank flows across the floodplain, preventing flood flows from concentrating and scouring a new channel in the floodplain. Floodplain flow spreaders are used in areas where the floodplain is susceptible to an avulsion or chute cutoff, either because it is newly constructed or it has little natural roughness due to land-management practices. A channel may also be prone to an avulsion if the basin hydrology is flashy (experiences rapid changes in flow level) or if the channel is aggrading, resulting in frequent overbank flow. Refer to Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for further discussion of site-based and reach-based causes and the consequences of an avulsion or chute cutoff. Floodplain flow spreaders are typically constructed as low berms across the floodplain, perpendicular to the flood flow direction. Tree rows and piles of large woody debris are also natural floodplain flow spreaders. Flow spreaders can be notched to allow flow passage between adjacent, elevated segments.

Flow spreaders are also used in combination with other bank-protection techniques, particularly toe erosion and channel migration techniques where there is a potential for a chute cutoff. For more information about chute cutoffs, refer to Chapters 2 and 3.

Floodplain flow spreaders are appropriate for areas with moderate avulsion or chute-cutoff potential. Refer to the matrices in Chapter 5, *Identify and Select Solutions* matrices further detail on situations where they are suitable for use.

Variations

A floodplain flow spreader may be used in conjunction with a floodplain grade-control structure and floodplain-roughness elements to provide further protection against avulsion or chute-cutoff development. The grade-control structure can be considered the subsurface component of the flow spreader. Flow spreaders may be a row of trees or they may be nondeformable and constructed of rock large enough to be immobile under a specified range of flows. They may also be deformable and constructed of wood or composite vegetation-based materials.

Emergency

A floodplain flow spreader is preventive by nature and not particularly applicable in emergency circumstances. It's difficult, overly time-consuming and impractical to build them during flow events, and they are unlikely to significantly reduce an avulsion or chute cutoff that has already begun.

EFFECTS

A floodplain flow spreader distributes the erosive forces of flood flows over the floodplain, thereby reducing the potential for an avulsion or chute cutoff. Flow spreaders impact the development of off-channel and side-channel habitat. Consequently, evolution of these habitats may be reduced or lost.

DESIGN

Currently, design guidelines are conceptual and preliminary but will become more defined as the technique is tested under a variety of situations. A conceptual design drawing is shown in *Figure 6-47*.

The critical design parameter of a floodplain flow spreader is the base elevation of the structure and depth of flow on the floodplain at the flood event of interest. The top of the spreader should be at or near the flood-event elevation, with allowances for increased stage due to backwatering caused by the spreader itself. Flow spreaders constructed with fill material must not act as levees to change the rate or location of flow from the main channel entering the floodplain or flood channels. To ensure even distribution of water across the width of the floodplain, the elevation of the top of the spreader must be uniform across its length (cross-valley direction). It is important to note that the spreader will only diffuse flows at the location of the structure. Once overbank flow has passed the spreader, the flow will again follow the existing flow paths. For this reason, a series of spreaders may be necessary to effectively distribute flows within the specified length of a reach.

The width (down-valley dimension) of the structure should be equal to (at a minimum) the depth of installation (predicted scour). If scour depth cannot be predicted, the width of the structure should be twice the diameter of the largest rock gradation. In design and construction, the potential for scour resulting from flow dropping over the structure must be addressed. In such instances, scour should be calculated, and rock or other armor material that is adequately sized should be installed to a sufficient depth or anchored in place to protect against scour that could jeopardize the structure. For further discussion of calculating scour, refer to Appendix E, *Hydraulics*. Additionally, further design guidance is provided in this chapter under *Floodplain Grade Control*.

Flow spreaders have been built in agricultural fields with a low enough elevation and profile that farming activities are not affected.

Flow spreaders should be tied in to higher ground to prevent water from flowing around the spreader and scouring at the margins of the spreader. Tie-in design will be site specific.

Flow spreaders can be constructed from live trees, rock, soil, wood or other hard material. Alternatives include vegetated soil berms, wooden sills, or piles of large woody debris. Vegetated soil berms may serve the dual purpose of providing floodplain roughness as well. Soil berms will require erosion protection in the form of fabric to hold soils in place while vegetation becomes established. Refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for further information on both planting and appropriate erosion-control materials for vegetated and soil berms.

While the spreader may be constructed of rock, it will be difficult to achieve uniform elevation across its length with larger rock. Rock must not be so small that it is subject to entrainment due to tractive forces at the design flood event. Rock should be placed in a stable configuration and keyed in below the floodplain surface to the depth of potential scour. Graded rock will allow interlocking of individual stones and should be sized such that the D_{50} is immobile at design flows.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

When this technique is used with a vegetative design, it usually restores natural streams and floodplains by returning roughness and complexity to the floodplain. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5 for additional guidance concerning mitigation.

Floodplain flow spreaders made of fill material may reduce the potential and function of off-channel habitats associated with flood overflow swales. Concentrated flows in the floodplain often maintain side channels by scouring, cleaning and sorting bed material within them. Such lost-opportunity impacts must be mitigated.

Mitigation Benefits Provided by the Technique

This technique provides protection for the maintenance and integrity of the floodplain or other elements at risk. If the risk of an avulsion or chute cutoff that is being managed is created or exacerbated by man-made conditions, there may be a biological benefit to controlling the induced avulsion or chute cutoff. Conditions that might warrant protection from an avulsion or chute cutoff include increased sediment or peak flood events specifically due to human land-use activities.

RISK

Infrastructure

This technique may decrease the risk to infrastructure on the banks and in the floodplain. A flow spreader may increase the depth of flow in the floodplain during a given flood event.

Reliability/Uncertainty of Technique

Reliability of the technique depends on the accurate prediction of where a headcut might occur, correct placement of a floodplain flow spreader to prevent headcutting and the time it takes for development of vegetative flow spreaders to be functional.

CONSTRUCTION CONSIDERATIONS

Materials Required

Flow spreaders can be constructed from woody vegetation, rock, compacted soil, large woody debris or other hard materials. Where rock is used, angular rock with a minimum density of 150 lbs/ft^3 is desirable. Compacted soil berms will require erosion-control fabric (refer to Appendix H) to hold soil in place until vegetation becomes established. Large woody debris must be anchored or buried such that it does not become mobilized. Refer to Appendix I, *Anchoring and Placement of Large Woody Debris* for further information.

Timing Considerations

Construction of a floodplain flow spreader is best timed after moderate, overbank-flow events when there is clear evidence of the route the overbank flow will take. Floodplain flow spreaders should not require work in the active stream channel and so are not affected by instream construction windows.

Cost

The primary cost of building a vegetative floodplain flow spreader is in the rooted plantings required. As with many vegetative techniques, the sooner the protection needs to take hold, the larger the plantings should be and, therefore, the greater the cost. The primary cost of building a flow spreader of fill material lies in the purchase and transport of materials to the site. Equipment costs may also be significant. For instance, an excavator may be needed to install the material from a central stockpile, or a loader may be needed to place material throughout the floodplain. Refer to further discussion of costs of materials, equipment and other construction components in Appendix L, *Cost of Techniques*.

MAINTENANCE

Floodplain flow spreaders do not require regular maintenance. However, maintenance may be needed following a large flood event if parts of the spreader is washed away or if irregularities in the elevation across the spreader develop. Vegetative flow spreaders may have to be replaced eventually when trees are so large they no longer trap debris to spread the flow.

MONITORING

Flow spreaders should be monitored following all overbank-flow events to determine effectiveness and need for repair or maintenance. Development of new channels downstream of the spreader may indicate the need for additional spreaders. Flow spreaders should be mapped at the time of installation, and photo points should be established and clearly identified on base maps. Monitoring should consist of visual observation and photo documentation from established photo points and will be largely qualitative. Any flow spreader materials lost during overbank flow events can be indicated on base maps and replaced or repaired as necessary. Monitoring should be conducted following all overbank flows to observe any scour development or channel development on the floodplain in addition to any debris deposited by large flood events. Refer to Appendix J, *Monitoring* for additional guidance on monitoring-plan development and monitoring methods.

a. Natural Floodplain Flow Spreader. Note debris accumulation in floodplain. Skykomish River.

b. Small earthen berm spreads flow across floodplain. Nooksack River.

Figure 6-46. Examples of natural and constructed floodplain flow spreaders.

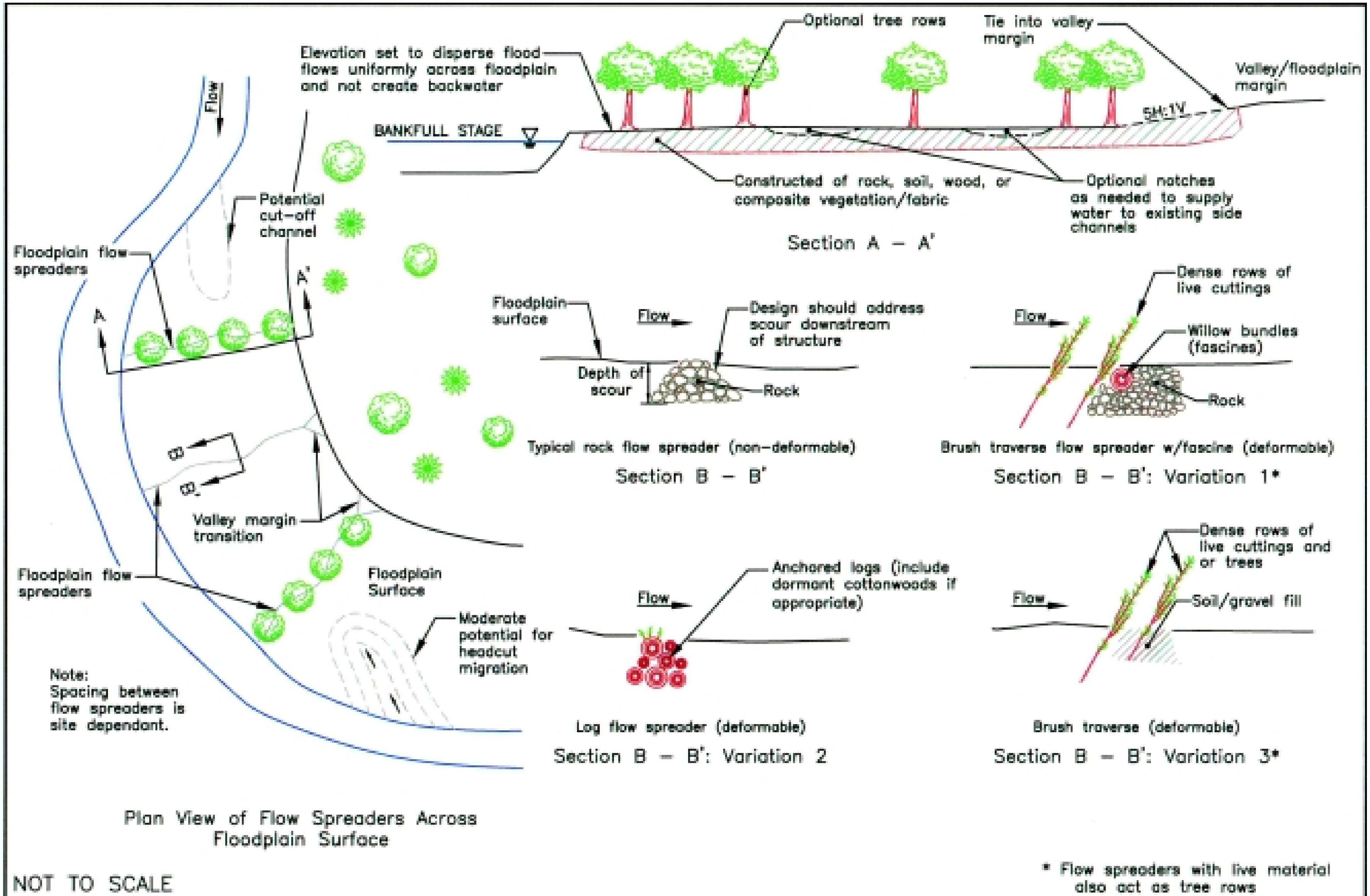


FIGURE 6–47

FLOODPLAIN FLOW SPREADER CONCEPTUAL DESIGN

INTEGRATED STREAMBANK PROTECTION GUIDELINES

www.wa.gov/wdfw/hab/ahg/strmbank.htm

Channel Modifications
Other Techniques

The following technique was developed for the Integrated Streambank Protection Guideline. Its focus is on streambank protection. While similarly titled techniques may appear in other Aquatic Habitat Guidelines, their contents may differ from the text presented here.

DESCRIPTION

Channel modification is the alteration of channel profile, planform, pattern, cross section, bed elevation and/or channel location of a stream segment or an entire reach. Channel modifications can be used separately or in combination to restore bank stability and to reduce bank erosion. Each of these modification techniques may specifically affect the local slope, length, sinuosity and dimensions of the channel, as well as alter basic channel processes related to sediment transport. While these techniques are not generally applied for the purpose of bank protection, channel-modification techniques are very useful for treating the underlying causes of bank erosion and for preventing future problems. They should, therefore, be considered as a potential solution where there are chronic or systemic bank-erosion problems present. *Figure 6-48* shows various applications of channel modifications.

The goal of channel modification is to restore or create an equilibrium (stable) condition in the stream reach (see Chapter 3, *Reach Assessment* for definition and discussion of channel equilibrium). A channel in equilibrium is one that has adjusted to the physiographic conditions (e.g., climate, geology, discharge, sediment supply) of its watershed. Keep in mind that throughout this document the terms "stable channel" and "equilibrium channel" refer to the geomorphic definitions described in Chapter 3 and do not necessarily mean a channel without erosion. A channel in equilibrium may still naturally erode as the channel migrates across the floodplain.

A channel in equilibrium can become unstable following some human or natural disturbance such as changes in hydrology or sediment loads, extreme hydrologic events or construction of channel confinements. Bank-protection and stream-restoration plans strive to attain or restore the channel to a state of equilibrium, based on the current and future hydrology and sediment supply of the stream.

Because all channel-modification techniques result in changes to channel process, a thorough understanding of fluvial geomorphology is an essential component of developing channel modification projects. Refer to Appendix F, *Fluvial Geomorphology* for further discussion of channel planform and profile, pattern, cross section and channel equilibrium.

APPLICATION

Channel-modification techniques can be used at a site to alleviate bank-erosion problems or to facilitate mitigation. They can also be used on a reach level to address geomorphic disequilibrium, thereby reducing risks of bank erosion. Common applications for channel modification include restoring a previously straightened stream reach to its historic channel planform and profile, or restoring an unnaturally braided channel to its natural, single-channel pattern. Other objectives of channel modification include:

- to increase habitat value and diversity,
- to dissipate excess stream energy, and
- to modify sediment-transport capability in either the project reach or downstream.[1]

For example, bank and channel stability may be achieved in a degrading channel system by modifying the channel to decrease the sediment-transport capability - the desired result being a reduction in bank erosion while still allowing moderate channel aggradation. In a stream that is aggrading, bank and channel stability may be restored by increasing the channel's sediment-transport capability, thereby transporting downstream any excess material delivered to the reach. Although channel modification can alleviate channel instability, using this technique without fully understanding its complexity (and that of the stream) could exacerbate existing problems or create new, more severe problems upstream and downstream. For this reason, it is absolutely essential that a qualified geomorphologist or engineer well versed in geomorphology be involved in channel-modification projects. For more information on site-based and reach-based causes of erosion and mechanisms of failure, refer to Chapter 2, *Site Assessment* and Chapter 3; and, for additional information about channel behavior and response, refer to Appendix F. Refer to the matrices in Chapter 5, *Identify and Select Solutions* for selection criteria of channel-modification techniques relative to various mechanisms and causes of failure.

Channel Profile and Planform Change

"Channel profile" is the slope, or gradient, of the channel bed. "Channel planform" is the shape of the channel looking down on it from above (referred to as "plan view"). One common descriptor of planform is "sinuosity," which is a measure of channel length relative to valley length. Whether a channel passes relatively straight through a valley or crisscrosses the valley several times is a function of its sinuosity. Sinuosity and profile are inseparable characteristics of a stream channel; its sinuosity is a function of its slope and vice versa. Adjustments to either slope or sinuosity will necessarily result in changes to the other. The exception to this rule is in channels with significant grade breaks, such as small dams or other drops, where slope can be changed significantly by removing the grade break. This type of change would not directly affect the channel's sinuosity. Additionally, changes to a stream's profile or plan will result in a change in its energy and sediment-transport capacity (see Appendix F).

Modification of the channel profile can occur by structurally altering channel planform or the channel slope. Channel slope can be increased by shortening the channel or decreased by lengthening the channel, depending upon the type of desired impacts to a reach. Channel shortening can best be accomplished by straightening a channel through a reach (reducing sinuosity). Channel lengthening can be accomplished by restoring a single meander or adding more meanders to a previously straightened channel. Modification treatments can also include the installation of drop structures that change the channel profile by increasing the channel-bed elevation at a certain point. This would reduce upstream slope and increase downstream slope.

Channel-Pattern Change

The most common channel patterns that occur naturally are straight, meandering and braided.[2] Several local and watershed-wide characteristics determine the pattern of a specific river reach, including hydrology, slope, bank structure, sediment, and the presence or absence of large woody debris. When any one of these factors changes enough to cross a threshold value, channel-pattern change may be abruptly initiated and usually results in a less stable channel system. In some cases, relatively small changes in climate or land use may trigger large changes in channel characteristics of natural streams.[3] For further discussion of the concept of geomorphic thresholds, refer to Appendix F.

Channel-pattern modification is used to force an unstable pattern into one that is likely to be more stable. This may entail changing the channel pattern from one form to another (e.g., from braided to meandering). Channel-pattern modification is a major undertaking, involving reconstruction of the channel bed, habitat features, channel banks and floodplain. Channel-pattern modification should be considered only where the existing pattern is in disequilibrium.

Channel Cross-Section Change

Changing a channel's cross section involves altering its bankfull width, depth or channel shape and can include modification of channel banks and bars. A common application of cross-section modification focuses on narrowing or widening a channel to effect a change in sediment transport by altering channel hydraulics. It can also be used to reduce shear stresses in a channel by reconstructing its floodplain. Another useful application of cross-section modification is to increase the availability and variety of fish habitat by creating asymmetrical features across the channel.

Narrowing a channel can also be beneficial in stabilizing a stream in disequilibrium, depending upon the particular circumstances at the site. This can be achieved artificially or by encouraging the channel to narrow itself by restoring vegetation and/or debris collection at the site or the addition of in-channel roughness elements.

If, on the other hand, a channel has become incised, it may become necessary to widen it. Widening efforts in such a situation would be used to develop a new floodplain surface that is connected to the channel at the new, incision-induced elevation.

Cross-section modification may also involve altering a channel bank slope to provide greater cross-sectional area. This involves excavating a bank and reshaping it from a steep or vertical face to a lower slope. Bank reshaping is a necessary component of several techniques described in these guidelines and provides a number of benefits to the stream system. Refer to the section in this chapter entitled, Bank Reshaping, for further discussion.

The removal of point bars is often perceived to be a beneficial cross section adjustment; however, its effectiveness is generally limited and temporary at best. Point bars are depositional features located on the inside of meander bends. While point bars and eroding banks evolve together, one does not generally create the other. They are simultaneous products of the channel flow-pattern. The channel planform creates the bend hydraulics. As the distribution of shear stress causes scour on the outside of the bend, it creates deposits on the inside of the bend. If the desired outcome of point-bar removal is to discourage bank erosion on the opposite side of a bend, it is not likely to have any lasting effect. It is also important to differentiate between point bars and midchannel bars, which evolve and influence stream flow differently. See Chapter 2 for additional information.

Although gravel-bar removal seldom provides any long-term protection for the opposite bank, it may temporarily reduce shear stress by increasing the cross-sectional area and reducing velocity. In order for this treatment to work, stream energy must be redirected downstream by lowering the water surface and straightening the channel. Point bars that are skimmed or removed, however, usually rebuild within the next flood season, and the cut bank may begin eroding again even before the end of that flood season. For only a temporary benefit at the project site, the unintended consequences generated in the upstream and downstream channel may be significant. It is important, therefore, to determine whether removal of a point bar is the correct solution for the problem, as well as if the impacts to the upstream and downstream reaches can be tolerated. Reaches with low bedload-transport rates and very stable downstream banks may be more tolerant of point-bar removal than others.

Cross-section change may also include the relocation and/or removal of levees to provide overbank flood relief. The removal of levees, if not planned well, can cause impacts comparable in magnitude to those of the initial levee installation. These implications must be well investigated and understood before attempting such a large-scale, cross-section adjustment.

Channel-Bed Elevation Change

The depth of a channel can be changed by raising or lowering its bed elevation. Bed elevation is linked to channel slope - if the bed elevation is changed, the channel profile must also change within the site, upstream and/or downstream. Channel-bed elevation changes are usually implemented by installing grade control, drop structures, roughness elements or steepened channel sections. Lowering the bed elevation is accomplished only through excavation (dredging) and has little practical application for establishing stream equilibrium or creating fish habitat.

Channel-bed elevation change is useful in restoring a degrading (incising) channel. An increase in bed elevation can aid in reconnecting the degraded channel to its floodplain. Degraded channels that are reconnected to an active floodplain become more stable because water depths and velocities in the channel are reduced. If flood flows spread out over the floodplain during relatively frequent floods (one- to five-year, return-interval events), channel erosion is minimized. Channels that are confined to ten-year or greater flood flows have sufficient energy to move large quantities of material. Massive channel erosion can occur if flood flow is confined within the channel during a 20-year or even 50-year flood event. Incised channels have a greater flow capacity, so that an even greater discharge level is needed for over bank flow. The results can be catastrophic in terms of bank and channel erosion, including the increased risk of catastrophic channel change. Therefore, raising the elevation of an incising channel bed should be seriously considered as an effective means of stabilizing it.

Channel Relocation

Channel relocation changes the location of the channel while preserving or recreating other characteristics, such as overall channel profile, pattern, cross section and bed elevation. The usual purpose of channel relocation is to move a channel away from an eroding bank. Relocation may also be used where a significant building or road is directly threatened by erosion. Channel relocation is often a means to solve problems of channel encroachment and/or confinement and to foster the development of a new, stable channel with healthy riparian buffers.

A channel can be entirely relocated to a new alignment, or just moved laterally within the existing alignment. One option is to deflect the flow laterally away from the hazard area using flow-realignment techniques (see the discussions in this chapter addressing *Groins, Barbs, Engineered Log Jams* and *Anchor Points*). Flow-realignment techniques should only be used in situations where there is no concern about impact to the channel, particularly the bank across from and downstream of the structure. Realignment techniques will change the meander shape locally and for some distance downstream, making appropriate site selection critical.

Emergency

Channel-modification treatments are not appropriate for emergency situations. Channel modification requires dewatering and careful analysis and design before implementation. However, it is possible to effect a change in channel alignment during an emergency using temporary groins. Refer to the discussion in this chapter addressing *Groins* for further information on their use and design.

EFFECTS

The potential effects of channel modification must be carefully assessed for a project reach. If implemented correctly, channel modification can restore natural features that fit the current and/or future conditions of the watershed. Erosion can be restored to a gradual and predictable rate, with habitat and other ecological conditions optimized.

When properly applied, channel-modification techniques can result in a one-time, cost-effective fix, preferable by far to the periodic and chronic fix alternative of treating one bank at a time. However, without a clear understanding of the complexities of channel-modification techniques and of the stream channel in question, problems may arise. Channel modification will generally result in changes to sediment-transport characteristics of a reach. For example, a decrease in stream gradient, resulting from channel lengthening, results in lower stream energy and may cause aggradation due to sediment deposition. This will result in a higher water surface during a flood, leading to more frequent inundation of the floodplain. Therefore, careful analysis and design are required.

DESIGN

Detailed designs are beyond the scope of this document because of the relative complexity and variability in channel-modification projects. A qualified geomorphologist or engineer well versed in geomorphology should be consulted to help evaluate the necessity and applicability of major channel-modification work and to assist in design.

At a minimum, field data collection should include the following seven elements:

1. stream gradient in the project area and adjacent reaches;
2. channel cross sections;
3. bedload and bed-material sizes;
4. streambank stratigraphy;
5. channel mapping with meander-belt width, meander wavelength, radius of curvature and sinuosity;
6. habitat mapping, including the influence of large woody debris, geology and confinements on channel character and habitat; and
7. floodplain mapping with topography.

An analysis of historic photos and maps can provide vital information for channel-modification work. However, if existing bank erosion is a result of changed hydrology or sediment supply, then historic photos cannot provide a basis for reconstruction. Careful analysis of the watershed should accompany any channel-modification work to determine if there has been significant alteration of the watershed hydrology. If urbanization, timber harvest, grazing, agriculture or other human activities have affected the watershed, the hydrology may be significantly and permanently altered. Natural changes such as fire should also be considered. Selection and design of channel-modification treatments should be based on historic photos only where changing watershed conditions can be accounted for, or where the watershed has already been restored to historic conditions. In any case, anticipated conditions for the long-term are a critical element of any channel modification design.

Reaches vulnerable to spontaneous channel-pattern change should be identified within flood-hazard management plans and watershed plans. Such reaches might be considered as possible off-site mitigation opportunities for other activities (see the discussion in this chapter addressing *Off-Channel Spawning and Rearing Habitat.*)

Reference Reach

The recommended design approach for channel-modification projects addressing site-specific erosion problems is based on the reference-reach concept (this approach assumes the reference reach is in a stable and unchanging watershed condition). A reference reach is a stable reach located either upstream or downstream of a project, or in a nearby watershed with similar hydrology, precipitation, soils, geology, relief, vegetation and land use. Applications for reference-reach design include channel modification to enhance or restore habitat and/or to address site-specific erosion problems.

If necessary, streams of differing size or drainage area can be used as reference reaches, as long as dimensionless parameters, such as width-to-depth ratio, are used. Several reference reaches might be used for added confidence. If a reference reach is not available, then regional hydraulic geometry relationships can be used to estimate channel dimensions, though this is not the preferred method.

Reference reaches may be used to generate a range of acceptable values for channel parameters such as pattern, plan and profile. However, whenever a reference-reach design approach is used, channel slope in both the reference reach and the design reach must be the same. Pattern, profile and dimensions of the project site are then compared to the reference reach. If the project reach varies significantly from the reference reach, it may be an indicator that channel modification is appropriate. The significance of variation can be roughly evaluated by comparison to the variance within relationships in regional hydraulic geometry data. Geometry and pattern of the constructed channel are then derived by correlation to the reference reach.

Habitat

Regardless of the design method used, there must be a component for habitat preservation or restoration included in the project. Habitat is directly associated with channel design in that most habitat features are inextricably linked to channel evolution and stability. Stable channels ideally provide sufficient habitat for wildlife and resident and migratory fish. However, because many components of a stable and natural system, such as large woody debris, may be absent, it will likely be necessary to install habitat features as part of the modification. Review Chapter 4, *Considerations for a Solution* in determining mitigation targets as a reference for quantifying habitat needs. Habitat must be designed as a self-perpetuating function rather than just as a feature. The hydraulics of the channel must support and maintain the habitat features intended, such that woody debris is recruited and retained, scour develops to form pools and gravels are sorted to form areas for spawning.

Debris

Debris and vegetation each perform significant roles in the evolution of channels, and their roles must be accommodated in the design of new channels. For instance, vegetation and large woody debris are historically abundant along streams in western Washington, so channel-modification techniques applied to streams there require the addition of large woody debris to restore natural processes. In eastern Washington, vegetation and large woody debris are less abundant, so large woody debris should be used only where it naturally occurs, or where habitat needs warrant its inclusion.

Riparian Planting

If riparian vegetation is damaged or limited in coverage, an extensive riparian-planting component should be included in the project. If livestock have access to the site, protecting the riparian corridor from them will be required to ensure success of the riparian plantings and long-term success of the project. Stockpiling fertile topsoil is critical for areas that will be highly disturbed. After the excavation and fill is complete, the topsoil can be replaced to provide an adequate base for riparian plantings. Refer to the discussions in this chapter addressing *Woody Plantings, Herbaceous Cover* and *Riparian-Buffer Management* and to Appendix H, *Planting Considerations and Erosion-Control Fabrics* for further information on riparian planting.

BIOLOGICAL CONSIDERATIONS

Restoring a stream to a more stable, natural shape can have tremendous benefits for fish and wildlife. If the floodplain is reactivated, the riparian community will be better able to re-establish and provide food and shelter for wildlife. Floodplain reactivation and the related increase in groundwater and surface-water interaction during summer and winter periods may also moderate water temperature extremes - a benefit to fish. Channel narrowing in combination with riparian-vegetation establishment might also moderate water-temperature extremes.

Channel modification can cause extensive, short-term disturbance to macroinvertebrates, amphibians, fish and some nesting birds due to instream disturbance, fine-sediment deposition, channel abandonment and loss of riparian vegetation. Although a stream with restored profile, pattern or cross section will provide better habitat in the long run, the necessary excavation, fill material and vegetative disturbance may cause substantial damage to existing habitat. If a stream channel is being completely moved or turned back into an historic meandering channel, much of the existing habitat can be lost for at least several years depending upon the stream system and ecoregion.

Fish trapping and relocation may be required to remove fish from the project construction area. The lower end of an existing channel might be left open and connected so there is instream habitat until the new channel is established with vegetation. A new channel may be left exposed for a winter so it can weather before flow is diverted into it.

Mitigation Requirements for the Technique

Mitigation may not be required for channel-modification treatments if there is a net habitat benefit created by the project. Mitigation may be required for one type of habitat that is replaced with another or for the time required for the habitat to become functional as described in Chapter 4. Impacts described in the previous section and associated with construction activities, site access and flow diversion may require mitigation. Refer to Matrix 3 in Chapter 5 for more detail on mitigation needs for this bank treatment.

Mitigation Benefits Provided by the Technique

Channel modification may provide substantial mitigation opportunities for spawning habitat, channel and habitat complexity and diversity, flood refuge, and lost opportunities associated with bank-protection projects elsewhere. Channel modification can greatly reduce the impact of bank-protection activities within a specific reach when compared to the alternative of cumulative impact due to chronic, individual, bank-protection projects throughout the reach. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this treatment.

RISK

Habitat

Channel-modification projects should be designed to provide habitat benefit. However, large-scale channel modification may result in temporary impacts to and loss of habitat due to disturbance. Months to years may be required for full recovery of some habitat components. There is a risk that a poorly designed channel-modification project may have a negative effect on habitat rather than a positive one. There is a trade-off between risk and habitat preservation and restoration as well. A channel must have a certain amount of deformability in order to sustain and generate quality habitat for fish. Additionally, a newly constructed channel that is not well protected by vegetative structure carries the risk that high-flow events could impact it and the downstream reach more severely than intended by the design.

Infrastructure

The intent of channel-modification treatments is to reduce channel instability and protect infrastructure. However, predicting the relationships among various channel attributes in the design and implementation of channel-modification treatments may result in risk to infrastructure if those predictions are inaccurate.

Reliability/Uncertainty of Technique

Because all channel-modification techniques result in changes to channel process, there is a risk that an inappropriate design or unanticipated conditions will cause a project to fail. A thorough understanding of fluvial geomorphology is an essential component of developing channel-modification projects. Refer to Appendix F for further discussion of channel planform and profile, pattern, cross section, and channel stability and equilibrium.

Materials Required

Construction of channel-modification projects will generally require dewatering of the channel either by diverting all flow or by isolating parts of the channel during construction. Dewatering is essential to facilitate construction and to control sediment inputs to the stream. Channel-modification projects are constructed using native materials available on site, through stockpiling, redistribution and rearrangement of existing channel materials. If large woody debris is not already present in the channel but is typical to streams in that region, it may have to be supplied from elsewhere. Many channel-modification projects require reconstruction of channel banks. Refer to specific bank-protection techniques in this chapter for descriptions of materials required for their construction. See Appendix M, *Construction Considerations* for additional information about construction.

Construction of channel-modification projects requires careful sequencing of work phases. Construction steps may include (not necessarily in this order):

- constructing a diversion channel;
- diverting stream flow;
- rescuing fish from areas to be dewatered;
- dewatering;
- gaining access to and stockpiling imported materials, waste materials and transitional, redistributed materials;
- restoring damaged banks and/or constructing new banks;
- installing erosion and sediment control;
- constructing and installing habitat features; and
- redirecting flow into the modified channel.

Further discussion of these components can be found in Appendix M.

Timing Considerations

Channel modification often requires complete dewatering. Consequently, the work should be timed to occur during low-water periods. Critical periods in resident and anadromous fish life cycles, such as spawning or migration, should also be avoided. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M.

Cost

Channel-modification project costs are site- and design-specific and vary according to the size of the channel. Reconstruction and relocation projects may range from $50 to $300 per foot of channel (including reconstructed banks and dewatering), depending upon the size of the channel and complexity of modification techniques. Key cost items will include dewatering systems, imported materials and bank reconstruction. Dewatering will be a significant cost for channel modification because it requires, in most cases, complete dewatering of the entire channel. The need to import materials for any component of the modification will greatly increase implementation costs. Since many channel-modification projects require reconstruction of channel banks, costs associated with acquiring bank-reconstruction materials will also need to be taken into account. Refer to Appendix L, *Cost of Techniques* for further discussion of bank-construction costs.

MAINTENANCE

Bank reconstruction and habitat elements associated with channel-modification projects require periodic inspection and maintenance or repair. They may be especially vulnerable to damage during the first years of operation, particularly if they are subjected to high flows before vegetative components are able to provide support. While the intent of channel modification is to create a stable channel, the design must allow some deformity to occur in order to create and sustain adequate fish habitat. For this reason, moderate erosion along banks should be expected and encouraged, and some degree of maintenance and repair should be anticipated, especially during the first three years of the new project. Refer to individual bank-protection techniques described in this chapter for additional information about deformity, maintenance and repair considerations.

MONITORING

Because channel-modification projects generally involve impacts to the channel and banks, they will require comprehensive monitoring of both channel and bank features, with particular attention to habitat monitoring.

Monitoring of channel-modification projects should be initiated prior to construction, with baseline-conditions surveys of the physical channel, its banks and its habitat value. This will allow comparison of modified conditions to pre-project conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Refer to Appendix J, *Monitoring* for further discussion of monitoring considerations and practices. For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[4] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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a. Channel Relocation to restore a channelized and eroding stream. Colony Creek, Tributary to Samish Bay, Puget Sound. 1999.

b. Floodplain terrace excavated and restored in a channelized and degrading stream. Austria.

Figure 6-48. Applications of channel modifications.

Riparian-Buffer Management

Other Techniques

DESCRIPTION

The term "riparian" refers to that area adjacent to a river or stream that is physically linked to the moisture regime of the streamside environment. The riparian buffer usually extends from the stream's ordinary high water line to the outer edge of the floodplain. Riparian buffers provide essential functions for river and stream ecosystems, including cover and shade, a source of fine or coarse woody material, nutrients, and organic and inorganic debris that maintain stream ecosystem function. Riparian corridors also provide habitat for wildlife, especially migrating and breeding birds.

Riparian buffers enhance bank protection in a number of ways:

- Roots knit soil and sediment particles together into a matrix that resists erosion.
- Plant stems increase hydraulic roughness on channel banks and floodplains, slowing flow velocity and reducing scour.
- Large trees act as anchor points and buttress banks to resist failure.
- Inputs of large woody debris may roughen and stabilize the channel and provide improved fish and insect habitat (see Appendix F, *Fluvial Geomorphology* for further discussion).
- Riparian vegetation moderates the rate of lateral channel migration. For example, in a study of lowland streams around Puget Sound, C. W. May, et al., found that streambank stability is strongly correlated to the width of the riparian corridor and inversely related to the number of breaks in the riparian corridor.[1]

APPLICATION

The establishment of riparian buffers can be a primary technique of bank stabilization when the risk to property is low, and stable vegetation is all that is needed. For example, fencing cattle out of the riparian zone to allow vegetation to become re-established can often provide adequate bank protection. Riparian buffers can be applied as mitigation, or as a technique for bank-stabilization projects to provide long-term protection benefits. When used as a supplemental technique for other bank-protection measures, a riparian buffer will provide future bank protection as short-term, impermanent techniques such as log toes or engineered debris jams decompose and erode.

The creation or restoration of riparian buffers is considered a proactive bank-protection technique because restoring natural riparian function will mitigate future bank-stability problems. In agricultural areas for instance, where riparian vegetation is removed for the benefit of land cultivation, stream channels may migrate into the now-unprotected fields. Historically, man's response to such migration has been to apply bank hardening (e.g., riprap) to the migration site. Unfortunately, this will just accelerate lateral migration movement upstream or downstream, worsening the problem. A proactive approach would be to protect riparian vegetation in the first place or to restore it using woody structures or biotechnical erosion control to reinforce the bank as the plants grow (see Appendix H, *Planting Considerations and Erosion-Control Fabrics*).

Riparian buffers are only appropriate where land use does not preclude establishment and growth of riparian vegetation. See Chapter 2, *Site Assessment* for detailed information about site-assessment considerations and to Chapter 3, *Reach Assessment* for reach-assessment considerations. Additionally, Chapter 5, *Identify and Select Solutions* provides instruction on how to select appropriate techniques.

The most effective bank-protection alternative that also protects riparian habitat is one that limits land-use activities in this critical ecological zone. For instance, in an agricultural setting where live stock are present, the riparian buffer should be protected with fencing that keeps livestock out of the buffer zone, accompanied by a clear understanding and commitment on the part of the landowner that the fencing will be maintained. Changes in land use or conversions of the buffer zone that are not compatible with the needs of the stream will reduce a riparian area's effectiveness as bank protection.

In some instances, other considerations may take precedence over protecting or restoring habitat, such as riparian buffers within Federal Emergency Management Agency jurisdiction, where effects on flood elevations are a concern. Therefore, a full understanding of the setting and the potential implications of riparian restoration should be recognized as part of the feasibility analysis when considering this technique for bank protection.

Variations

Woody plantings, herbaceous cover and floodplain roughness are additional techniques that promote riparian buffer protection and development. Each of these techniques are discussed in detail in this chapter.

Emergency

Riparian-buffer management is not a technique that is effective in emergency situations. However, bank-stabilization techniques that are used during emergencies should be designed so that they will not rule out the potential for future buffer-management techniques to be applied at the site.

EFFECTS

Riparian buffers generally increase in-channel and riparian habitat value adjacent to the stream. A buffer may provide wood for recruitment, slow down flow velocities and reduce associated shear along banks and on the floodplain. Riparian buffers may increase floodwater surface elevations on the floodplain.

DESIGN

Floodplain Function

The most essential consideration for establishment of a riparian-buffer area is the soil-moisture regime within the buffer. Riparian plants depend on regular access to soil moisture through their roots and on occasional inundation by floodwaters to limit competition of nonriparian species. Evaluation of floodplain function is best determined by characterizing existing riparian plant community health. Incised channels may have a perched floodplain that restricts access of plants to the soil moisture.

Buffer Widths

The Washington Department of Fish and Wildlife makes several recommendations for riparian habitat area widths[2]:

- for Types 1 and 2 streams ("Shorelines of the State" and channels with widths greater than 20 feet), the buffer-zone width should be 250 feet on each side of the stream;
- for Type 3 channels that are five to 20 feet wide, the buffer-zone width should be 200 feet on each side of the stream; and
- for Type 3 channels that are less than five feet wide, the buffer-zone width should be 150 feet on each side of the stream.

These widths are applied to each side of the stream, starting at the ordinary high water line. The widths are set primarily for forested lands, with the objective of optimizing ecological benefits. Other widths may be more appropriate for other objectives, such as those that center on stabilizing a streambank only. It is best to determine an appropriate buffer width on the basis of site conditions and the best available science applicable to the area. On steep-gradient streams (two to four percent and greater), buffer widths may be narrower. Less then 32 feet of buffer is considered to be ineffective.[1] A. J. Castelle and colleagues found that 98 to 197 feet of buffer was adequate to control streambank erosion.[3] A. W. Johnson and D. M. Ryba recommend 98 feet of buffer to protect instream habitat, 98 to 164 feet for recruitment of large woody debris and 328 to 656 feet to benefit birds and mammals.[4]

Vegetation

Selection of appropriate vegetation is essential for viable riparian buffers. Plant selection should include the use of native species with diversity that insures a well-developed shrub layer and variability in tree age, shape and species. Appendix H provides more specific guidance on the selection and care of appropriate riparian plants. King County's *Guidelines for Bank Stabilization Projects*, has additional information on the selection of riparian plant species.[5]

Conducting an historical analysis of the area to be restored may be beneficial, particularly where all evidence of endemic vegetation and natural channel shape and process have been obscured by human activity.

Vegetation establishment often requires irrigation and weed control for success. Refer to the discussions in this chapter addressing the techniques *Woody Plantings* and *Herbaceous Cover* for additional information on cultivating and maintaining bank vegetation.

Conservation Easements

Conservation easements or other land-use controls can be beneficial and may be necessary to prevent incidental use and conversion of riparian areas to uses that are destructive to fish habitat in the stream. Conservation easements are legal, recorded documents providing continuous protection that carries forward even when the land is sold. They are voluntary agreements between the property owner and the holder of the easement that limit activities on the property (within the easement) in order to protect specified conservation values. The ownership of the land, however, remains with the private landowner.

Conservation easements are particularly important for long-term mitigation, where the mitigation must last for the life of the project. Various groups or agencies negotiate and/or provide compensation for conservation easements, such as local land trusts, conservations districts through Natural Resource Conservation Service programs and the Interagency Committee for Outdoor Recreation's Riparian Habitat Program.[6]

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements of the Technique

No mitigation is required for this technique.

Mitigation Benefits Provided by the Technique

Because of its importance to fish and wildlife, restoration of riparian function may be considered mitigation for the loss of habitat caused by other types of bank-protection projects. The protection, restoration or creation of riparian buffers can be used as mitigation. Refer to Chapter 5 matrices for further information on the benefits of this treatment.

There are three components necessary for a riparian buffer to be considered acceptable as mitigation:

1. buffer widths must be defined in relation to stream type (as defined previously),
2. conservation easements must be provided, and
3. native riparian vegetation must be present.

Less-stringent requirements can be placed on buffers restored solely for bank protection or habitat enhancement and not as mitigation. The greatest benefit and full mitigation can only result from applying all three components.

When construction of a project leads to the destruction or displacement of upland vegetation, restoration is the appropriate mitigation. When a project confines a channel to an area narrower than the meander belt, one of the few mitigation opportunities available is to restore or improve the natural riparian function of the banks of adjacent reaches that might be affected by the confinement eventually.

RISK

Infrastructure

Development of riparian buffers may increase floodwater surface elevations compared to bare or smooth buffer zones. Hydraulic modeling of the possible impacts should be used to evaluate flood hazards to existing structures.

Reliability/Uncertainty of Technique

Development of riparian buffers is a reliable and proven technique. However, because robust development of plant growth depends upon soil conditions, climate and weather, site-specific outcomes are not easily predicted. There is risk in using the technique as bank protection due to the time it takes for vegetation to develop and function fully. Combining riparian-buffer management with other techniques that provide immediate protection often reduces this risk.

CONSTRUCTION CONSIDERATIONS

Materials Required

Establishment of a riparian buffer may require nothing more than restricting or minimizing land use within the buffer and allowing the stream to function naturally. The restoration or creation of riparian buffers may also require establishing or enhancing plant materials. This may include fostering the growth of existing plants or propagating them through natural recruitment. It may even require importing plant materials from other sites. Cultivation may require irrigation, mulch and soil amendments and may require riparian fencing. Refer to Appendix H for further information.

Timing Considerations

There are no timing restrictions other than those required to optimize plant propagation and survival.

Cost

Cost will depend upon the plant materials applied and the methods used to promote their growth. Direct costs include soil preparation, plant materials and installation, first-season irrigation and maintenance. Indirect costs may include establishment and administration of easements and fencing where livestock exclusion is necessary. The most significant costs of developing a riparian buffer may be in ensuring that there is a functional riparian hydrologic regime such as a channel elevation that supports groundwater access to the appropriate vegetation. If the channel is incised or entrenched, significant channel and/or floodplain restoration and manipulation may be required to restore functional riparian hydrologic regime. More information on cost of this technique is provided in Appendix L, *Cost of Techniques*.

MAINTENANCE

Propagation and promotion of plant growth may require irrigation and weed control. A maintenance plan should accompany all projects and should be written using other local projects as a guide, building on their methods of success as well as recognizing and avoiding techniques that have failed. The maintenance plan should be included in the monitoring plan (see next section); monitoring provides a means for determining when maintenance is necessary. This plan must be modified if monitoring indicates a high mortality rate for introduced vegetation. A clear threshold should be established for when replanting is required or when watering should be introduced due to reduced growth or high mortality.

MONITORING

Plant growth and mortality should be monitored annually, at a minimum, during the growing season. During the first year, and in arid areas, monitoring should be more frequent to identify and correct any problems early on. The monitoring plan should include criteria for initiating maintenance activities and should be correlated with the maintenance plan. The monitoring plan should indicate the methods used to quantify plant establishment and growth relative to design criteria and should include photo documentation from monumented photo points. Refer to Appendix J, *Monitoring* for further discussion of monitoring requirements.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[7] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

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Spawning-Habitat Restoration
Other Techniques

The Aquatic Habitat Guidelines program intends to publish a guideline entitled, "Stream Habitat Restoration Guidelines," in the near future, which will serve as the guideline series' most authoratative information on spawning habitat and off-channel spawning and rearing habitat.

DESCRIPTION

Spawning habitat is comprised of streambed gravel and the flow of water over and through the gravel. Spawning habitat includes any areas with substrate and hydraulic conditions suitable for spawning and adjacent cover habitat such as pools or woody debris. More importantly, the hydraulic conditions of the channel sort the gravel and create the conditions desired for spawning. Because spawning habitat is based on complex channel processes, spawning habitat may be difficult, if not impossible, to create in some situations. For this reason, spawning-habitat replacement as a mitigation technique has only limited application and should be done carefully and with full understanding of the potential biological implications. *Figure 6-49* shows various applications of restored spawning habitats.

Mitigation of spawning habitat that has degraded due to changes in land use must occur at a broad, watershed scale rather than at a site-specific level. For instance, mitigation for spawning habitat that is degraded in a watershed that has been clearcut requires a comprehensive investigation of changes in hydrology, as well as sediment production and transport, among other factors.

Various hydraulic projects can affect spawning habitat both directly and indirectly. Direct effects, which are often irreversible, include burying or covering spawning habitat with a bank-protection project or during construction activities. Channelization projects that shorten or abandon a portion of the channel also result in the reduction or elimination of spawning habitat. Indirect effects can include disruption of gravel recruitment from eroding banks and alteration of natural, channel-migration processes that create spawning habitat. Removing or reducing streambank and channel complexity can result in changes to the naturally occurring gravel-sorting process. Bank hardening can also result in lost opportunity by not allowing development of side channels and sloughs that often provide excellent spawning and rearing conditions. Any project that changes the flow, introduces sediment to a stream, or affects sediment characteristics can affect spawning habitat.

APPLICATION

Restoration or mitigation for damaged or degraded spawning habitats might include creation of instream habitat, off-channel habitat, spawning-gravel supplementation and/or cleaning spawning habitat that has been contaminated with fine sediment. Mitigation or restoration can be conducted at a specific site to correct and enhance localized conditions, or it can integrate stream- and sediment-transport processes for a larger-scale effect.

Designing projects that provide spawning habitat can be approached in two ways. One is to develop spawning criteria or suitability curves, maintaining a bed elevation using gravel of the proper size that will have acceptable depths and velocities at design flows.[1,2] This method is generally not practical except where flow is controlled (e.g., spawning channels with controlled flow and spring channels). The second approach, more common and preferred, is to mimic natural conditions and encourage stream processes that produce localized scour zones and tailouts with sorted gravels. The tailout of a pool provides a continuum of velocities and depths with changing flows, creating suitable holding and spawning habitat for a variety of fish species.

It is crucial to understand stream hydrology and local hydraulic conditions when undertaking a project that creates or enhances spawning habitat. The hydraulics ultimately sort and deposit gravel into spawning habitat. Hydrology and the supply of gravel to the site are also critical. A clear understanding of site and reach limitations will help define project objectives. Are limitations caused by channel character, such as low recruitment of debris that can create habitat? Are limitations created by a lack of spawning-gravel source? Site-specific projects are often unsuccessful, or have only limited success, when the designer does not consider or understand stream processes. An appreciation of sediment-transport dynamics within the watershed and at the site is critical to project success. For instance, projects relying on gravel supplementation can appear successful immediately after construction only to be destroyed after a high-flow event. For more information on sediment transport, refer to Chapter 3, *Reach Assessment*.

Spawning Pads

Spawning pads are short channel sections in which spawning gravel is placed either with or without other structures. They are placed in situations where high-flow hydraulics sort and maintain the gravel as spawning habitat. Some locations, such as constricted channels, are not appropriate for large, in-channel structures. For these sites, partial- or full-spanning bed controls, such as porous weirs and grade controls, may be the most appropriate method to retain the gravel needed to form spawning pads. Drop structures normally result in sediment deposition upstream of the structure and a creation of a gravel bar downstream at the tailout of the plunge pool. These drop structures are typically made of logs or large boulders. They are usually not appropriate for large or low-gradient channels that have well-developed riffle-pool morphology. Low-gradient channels that have a consistent and reliable source of groundwater generally make excellent locations for creating gravel spawning-pads because they do not typically experience high flows that could scour away placed gravel, and they have an abundance of rearing area.

Promotion of Spawning Habitat Adjacent to Bank Protection

The best bank-protection techniques that also protect spawning habitat are those that maintain or create diversity in the hydraulic characteristics along the streambank. This, in turn, leads to creation of more complex structures, which then develop scour holes, enable gravel sorting in the tailout and spawning habitat, and provide complex cover. Features such as engineered log jams are an example of a bank protection technique that can create spawning habitat from the tailout of the scour pool as shown in *Figure 6-50*. An exception to the use of large, complex structures in large rivers is where the bank is immediately adjacent to a known spawning area used by mass-spawning fish like pink or chum salmon. In that instance, a structure that is set back into the bank or a log revetment may have fewer impacts to spawning habitat.

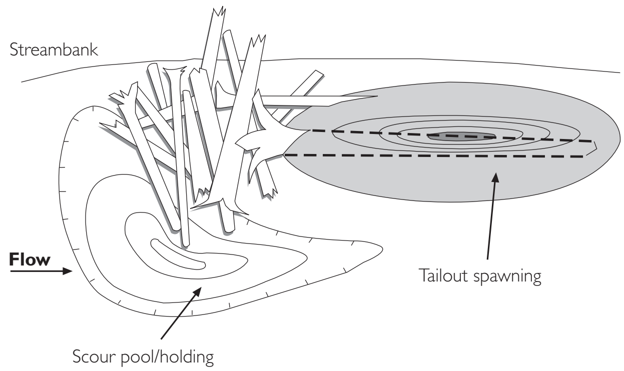

Figure 6-50. Spawning habitat created from tailout of scour pool.

In-Channel Structures

A channel may have an abundance of spawning gravel that is not being used because of the lack of cover for adult fish. In that instance, placing pieces of stable, large woody debris either in the bank or in the channel as cover structures will mitigate for some bank protection impacts. The cover structure must be large and complex enough to create and maintain a scour hole and stable enough to remain as long as the life of the bank-protection project. Cover logs can also be placed on the bank to span existing local scour holes.

Off-Channel Habitat

Another form of mitigation for bank protection is off-site construction of a side channel for spawning habitat. This may be as simple as reconnecting an abandoned side channel or oxbow, or it may involve excavating a new channel on a well-vegetated river bar. This technique has been widely used in Washington State and British Columbia.[3,4,5] See the technique discussed in this chapter entitled, *Off-Channel Spawning and Rearing Habitat,* for more information.

Spawning-Gravel Supplementation

Supplementation - the addition of spawning gravel to a stream - can increase usable habitat. The added gravel becomes hydraulically distributed in such a way that it creates new spawning habitat. The mechanisms of gravel and sediment transport in the watershed must be understood for a project like this to be successful (see Appendix D, *Hydrology* and Appendix E, *Hydraulics*). A reasonable estimate of gravel retention and/or distribution is critical to project success. Spawning gravel may be added to a channel in a variety of ways, including using a helicopter, conveyor belt or dump truck. It can also be deposited simply by placing a pile of properly sized gravel along the streambank and allowing high flows to entrain and distribute the gravel in the channel. In that case, the added gravel might be placed either to mimic an eroding gravel bank or a gravel bar. It may be necessary to add new gravel periodically.

Supplementation is usually undertaken in situations where recruitment of gravel is limited, and a shortage of spawning habitat has been documented. Examples include urbanized streams that have been armored extensively and channels that are affected by reservoirs. Supplementation is the only measure that can provide mitigation for the loss of a gravel source.

Cleaning Spawning Habitat

A variety of techniques have been used to reduce levels of fine-sediment deposition within spawning gravel. Ideally, techniques should be employed that remove and directly replace fine-grained sediment with clean, course gravels. Gravel-cleaning techniques are most useful only when a streambed has been adversely impacted by a single event or by a situation that has been corrected so recontamination won't occur. Rivers and streams with chronic, nonpoint-source pollution are not good candidates for gravel cleaning.

Rehabilitation of spawning gravels has usually been conducted on a relatively small scale in discrete reaches of a river. The simpler methods of gravel cleaning in the past involved the use of heavy equipment such as a bulldozer, backhoe or front-end loader to physically disturb the substrate. These methods aren't generally acceptable, however, due to the release of sediment and potential for contamination of other spawning habitat downstream. A channel bed is less stable following this type of cleaning, since the channel hydraulics will redistribute the bed material during subsequent high flows. Even so, there have been some successes worthy of note. R. J. Gerke[6] supervised the successful use of a bulldozer in cleaning spawning beds in several Washington rivers that suffered from heavy siltation caused by landslides. On the Cedar River, 29,000 square meters of gravels were cleaned using a bulldozer. About 3,000 sockeye salmon and 50 chinook salmon spawned following the cleaning operation. A section of the Entiat River in Washington was also successfully cleaned using a bulldozer, according to D. A. Wilson.[7] J. R. West reported that spawning by chinook salmon increased in Scott River in Northern California after gravels were cleaned there with a bulldozer.[8]

Another approach to the rehabilitation of spawning gravels incorporates the use of a hydraulic flushing action to mobilize and collect fine sediments. The "Riffle Sifter," developed in 1963 by the U.S. Forest Service, was the first machine designed to hydraulically clean sediment-choked spawning areas. The Riffle Sifter flushes fine sediments from the substrate by injecting a high-speed jet of water into the stream bed through a series of pipes. The apparatus then collects the fine sediments through a suction system and jets them onto the floodplain. The Riffle Sifter has been shown to remove up to 65 percent of the particles smaller than 0.4 mm.[9] However, it has developed several mechanical problems in the course of cleaning in natural streambeds.[10]

The "Gravel Gertie" was developed in 1979 by the Washington Department of Fisheries as a more advanced version of a hydraulic gravel-cleaning machine.[11] The Gravel Gertie is mounted on a low-bearing-pressure tracked vehicle that drives through the riffle during operation. The hydraulic cleaning action of the Gravel Gertie uses a vertical jet of water, which is directed towards the streambed to flush out fine sediments. A suction system within a rectangular collection hood removes fines from stream flow. The Gravel Gertie was field tested on the Palouse River in Northern Idaho and on Kennedy Creek and several other streams in western Washington. Effective cleaning was accomplished to substrate depths of 12 inches. All of these streams showed a decrease in the percentage of fines after one pass, with a reduction of fine sediments (<0.841 mm) ranging from three to 78 percent. These techniques are recommended only where material cannot be removed and replaced effectively.

Emergency

The restoration or creation of spawning habitat is rarely conducted under emergency conditions. Construction and enhancement of spawning habitat is typically conducted under low- or moderate-flow conditions. Careful design integrates the full consideration of stream hydrology and hydraulic conditions necessary to create and maintain the desired habitats. This is typically not advisable or even possible in an emergency situation.

EFFECTS

Modifications to channel characteristics by the addition of spawning gravel or gravel-retention structures can have unanticipated effects on banks and adjacent channel segments (see the techniques described in this chapter called *Channel Modifications, Porous Weirs,* and *Drop Structures,* and Appendix F, *Fluvial Geomorphology*).

DESIGN

Use of Large Woody Debris to Enhance Spawning

The enhancement of spawning habitat often relies on the placement of large woody debris to create the desired hydraulic conditions for sorting and retaining adequate quantity and quality of gravel (*Figures 6-51* and *6-52*). A log jam concentrates energy by acting either as a constriction or as an obstruction, resulting in the creation of a scour pool, with the tailout providing spawning habitat. Siting of log jams must be carefully planned because of their potential to increase in size and to alter the existing channel (see the technique described in this chapter called *Engineered Log Jams* and Appendix I, *Anchoring and Placement of Large Woody Debris*).

Spawning Pads

Spawning pads are usually installed in streams less than 40 feet wide. They are created by building a channel constriction or a drop structure across the channel, then placing a specified mix of spawning gravel upstream and/or downstream of the structure or allowing native gravel to deposit during high flows. Either structure creates a backwater upstream and a pool and tailout downstream that can collect gravel. The upstream gravel placement can also be designed to feed gravel to the tailout area. The channel constriction can create more diversity and intragravel flow than a cross-channel weir. It also has a much lower risk of creating a fish-passage barrier.

Spawning pads might be necessary where natural, woody debris has been removed and no structure exists within the stream channel to retain gravel in stable bars. They are usually built as a series of drop structures. Spacing between structures is based on channel gradient and the height of drop at each structure. The drop should be one foot or less during all flows occurring during periods of adult fish migration to facilitate fish passage. If juvenile fish passage is critical, the drop should not exceed six inches. If upstream juvenile fish passage is necessary, the drop required may be as small as six inches. However, structures with small drops are not as effective at sorting downstream gravel. In addition, the lower hydraulic head results in less intragravel flow. A potential risk with spawning pads is that spawners are often attracted to the newly placed gravel before it has had a chance to distribute hydraulically and stabilize. The eggs may not survive if the gravel in the spawning pad shifts during the first flood flows. Several high flows are needed to stabilize the spawning pad.

Channel constrictions can be used effectively to create spawning pads, but they should be considered only with a clear understanding of the dynamics of channel instability. Channel constrictions can create a backwater condition resulting in gravel deposition and ultimately lead to channel reconfiguration, a situation that creates spawning habitat but can also jeopardize bank stability. These dynamic processes are what naturally create spawning habitat. Constriction spawning pads usually only constrict the flow at moderate flood levels when gravel sorting occurs. They are generally constructed as low structures that will not constrict the channel during large floods.

A channel constriction is more effective in low-gradient, spring-fed channels than in a cross-channel structure. A channel constriction should be designed to increase velocities enough to keep fine sediment flushed out of gravels, maintain a tailout and be attractive to spawners. Spawning can occur in the constriction or at the tailout area. The spacing of constrictors is based on the channel gradient and the degree of backwatering developed by the constrictor. A common mistake is to place constrictors too close together, resulting in the backwatering of the upper constrictor, which, in turn leads to reducing velocities, thereby negating the intent of the application. Constriction design, including spacing and size, can be accomplished using either hydraulic models or through trial and error in the field.

An advantage of porous weirs and drop structures in creating spawning habitat is the high intragravel flow developed through the structure and bed upstream. However, this can be a problem if the stream experiences very low flow, and the entire flow goes subsurface. The standard log-drop-structure technique developed by the Washington Department of Fish and Wildlife is a good solution that has been effective and durable in many Washington streams over the last 15 years.[12]

Gravel Supplementation

Gravel supplementation can provide an alternative means of mitigating for degraded or lost spawning habitats. In reaches that are limited in gravel recruitment, a streambank or a gravel bar can be constructed of gravel and designed to erode, which provides a source of spawning gravel. However, because the lack of cohesion in a gravel-constructed bank, this application, if not well planned, can result in bank erosion. Other techniques add gravel directly to the stream and rely on high flows to distribute the gravels. A designer must consider sediment transport, hydrology and hydraulic conditions as well as channel morphology and structure. Refer to Appendix F for further discussion of gravel transport.

Groundwater Channels

Groundwater channels or off-channel, groundwater-fed channels, can be developed for both spawning and off-channel rearing habitat. These are low-gradient channels with low flows. Spawning usually occurs either at points of upwelling or on constructed spawning pads. If the native bed material is not the correct size, it will need to be replaced or supplemented with spawning gravel. Refer to the technique described in this chapter called *Off-Channel Spawning and Rearing Habitat* for information on the design of groundwater channels.

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

Mitigation for construction-related impacts may be required depending upon the type of construction technique(s) used. Riparian habitats can be impacted by type of equipment and site access. Careful planning and the proper use of installation equipment (helicopter, conveyor, etc.) to distribute gravel can significantly reduce potential impacts. Dewatering - isolating the area under construction and removing water from it using a coffer-dam system - is required to control turbidity associated with in-channel excavation. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5, *Identify and Select Solutions* for more detail on mitigation needs for this technique.

Mitigation Benefits Provided by the Technique

Spawning habitats are often the most difficult habitats to replace. Their stability and longevity are important to whether or not future generations of fish can and will use them. Longevity as habitat includes appropriate sorting of material and intra-gravel hydraulics. For this reason, it is crucial that the habitat-restoration project be designed in a way that it is self-maintaining.

Carefully planned and properly constructed instream and off-channel spawning habitats can also mitigate for lost or damaged juvenile rearing habitats and, to a lesser extent, adult holding habitats. Projects that integrate certain structural aspects, such as large woody debris, can produce diverse habitat for a variety of life stages and species of fish.

Refer to Matrix 3 in Chapter 5 for more detail on the mitigation benefits of this technique.

RISK

Habitat

Poorly designed and constructed projects may retain their utility for only a short period. Material (gravel, debris, boulders) selection is critical to the maintenance of the project over time. Newly placed spawning habitat is attractive to fish as perceived spawning habitat. If material is not properly placed or sized, or has not been hydraulically distributed, it can shift or even wash away after the fish have spawned, causing a loss of eggs. It is therefore important to take salmonid life cycles into account when scheduling installation (see information later in this technique discussion under *Timing Considerations*). Improperly sized gravels may also flush out, filling downstream habitats.

Infrastructure

With the exception of poorly installed large woody debris becoming dislodged, spawning-habitat enhancement poses minimal risk to existing infrastructure. There is some risk if channel constrictions or drop structures are placed without consideration or proper understanding of backwater and flooding implications, however.

Reliability/Uncertainty of Technique

Reliability and success is greatly increased when the finished project mimics natural conditions and allows for natural channel process and gravel mobility. Salmonids' spawning needs are highly particular, and replicating the necessary conditions is critical to project success. The creation of desirable spawning habitat for adults is in vain if conditions during egg incubation are unstable.

CONSTRUCTION CONSIDERATIONS

Materials Required

Large woody debris should be large enough to achieve the hydraulic effect necessary to create and maintain spawning habitat. Woody debris and boulders should be of sufficient size to be stable and perform their function of creating hydraulic conditions for gravel stability and/or retention.

The selection of correctly sized spawning gravels is also critical to the success of the project. The proper size of material should be determined first by hydraulic characteristics and then by spawning characteristics. Refer to Appendix E for further information on sediment transport. Angular or crushed gravels should not be used as spawning substrate. Rounded rock, uniformly graded from 0.25 to 3.0 inches in diameter, provides ideal spawning habitat for many salmonids in the Northwest. Specific mixes vary for sizes and species of fish and hydraulic conditions. The following table shows examples of gravel sizes and distributions for salmon.

Grain Size	Avulsion-Prevention Techniques		
	Chum, Pink	Coho, Fall Chinook	Coho, Fall Chinook
6"			100%
4"		100%	90%
3"	100%	85%	75%
1"	85%	55%	60%
0.25" to 0.75 "	40%	25%	20%

Table 6-2. Examples of spawning gravel mixes for salmon.

These mixes are intended for spawning only and are most suited for gravel supplementation or spring-fed channels where the gravel will not be greatly affected by flood flows. In other applications, it may be appropriate to augment spawning gravels with larger materials to add initial stability. The smaller material in the mix protects individual eggs by cradling the eggs. Eggs may be damaged in a mix of gravel with large open spaces.

Timing Considerations

Construction timing should avoid critical periods in resident and anadromous life cycles such as spawning, migration and egg incubation. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction timing and dewatering can also be found in Appendix M, *Construction Considerations*.

Ideally, a newly constructed project should experience a high-flow season before fish are expected to use it as spawning habitat. High flows allow the placed gravel to sort and stabilize prior to its use for spawning.

Cost

Cost is highly variable in spawning restoration projects. Availability and delivery of materials contribute to variability in costs. A cost-saving option used by the Washington Department of Fish and Wildlife for obtaining spawning substrate is to sort gravels near the site. This technique involves the use of a mobile sorting operation positioned close to the project site. Delivery costs are significantly reduced using this method. Sorted and washed gravels may cost $20 to $40 per cubic yard.

Dewatering of a project site can add significant cost to a project. Dewatering costs are greatly affected by the size of the channel and other site-specific factors.

For further discussion of costs, refer to Appendix L, *Cost of Techniques*.

MAINTENANCE

If properly designed and constructed, a spawning habitat mitigation project should not require any maintenance. Gravel supplementation projects may require periodic additions of new gravel.

MONITORING

Biological monitoring provides the ultimate measures of project success. For a comprehensive review of habitat monitoring protocols, refer to Johnson, et al.[13] Monitoring the project for its integrity as a spawning site will likely require a more comprehensive schedule than that required for the integrity of the structures.

In addition to biological monitoring, monitoring the physical conditions is important to documenting project performance. Measurements of the degree of scour, distribution and abundance of gravel, gravel sorting, channel movement, composition of the spawning bed, and the condition of retention structures are recommended elements of a monitoring plan. Constructed spawning habitat, including bed forms and woody debris, can be carefully surveyed immediately after construction and again after initial high flows to document changes that might affect spawning success. Scour chains or other devices intended for measurement of spawning-gravel stability and scour can also be used. However, it is very difficult to quantify impacts of bed instability near hydraulic structures, since the hydraulics will be quite varied around the structure.

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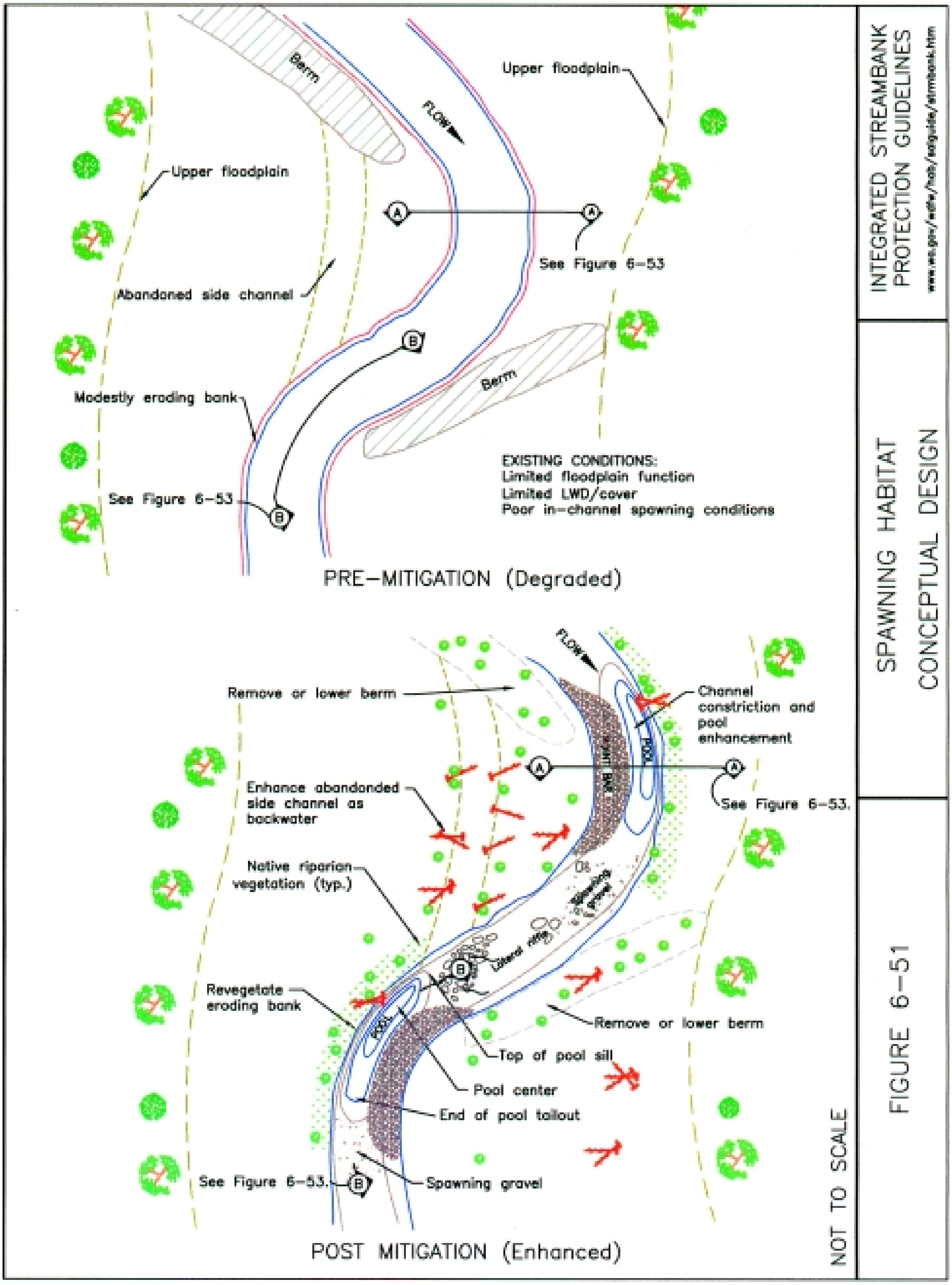
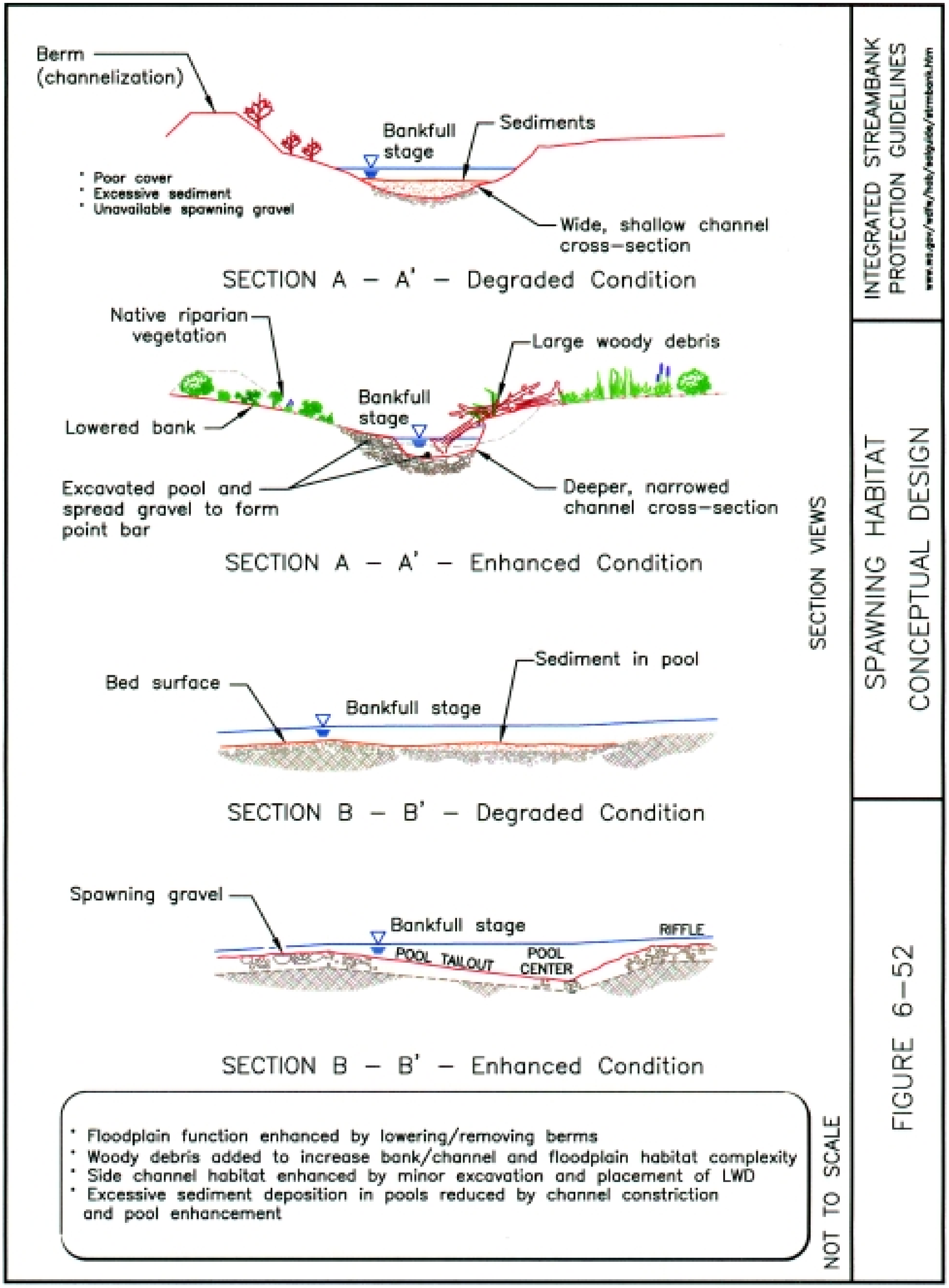
a. Unidentified stream in AK.

b. Spawning-Habitat Restoration upstream from bed control. Cedar Creek. 2001.

Figure 6-49. Applications of restored spawning habitats.



Berm
FLOW
Upper floodplain
Upper floodplain
See Figure 6-53
Abandoned side channel
Berm
Modestly eroding bank
See Figure 6-53
EXISTING CONDITIONS:
Limited floodplain function
Limited LWD/cover
Poor in-channel spawning conditions
PRE-MITIGATION (Degraded)
FLOW
Remove or lower berm
Channel constriction and pool enhancement
Enhance abandoned side channel as backwater
See Figure 6-53.
Native riparian vegetation (typ.)
Lateral riffle
Spawning gravel
Revegetate eroding bank
Pool
Pool
Remove or lower berm
Top of pool sill
Pool center
End of pool tailout
See Figure 6-53.
Spawning gravel
POST MITIGATION (Enhanced)
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
SPAWNING HABITAT CONCEPTUAL DESIGN
FIGURE 6-51


Berm (channelization)
Bankfull stage
Sediments
* Poor cover
* Excessive sediment
* Unavailable spawning gravel
Wide, shallow channel cross-section
SECTION A – A' – Degraded Condition
Native riparian vegetation
Large woody debris
Bankfull stage
Lowered bank
Excavated pool and spread gravel to form point bar
Deeper, narrowed channel cross-section
SECTION A – A' – Enhanced Condition
Sediment in pool
Bed surface
Bankfull stage
SECTION B – B' – Degraded Condition
Spawning gravel
Bankfull stage
RIFFLE
POOL TAILOUT
POOL CENTER
SECTION B – B' – Enhanced Condition
* Floodplain function enhanced by lowering/removing berms
* Woody debris added to increase bank/channel and floodplain habitat complexity
* Side channel habitat enhanced by minor excavation and placement of LWD
* Excessive sediment deposition in pools reduced by channel constriction and pool enhancement
SECTION VIEWS
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
SPAWNING HABITAT CONCEPTUAL DESIGN
FIGURE 6–52

Off-Channel Spawning and Rearing Habitat
Other Techniques

The Aquatic Habitat Guidelines program intends to publish a guideline entitled, "Stream Habitat Restoration Guidelines," in the near future, which will serve as the guideline series' most authoratative information on spawning habitat and off-channel spawning and rearing habitat.

DESCRIPTION

Since 1980, salmon-habitat-enhancement programs in British Columbia and Washington State have given serious attention to the development of off-channel spawning and rearing habitat.[1,2,3] Projects have included restoration and modifications to river floodplain swales, abandoned side channels and floodplain channels along steep, terraced bluffs, all in order to increase spawning and rearing habitat.

P. N. Peterson and L. M. Reid[4] describe three types of habitat within a river floodplain:

1. overflow channels,
2. percolation-fed channels, and
3. wall-based channels.

Figure 6-53 shows various examples of these different types of off-channel features.

Overflow channels are very active and prone to frequent flooding. Percolation-fed channels are protected somewhat from flood flows and have the benefit of providing winter and summer refuge for juvenile fish and spawning habitat for adult fish. Wall-base channels often sit high in the river floodplain where they are protected from flood flows. They serve mainly as overwintering habitat for juvenile coho and trout.

APPLICATION

Off-channel spawning and rearing areas serve as mitigation for bank-protection projects that confine a channel (e.g., bank protection, bridges) and as habitat restoration. Rearing habitat can also be gained by providing access for juvenile fish to existing off-channel ponds.

Many types of bank-protection projects harden the bank of a river so that natural channel meandering cannot occur, thereby preventing the creation of new floodplain channels and fish habitat. Construction of off-channel spawning and rearing habitat may provide mitigation for the future loss of this habitat. Enhancing spawning and/or rearing habitat by developing groundwater-fed channels can result in significant production of coho and chum salmon.[5] If designed correctly, the lifespan of many of these channels can reach 20 years.

The primary objective in establishing groundwater or spring-fed channels is to provide quality habitat for spawning and/or rearing. The proportion of the site used to meet a particular fish life-cycle requirement can vary. It is site- and species-specific and should be based on mitigation requirements and/or on targeted fish species and limiting factors to their production in the watershed. Some sites are allocated and designed solely to function as spawning sites, whereas other sites may incorporate juvenile rearing and adult holding habitat into the design. Numerous variations are possible with this type of enhancement project relative to site conditions and biological considerations.

Variations

Overflow Channels

Overflow channels are flood swales that are directly connected to the main river channel during high flows. Fish habitat associated with overflow channels is often unstable and typically prone to flooding and channel shifting; however, periodic floods through these channels can also help maintain their productivity.

Percolation-Fed Channels

Percolation-fed channels are relict river and/or flood channels supplied by water that percolates as local groundwater from the river. They are usually somewhat protected from floods, can provide ideal sites for spawning-habitat enhancement and provide winter and summer refuge for juvenile fish.

Wall-Based Channels

Wall-based channels can be groundwater-fed but are often fed from springs or surface water from the adjacent terrace. They are usually higher in elevation relative to percolation-fed channels. Wall based-channels can often be enhanced to provide excellent rearing and overwintering habitat for certain species of juvenile salmonids.[6]

EFFECTS

A carefully designed, groundwater-fed side channel at a suitable site can provide spawning and year-round rearing habitats. Furthermore, groundwater-fed channels are often protected from frequent flooding. This stability enhances the success of the project. However, catastrophic flow events that reach the channel can headcut through to the river mainstem and encourage avulsions. These floods can potentially alter habitat conditions, scour the streambed and destroy incubating eggs.

DESIGN

The following design components are important to the development of successful off-channel habitat. *Figure 6-54* shows a conceptual design drawing.

Site Selection and Inventory

The site can be selected from an inventory of site opportunities. Such an inventory should be compiled as part of watershed-restoration planning or flood-hazard management planning. Potential sites should be identified from aerial photos and U. S. Geological Service quad maps. Confirm potential sites by conducting a field survey, and identify any swales or depressions within the floodplain that are protected from frequent river flooding but appear to be deep enough to be near groundwater.

Identify and characterize nearby surface water sources. Identify likely areas in the main channel into which the side-channel flow can discharge to attract fish to the site. The preferred location for a channel outlet is at a point where the channel approaches a terrace at the downstream end of a bend. At such locations, a natural river pool is often present to provide a fish holding and transition area into the side channel, and the location is most protected against closure by river bar deposits. These areas can also be created or enhanced by placing scour structures such as boulders or debris jams in the channel outlet.

Survey

Survey the river's water-surface elevations upstream, adjacent to and downstream of the proposed side channel site. Record elevations of any surface water within the project area. Record recent high water marks, and estimate the return period based on past records. Set elevation reference points at the three locations, and tie the elevations together with a survey that includes elevation reference points for other fieldwork on the project site. For off-channel rearing ponds above the river floodplain, measure the proposed pond elevation relative to the access channel to determine the type and magnitude of channel modifications to ensure fish passage.

Evaluate Percolation Capabilities

The amount of percolation flow may determine the success of the project. Observe and evaluate soil characteristics and percolation capabilities. Dig test pits, analyze percolation, and test water chemistry to determine the nature of soils, the potential of groundwater flow, and the temperature and quality of the water. Record descriptions of the soils, and survey the elevation of soil strata in the test pits.

Pump tests may be necessary to predict percolation rates more accurately. Since analytical hydrologic methods are not available for spring flows, direct flow measurements should be made for a period of a year. A flow-measuring weir can be installed, but be aware that a slight change in water surface elevation can significantly change the volume of measured flow.

To accurately quantify groundwater-flow potential, an extensive aquifer test with at least several high-capacity wells and a long-period, high-capacity pump test is required. The Washington Department of Fish and Wildlife has developed a simple pump-test method of evaluating groundwater-flow potential. This pump-test procedure simplifies the assessment of the groundwater by making the assumption that the water is unconfined. Restated, the aquifer has no impermeable boundaries. This method calculates relative aquifer permeability and relative aquifer supply rates.

Water is pumped from a test pit excavated by backhoe. Two parameters are used to analyze the groundwater potential: drawdown index and apparent velocity. The drawdown index is the pump rate divided by the drawdown rate, and the apparent velocity is the pump rate divided by the wetted area of the test pit. These parameters have been measured for 12 different projects, and comparative ratings have been developed.[7] Piezometers should be installed in the test pits and at additional sites along the proposed channel alignment.

Monitor Water Levels

River and groundwater levels and/or flows should be monitored during a wide range of river flows (at least three per monitoring site) and seasons. This usually requires a period of one year to cover winter and summer groundwater levels. These measurements can then be used to determine channel-control elevations, the depth of excavation and the potential of backwater effects from the river downstream.

For groundwater-fed channels, the design of the channel elevation requires balancing the optimum water surface elevation for maximum groundwater flow against the potential that the channel will be backwatered too frequently from the river mainstem. Percolation flow and concomitant upwelling intergravel flow are reduced when the channel is backwatered. The channel should operate most of the time without backwater effects from the river unless strong upwelling is expected to continue. The channel should be designed to maintain surface flow during summer months.

Once the design elevation is selected at the upstream end of the channel, the gradient of the channel can be selected. Log or plank weirs are usually installed to provide water depths throughout the channel from 0.7 to 3.0 feet. Required channel depth is often species-specific. Water-level controls should be designed with drop structures of less than six inches to ensure passage for juvenile fish and to minimize loss of flow around the structures. Since the structures are built in a porous bed, it is often difficult to maintain flow over a water-control structure that is higher. Water-level controls such as log weirs need to be sealed with an impervious geotextile material to prevent loss of flow over the control and loss of fish passage there.

Generally, channel widths should be in the range of eight to 20 feet and may be restricted by the type of excavation equipment used. Cost is directly driven by channel width.

Physical Habitat

Physical habitat features such as spawning gravel and woody debris should be incorporated into the design. Exposed gravel in the channel can be used, or processed material can be imported. Many channels have provided successful spawning habitat using existing substrate. Evaluate the presence and quantity of potential spawning gravel during excavation of the initial project test pits. It may be economically viable to screen gravel from the overburden for use as spawning bed material. During construction of the channel, a layer of sand will likely accumulate on the gravel bed. It may have to be cleaned with a gravel-cleaning machine.

Cover structures should be located throughout the channel to provide refuge for adult and juvenile fish. Intermittent deep pools can be provided with cover for adult fish holding. Riparian structures should be built into the banks of the channel.

Water Supply

A channel that is fed primarily by groundwater flow provides a more stable environment for incubation and rearing than does a channel that relies solely on surface flow. Flow conditions and water temperatures are more consistent and predictable in channels fed by groundwater. Furthermore, groundwater-fed channels run warmer and clearer in the winter, providing better prey production and feeding opportunities and a less harsh overwintering habitat.

A hydraulic gradient is created when a channel or pond that is excavated into the water table with the channel outlet and water level control elevation below the static water level. This hydraulic gradient controls the amount of surface water flow and is an important parameter in the success of a project. The gradient has much more influence than does the area of the channel or the depth of the channel bed. The amount of flow can be a controlling factor for adult usage and juvenile recruitment. Furthermore, the amount of inter-gravel flow is also closely related to egg-through-fry survival.[6,8] The quantity of groundwater flow is important, so it is desirable to make preproject estimates of the flow potential.[7]

BIOLOGICAL CONSIDERATIONS

Mitigation Requirements for the Technique

This technique is typically used as a form of mitigation for lost or degraded spawning and rearing habitats. Mitigation for construction-related impacts or impacts to wildlife might be required.

It's important to note that an excavated channel can affect the local groundwater level. There is a potential that wetlands may be drained, and vegetation characteristics of the floodplain can be adversely affected. These impacts can be roughly estimated with an accurate assessment of groundwater conditions and anticipated changes. Refer to Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5, *Identify and Select Solutions* for more detail on mitigation needs for this treatment.

Mitigation Benefits Provided by the Technique

Use of this technique may have significant restoration or mitigation potential in watersheds where off-channel rearing and/or spawning are limiting factors to overall fish production or where mitigation is needed for lost opportunity. Creating successful spawning and rearing habitat can result in production of many generations of fish. Refer to Matrix 3 in Chapter 5 for more detail on the mitigation uses of this bank treatment.

RISK AND UNCERTAINTY

Risk to Habitat

Risks to habitat associated with this technique are low, primarily because the work is done out of the main river channel and often in what is initially an upland area. There is a risk of beavers changing the channel-control elevation and the channel or pond becoming contaminated with sediment. There is a risk of stranding fish if elevations and flows are not correctly estimated and surface flow is lost from portions of the project. Over time, leafy material from trees and fine sediment may accumulate and limit productivity or fish passage. These processes are usually part of the natural evolution of side channels. Some maintenance is needed to ensure continued operation at an optimum sole-purpose habitat.

Infastructure

There is also some risk when excavating in the floodplain that major shifts in the river could capture the constructed channel during a large flood. The site and reach assessment and project design should take this risk into account and the risk to infastructure should thus occur. Separation of the constructed channel from the river channel will reduce risk of avulsion. Constrictions made of boulders and/or debris within a constructed side channel can control how much flow it can pass and thereby reduce the risk of avulsion. Constructed spillways in areas where floodwaters will enter the side channel can help lessen the risk of headcuts forming at those places. See the techniques discussed in this chapter entitled, *Floodplain Roughness, Drop Structures, Floodplain Flow Spreaders, and Riparian-Buffer Management* for ideas that can supplement channel construction to manage risk.

Reliability/Uncertainty of Technique

This technique, while proven successful, does rely on the assumption that a consistent and reliable source of groundwater is available. Adequate site assessment as described earlier in this technique discussion can minimize any uncertainty as to the presence and quantity of groundwater available. Changes in land use should also be kept in mind as they may alter groundwater dynamics.

CONSTRUCTION CONSIDERATIONS

Off-channel spawning and rearing habitat is usually constructed outside of the active river channel and therefore requires less attention to factors that complicate construction at sites with moving water. If a channel is to be constructed in a surface-water channel or in a spring-fed channel with substantial flow, a thorough plan for project sequencing and care of the water must be developed. This might include using temporary closure berms to isolate work areas, pumping water onto the forest floor or into settling basins and installing substantial filter devices to clean water that will discharge into the main river. Factors such as access, materials availability, equipment, labor and sediment control must be considered. Further discussion of these elements is provided in Appendix M, *Construction Considerations*.

Clean and correctly sized spawning gravel is critical to the success of a groundwater-fed spawning channel. Washed, rounded rock, generally 0.25 to 3.0 inches in diameter, provides ideal spawning habitat for many salmonids in the Northwest. Angular or crushed gravels should never be used as spawning substrate. Specific spawning-gravel mixtures are addressed in the technique discussed in this chapter entitled, *Spawning Habitat*.

If the channel sub-base material is sandy or clayey, a gravel filter or geotextile blanket is often required to support imported spawning gravel. Additionally, special, low-bearing-pressure equipment may have to be used for at least part of the excavation. Any debris should be anchored to accommodate large fluctuations in main-channel water levels that backwater the side channel.

Timing Considerations

Timing considerations are less of an issue in the establishment of off-channel habitat because the projects are usually somewhat removed from nearby bodies of water. Construction should be conducted when potential impacts to migrating or spawning fish are minimized. Additionally, construction should occur during seasons of low groundwater levels to facilitate construction. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*).

Cost

Cost is highly variable in spawning and rearing habitat restoration projects. Location of spoil piles, availability and delivery of gravel and large, woody debris, and site access are the primary factors that result in variable costs. One option used by the Washington Department of Fish and Wildlife to obtain spawning substrate is to sort gravels near the site. This technique involves the use of a mobile sorting operation located within close proximity to the project site. This technique significantly reduces delivery costs. Using on-site materials, construction costs may range from as little as $6 to $8 per cubic yard of material excavated, which includes bed controls, habitat structures and revegetation. However, imported gravel may cost $40 to $60 per cubic yard.

For further discussion of costs associated with off-channel spawning, refer to Appendix L, *Cost of Techniques*, which describes costs associated with wood materials and complementary project components, such as creation of large woody debris jams.

MAINTENANCE

Maintenance is minimal with this type of project; however, fine sediment and organic debris that can accumulate in the gravel bed may require periodic cleaning of gravel and/or supplementation with new gravel to maintain or restore full habitat potential.

MONITORING

Biological monitoring provides the ultimate measure of project success. Annual spawner counts are the most direct measure of project success. Trapping juvenile fish as they enter and leave a site will be necessary to evaluate the rearing use of a channel. For a comprehensive review of habitat monitoring protocols, refer to Johnson, et al.[9] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

In addition to biological monitoring, the monitoring of physical conditions is important to the documentation of project success. Periodic flow measurements in the channel will determine whether the flow is constant or diminishes over time. Analysis of sediment in the gravel bed can be used to evaluate its quality over time. An evaluation of potential headcutting should be done after large floods occur that are high enough to enter the channel.

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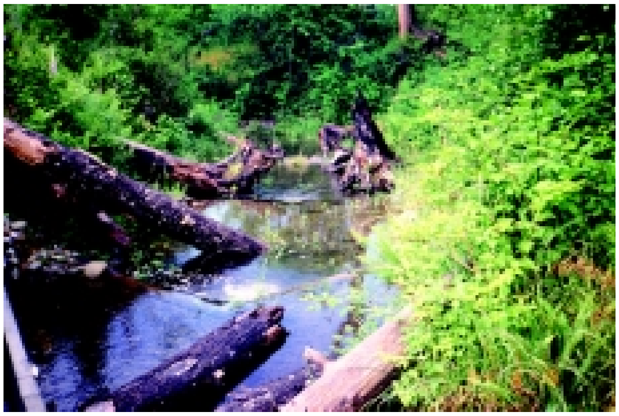
a. Before construction, Creamer Slough, Tributary to Satsop River. 1998.

d. During construction, Creamer Slough, Tributary to Satsop River. 1998.

b. After construction of Off-Channel Spawning, Creamer Slough, Tributary to Satsop River. 1998.

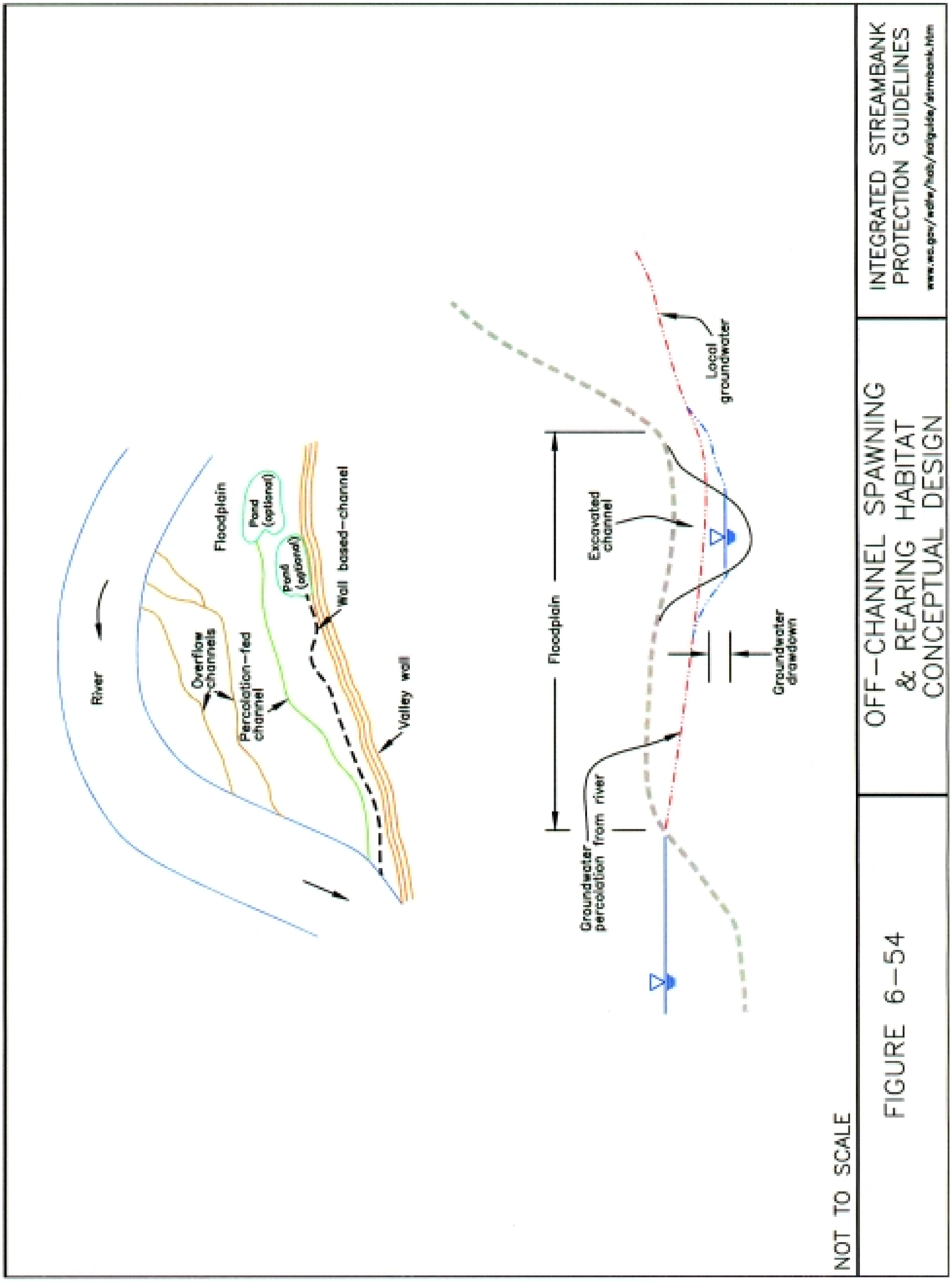
e. Calawah Springs. 1993.



c. Hoh Springs. 1993.

f. Park Slough, Skagit River. 1990.

Figure 6-53. Various examples of off-channel spawning and rearing habitat restoration.


River
Overflow channels
Percolation-fed channel
Floodplain
Pond (optional)
Pond (optional)
Wall based-channel
Valley wall
Floodplain
Excavated channel
Local groundwater
Groundwater drawdown
Groundwater percolation from river
NOT TO SCALE
FIGURE 6-54
OFF-CHANNEL SPAWNING & REARING HABITAT CONCEPTUAL DESIGN
INTEGRATED STREAMBANK PROTECTION GUIDELINES

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Appendix A

Registration Form

To obtain copies of this and other available Aquatic Habitat Guidelines documents, downloadable versions of our state-of-the-knowledge white papers and drafts of guidelines in development, visit our web site www.wa.gov/wdfw/hab/ahg/. To receive publication updates or workshop schedules, please complete the form at the above web site. The Aquatic Habitat Guidelines program appreciates receiving ideas and comments on this guideline. E-mail your comments to AHGComments@dfw.wa.gov.

Your Information

If you do not have access to e-mail or the internet and wish to receive publication notices and workshop schedules, please complete the following form and mail or fax to the address below:

First Name: ____________________

Last Name: ____________________

Affiliation (if applicable): ____________________

E-mail: ____________________

Mailing Address: ____________________

City: ____________________ State/Province: ____________________

Country: ____________________ Zip: ____________________

Please check the topics below for which you would like to receive publication notices or workshop schedules.

- ☐ Fishways - Design, Operation, and Evaluation
- ☐ Design of Road Culverts for Fish Passage
- ☐ Fish-Protection Screens
- ☐ Stream-Habitat Restoration
- ☐ Streambank Protection
- ☐ Overwater Structures: Marine
- ☐ Overwater Structures: Freshwater
- ☐ Overwater Structures: Treated Wood
- ☐ Marine Shoreline Modifications
- ☐ Marine Nearshore and Estuary Restoration
- ☐ Water Crossings
- ☐ Marine Dredging
- ☐ Freshwater Gravel Removal
- ☐ Lakeshore Protection

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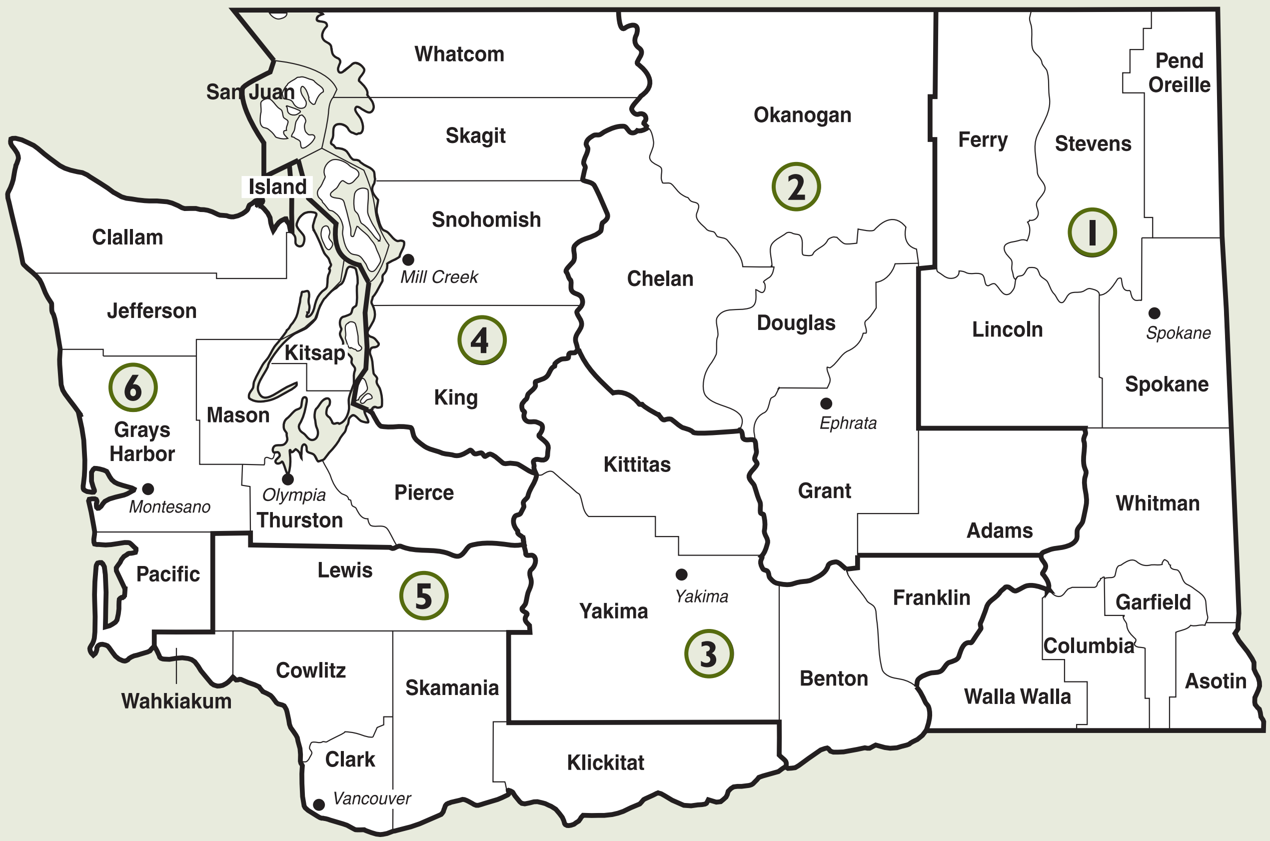
Send this form by mail or fax to:

Washington Department of Fish and Wildlife
Habitat Program
Aquatic Habitat Guidelines
600 Capitol Way N.
Olympia, Washington 98501-1061

Fax 360-902-2946 (Send to the attention of: Aquatic Habitat Guidelines)
Phone 360-902-2534

Appendix B

Washington Department of Fish and Wildlife Contact Information



Region 1
North 8702 Division Street
Spokane, WA 99218-1199
(509) 4456-4082

Region 2
1150 Alder Street NW
Ephrata, WA 98823-9651
(509) 754-4624

Region 3
1701 South 24th Avenue
Yakima, WA 98902-5720
(509) 457-9317

Region 4
16018 Mill Creek Boulevard
Mill Creek, WA 98012
(425) 775-1311

Region 5
2108 SE Grand Boulevard
Vancouver, WA 98661
(360) 906-6700

Region 6
48 Devonshire Road
Montesano, WA 98563-9618
(360) 249-4628

APPENDIX C >>>
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Appendix C
Glossary

A

aggradation: The geologic process by which a streambed is raised in elevation by the deposition of additional material transported from upstream (opposite of *degradation*).

alevin: The life stage of salmon and trout immediately following the egg stage. Hatchlings still have their yolk sacs attached to them, and they live within the spaces in the gravel.

allochthonous: Leaf litter.

alluvial fan: A relatively flat to gently sloping landform shaped like an open fan or a segment of a cone, composed predominately of coarse-grained soils. The stream deposits these soils wherever it flows from a narrow mountain valley onto a plain or broad valley, or wherever the stream gradient suddenly decreases.

alluvial stream: Streams that have erodible boundaries and are free to adjust dimensions, shape, pattern and gradient in response to change in slope, sediment supply or discharge.

alluvium: Sedimentary deposits created by streams on river beds, floodplains and as alluvial fans. The term applies to stream deposits of recent time.

anadromous: Fish that are born in freshwater, migrate to and live a portion of their lives in saltwater, then return to freshwater to reproduce.

anastomosing channel: A channel that is divided into several smaller channels, which successively meet and then redivide. Synonymous with *braided channel*.

anchor point: Either natural (e.g., tree or rock outcroppings) or man-made hard structures (e.g., rock or log trenches) at the upstream and/or downstream end of an isolated scour hole.

avulsion: A significant and abrupt change in channel alignment resulting in a new channel across the floodplain. Straightening or relocating the channel by constructing dikes or levees is a common causes of channel avulsions.

B

backwater: Stream water, obstructed by some downstream hydraulic control, that is slowed or stopped from flowing at its normal, open-channel flow condition.

backwater bars: Gravel bars that form upstream due to backwater conditions.

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bank erosion: The process by which water loosens and wears away soil and rock from the edge of a body of water, usually resulting in an enlargement of the body of water and a corresponding reduction in the size of the land.

bank fill: Any material used to construct a streambank. Bank fill is usually composed mostly of mineral content, as opposed to topsoil.

bankfull: The full capacity of the channel clear up to the top of the channel bank on either side (the transition point between the bank and the floodplain).

bankfull discharge: A flow of water large enough to fill the width and depth of a stable, alluvial stream. Water fills the channel up to the first flat depositional surface (active floodplain) in the stream. Such a discharge typically occurs every 1.5 years or so.

barbs: Low-elevation structures projecting from a bank and angled upstream to redirect flow away from a streambank, thereby controlling erosion of the streambank.

baseflow: Flow in a channel generated by moisture in the soil or groundwater.

batter: The receding, upward slope of a wall or the face of a structure. To give a structure or wall a receding, upward slope.

bed: The land below the ordinary high water lines of state waters. This definition does not apply to irrigation ditches, canals, storm-water run-off devices or artificial watercourses, except where they exist in a natural water course that has been altered by man.

bed erosion: The process by which water loosens and wears away soil and rock from the bottom of a body of water, usually resulting in a deepening of the body of water.

bedload: The part of a channel's sediment transport that is not in suspension, consisting of coarse material that is moving on or near the channel bed.

bed roughness: The unevenness of streambed material (i.e., gravel, cobbles) that contributes resistance to stream flow. The degree of roughness is commonly expressed using "Manning's roughness coefficient."

benthic: Of or pertaining to animals and plants living on or within the substrate of a water body.

benthic drift: The downstream movement of bottom-dwelling plants and invertebrates, accomplished by floating in the current.

bioengineering: An engineering technique that applies biological knowledge when designing and constructing earth and water constructions and when dealing with unstable slopes and streambanks.

bole: The trunk or stem of a tree, without rootwad.

braided channel: A river channel having multiple subchannels that meander away from each other and then reunite at intervals.

brush mattress: A mattress-like covering that is placed on top of the soil. The mattress is made of living, woody plant cuttings that are capable of sprouting roots, branches and leaves.

buttress: A lateral restraint against slope movement.

C

channel: A natural or artificial waterway that periodically or continuously contains moving water. It has a distinct bed and banks that confine the water flowing in the channel.

channel bed slope: A channel's vertical change over distance (the gradient).

channel bed width: The width of the bankfull channel. In some channels, there is not a floodplain or a bench present to define bankfull width. In those cases, bankfull width is determined by features that do not depend on a floodplain; features similar to those used in the description of an active channel and ordinary high water.

channel flanking: See *flanking*.

channelization: Straightening a stream or dredging a new channel into which the flow of the original channel is diverted.

channel top width: The horizontal distance along a transect line from top of bank to top of bank, measured at right angles to the direction of flow.

char: Char belong to the Family "Salmonidae" genus "Salvelinus," and are described as having a body with light spots on a darker background, very fine and embedded scales, and the absence of teeth on the shaft of the vomer. Char include bull trout, Dolly Varden, eastern brook trout and lake trout.

chimney drain: Vertical drains that typically feed into a collection drain at their base.

chute cutoff: A new channel formed by the truncating of a meander bend across the floodplain. The channel flow bypasses the meander bend by cutting straight through it.

coffer dam: An impermeable structure placed in a stream channel that allows water on one side of the structure to be pumped out so that construction can occur in dry conditions.

cohesive soil: Soils that have natural resistance to being pulled apart.

coir: Coconut fiber used in a variety of ways to protect streambanks from erosion.

coir logs: Cylindrical objects constructed from coconut fiber (coir) and bound by mesh.

conifer: Any of a large family of evergreen shrubs and trees, characterized by needle-shaped leaves and cones, such as pines, firs, hemlocks and spruces.

cribwall: A structure built of logs laid horizontally and separated by smaller wooden spacers. Cribwalls are sometimes used to protect streambanks from the erosive effects of channel flow.

cross section: The characteristics of an object when viewed crosswise; for streams, a transect taken at right angles to flow direction.

current: The flow of water moving in a downstream direction. See also *velocity*.

D

D_{50}, /D_{100}: The particle size for which 50 and 100 percent of the sample is finer.

debris: Material distributed along and within a channel or its floodplain either by natural processes or human influences. Includes gravel, cobble, rubble and boulder-sized sediments, as well as trees and other organic detritus.

deciduous: Any of a large family of trees and shrubs that shed their leaves each year, such as maple, birch, cottonwood and alder.

degradation: The removal of streambed materials caused by the erosional force of water flow that results in a lowering of the bed elevation throughout the reach (opposite of *aggradation*).

deposition: The settlement of material onto the channel bed.

dessication: To dry up.

dewater: To remove water from an area.

discharge: The rate of flow expressed in volume per unit of time. For example, cubic feet per second. Discharge is the product of the mean velocity and the cross-sectional area of flow.

doloes: A specific form of concrete armor unit in the shape of an "H," commonly used in bank-stabilization applications where rock is unavailable and/or to create porous treatments.

dominant discharge: The discharge responsible for the largest volume of sediment transport over a long period of record. It is typically a one- to three-year event.

drop structure: Any in-channel structure that creates a distinct drop in water-surface elevation in a downstream direction.

drop/weir scour: Scour resulting from an increase in flow velocity through a weir or due to hydraulic forces associated with a drop in water-surface elevation.

E

ecology blocks: Concrete blocks.

effective discharge: Discharges as determined from measured or calculated flow and sediment records.

energy sink: A scour pool formed by flow in the corner of a tight-radius bend that dissipates the energy of the entire momentum of the flow.

engineered log jam: Constructed collections of large woody debris that redirect stream flow.

entrainment: The incidental trapping of fish and other aquatic organisms in waters being diverted for other purposes. Sediment entrainment refers to sediment transported by flows.

erosion: A process or group of processes whereby surface soil and rock is loosened, dissolved or worn away and moved from one place to another by natural processes. Erosion usually involves relatively small amounts of material at a time; but, over a long period of time, it can involve very large volumes of material.

evapotranspiration: The combination of evaporation from the soil surface and transpiration from vegetation.

F

fascine: A long bundle of live cuttings bound together and secured to the streambank or floodplain with live and dead stakes.

flanking: The process by which channel flow occurs behind a channel feature, such as a constructed bank.

floodplain: Any lowland that borders a stream and is inundated periodically by the stream's waters.

floodplain roughness: Any objects on the floodplain that, through friction, reduce flow velocity over the floodplain.

fluvial geomorphology: The science of or pertaining to river processes. Also, the distinctive channel features produced by the action of a stream or river.

forbe: A broad-leafed herb or herbaceous plant other than grass.

freshet: Rapid, temporary rise in stream flow caused by snow melt or rain.

G

geogrid: Sheets manufactured from durable, synthetic fibers used for erosion control.

geomorphic equilibrium: The "sediment-transport continuity" of a stream, wherein the quantity and size of sediment transported into the reach is approximately the same as the quantity and size of sediment transported out of the reach. If a stream is in geomorphic equilibrium, the processes of bank erosion and channel migration will be stable or occur only gradually.

gradient: The slope of a stream-channel bed or water surface, expressed as a percentage of the drop in elevation divided by the distance in which the drop is measured.

groins: Large structures that project into the channel from the bank and extend above the high-flow, water-surface elevation. Their purpose is to dissipate energy and slow the velocity of the flow. Groins differ from barbs in size and function.

H

headcuts or nickpoints: The erosion of the channel bed, progressing in an upstream direction, recognized as small drops or waterfalls or abnormally over-steepened channel segments.

herbaceous cover: A bank-stabilization technique that consists of planted or installed, nonwoody vegetation, such as grass and grass-like wetland plants, rushes, sedges, ferns, legumes, forbes and wildflowers.

holding areas: Areas in a stream that are protected from the current, where salmon can rest while migrating, usually upstream.

hydrograph: A graphic representation of time versus the flow in a channel.

hydrology: The properties, distribution and circulation of water in a stream channel.

hyporheic zone: The zone of saturated sediment adjacent to and underneath the stream. It is directly connected to the stream, and stream water continually exchanges into and out of the hyporheic zone.

I

incised channel: A stream channel that has deepened, becoming disconnected from its floodplain.

incision: The change in channel cross section resulting from the process of degradation.

J

jet scour: Scour resulting as a jet of flow enters the stream (similar to flow ejecting from the nozzle of a hose).

K

key: Structural material (e.g., rock and/or wood) buried into the streambank or into the channel bed to prevent flanking of a bank-protection structure due to erosion in the near-bank region.

L

lithology: The description of rocks or earth materials on the basis of color, composition and grain size.

local scour: Discrete, tight scallops along the bankline or as depressions in the streambed resulting from erosion. It is generated by flow patterns that form around an obstruction in a stream and spill off to either side of the obstruction, forming a horseshoe-shaped scour pattern in the streambed.

log toe: A structure installed at the base of a bank slope constructed of log materials to protect the base of the bank from erosive forces.

M

macroinvertebrates: Invertebrates large enough to be seen with the naked eye.

Manning's roughness coefficient: An equation used to quantify flow in an open channel.

manufactured retention system: Materials made and installed to stabilize channel banks and beds, usually consisting of interlocking or connected units.

mass failure: The sudden breaking away and downward movement of a cohesive portion of the land surface, as opposed to the gradual erosion of soil.

mean annual discharge/mean annual flow: The averaging of the daily mean discharge over a period of years.

mean high flow: The mean of the highest flows over a period of time.

meander: The snake-like appearance of the reach of a stream. More specifically, a stream reach is said to be meandering if its length is 1.5 times (or more) the length of the valley through which it passes. Any reach that exceeds the length of the valley can be taken as evidence of meandering, but 1.5 is the standard minimum used to confirm meandering activity.

meander pattern: A series of sinuous curves or loops in the course of a stream that are produced as a stream swings from one side of its floodplain to the other.

mechanism of failure: The physical process of erosion. Examples of mechanisms of failure include scour and avulsion.

mitigation: Actions taken to avoid or compensate for impacts to habitat resulting from man's activities (WAC 220-110-050).

N

neck cutoff: The loss of a meander resulting from the intersection of meander bends.

O

ordinary high water mark: Generally, the lowest point at which perennial vegetation grows on the streambank. Legal definitions of the ordinary high water mark describe erosion and sediment characteristics as well.

The ordinary high water mark can usually be identified by physical scarring along the bank or shore, or by other distinctive signs. This scarring is the mark along the bank where the action of water is so common as to leave a natural line impressed on the bank. That line may be indicated by erosion, shelving, changes in soil characteristics, destruction of terrestrial vegetation, the presence of litter or debris or other distinctive physical characteristics.

The legal definition of ordinary high water mark per WAC 220-110-020(31) is:

> "Ordinary high water line means the mark on the shores of all waters that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual and so long continued in ordinary years, as to mark upon the soil or vegetation a character distinct from that of the abutting upland: Provided, That in any area where the ordinary high water line cannot be found the ordinary high water line adjoining saltwater shall be the line of mean higher high water and the ordinary high water line adjoining freshwater shall be the elevation of the mean annual flood."

Considerable judgment is required to identify representative ordinary high water marks. It may be difficult to identify the mark on cut banks. In warm months, grasses or hanging vegetation may obscure the mark. Artificial structures (culverts, bridges or other constrictions) can affect the mark in their vicinity by creating marks on the shore that are consistent with ordinary high water marks, but they are above the elevation that is usually found in undisturbed river reaches.

Where the ordinary high water mark cannot be determined reliably, the surveyor should move to a location where the channel section will allow for a more precise measurement. At a location beyond the influence of artificial structures, measure the indicators at five different places (spaced about five channel widths apart straight channel sections), and take the average of these distances.

oversteepened bank: A streambank that has been steepened beyond the angle of repose or beyond the point to which soil cohesion supports the bank.

P

pelagic: Of or occurring in the open sea; ocean inhabiting.

perched floodplain: A terrace. A floodplain surface that, because the streambed has degraded, becomes high enough above the channel that it is no longer inundated by the current hydrologic regime.

piezometer: An instrument used to measure pressure by examining its effect on a volume of liquid or solid.

planform: The characteristics of a river as viewed from above (in an aerial photo, on a map, etc.), which are generally expressed in terms of pattern, sinuosity (channel length/valley length) and individual meander attributes such as amplitude, wavelength and radius of curvature.

plan view: The view from above.

point bar: A stream depositional feature, usually found on the side opposite the concave bank, that helps move bedload from one meander to the next.

pool: A portion of a stream that is deeper than adjacent areas and has a reduced current velocity during base flow.

porous weir: A low-profile structure consisting of loosely consolidated boulders that span the width of the channel.

profile: A cross-sectional depiction of certain characteristics; with streams, these usually include depth, bed configuration, substrate and velocity.

Q

quiescent zone: A calm zone of water in a stream; opposite of turbulent.

R

reach: a) Any specified length of stream;

b) A relatively homogeneous section of a stream having a repetitious sequence of physical and biological characteristics;

c) A regime of hydraulic units whose overall profile is different from another reach.

rearing: The process by which young fish spend up to two years (depending upon the species) in small streams, back channels and lakes where they feed and grow. Juvenile salmon may rear in different streams than they were born in, including intermittent or seasonally wetted watercourses.

recurrence interval: The frequency at which a certain magnitude of flood occurs. Also called "return period."

redd: A nest in a stream, excavated by spawning fish, where they deposit their eggs. Excavation is accomplished by whipping their tails back and forth in the gravel.

refugia: An area protected from disturbance where fish or other animals can find shelter from bad weather, sudden flow surges or other short-duration disturbances.

regression (as in channel-regression equations): Equations that define the mathematical relationship among channel attributes and other variables.

return period: See *recurrence interval*.

revetment: Bank protection accomplished by armoring the bank with erosion-resistant material.

riffle: A reach of stream in which the water flow is more shallow and more rapid than the reaches above and below; natural streams often consist of a succession of pools and riffles.

rill: One of a set of well-defined, subparallel channels that vary in size according to the erodibility of the soil; generally these channels are only a few inches wide and deep.

riprap: Large, durable materials (usually rocks, sometimes broken concrete, etc.) used to protect a streambank or lake shore from erosion; also refers to the materials used for this purpose.

riparian: The area adjacent to flowing water (e.g., rivers, perennial or intermittent streams, seeps or springs) that contains elements of both aquatic and terrestrial ecosystems, which mutually influence each other.

riparian buffer: A swath of riparian vegetation along a channel bank that provides some measure of protection from the erosive forces of water along the channel margins.

riverine: Of or pertaining to rivers and river environments.

rock toe: A structure composed of rock materials, installed at the base of a bank slope to protect the base of the bank from the erosive forces of stream flow.

rootwad: The root mass of a tree.

roughness trees: Trees anchored to a channel margin or within the floodplain to increase roughness, or the resistance to flow. Their function is to slow stream flow.

S

salmonids: Members of the fish family Salmonidae. Salmonids include salmon, trout, char, whitefish and grayling.

scalp: To remove a layer of sand and gravel from a gravel bar.

scarp: A sharp break in slope, resulting from either mass failure or erosion.

scour: The process of removing material from the bed or banks of a channel through the erosive action of flowing water.

sediment: Any mineral or organic matter of any size in a stream channel.

sediment load: The sum total of sediment available for movement in a stream, whether in suspension (suspended load) or at the bottom (bedload).

sediment-transport continuity: The condition wherein the volume of material transported into and out of a reach of river is roughly equal.

shear strength: The characteristic of soil, rock and root structure that resists the sliding of one material against another.

shear stress: A measure of the erosive force acting on and parallel to the channel boundary. It is expressed as force per unit area (lb/ft^2). In a channel, shear stress is created by water flowing parallel to the boundaries of the channel; bank shear is a combined function of the flow magnitude and duration, as well as the shape of the bend and channel cross section.

sheet drain: A planar, surface-formed drain that separates the native bank material (or fill) from the surface bank treatment.

sinuosity: The ratio of stream-channel length, measured in the thalweg from the top of the valley to the bottom of the valley, or ratio of the valley slope to the channel slope. When measured accurately from aerial photos, channel sinuosity may also be used to estimate channel slope (valley slope/sinuosity).

slope: See *channel bed slope*.

spatiotemporal heterogeneity: Synonymous with habitat diversity and habitat complexity. Habitat diversity or complexity refers to the number of different types of habitats at a location. Different habitats at a location can support different life-cycle requirements for a single species, such as foraging, resting and breeding habitat. In addition, habitat diversity is also related to species richness (numbers of different kinds species) since habitats at a single location often can support different types of species.

stage: Water-surface elevation.

stage-discharge relationship: Discharge plotted against corresponding stage (water-surface elevation).

substrate: Mineral and organic material that forms the bed of a stream.

surcharge: A weight on a slope that exerts a down-slope (destabilizing) stress and a perpendicular stress component, the combination of which tends to increase resistance to sliding.

swale: A marshy depression in a stretch of land.

T

tailout: The downstream end of a pool where the bed surface gradually rises and the water depth decreases. It may vary in length, but usually occurs immediately upstream of a riffle.

terrace: A level bench breaking the continuity of a slope, usually a remnant or historic floodplain surface.

thalweg: The longitudinal line of deepest water within a stream.

toe: The base area of a streambank, usually consisting of the bottom margin of vegetated bank and that portion of bank that is submerged during low flow.

toe erosion: The erosion of particles from the streambank and/or bed which results in the undermining of the toe and subsequent gravity collapse or sliding of overlying layers.

transect: A predetermined line along which vegetation occurrence or other characteristics such as canopy density are counted for monitoring purposes. A channel cross section.

transpiration: The loss of water vapor through plant tissue.

W

watershed: An area of land surface that collects precipitation, draining it into a stream. Sometimes referred to as a drainage basin.

wattle: See *fascine,*

V

velocity: The distance that water travels in a given direction during a given interval of time.

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Appendix D
Hydrology

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Appendix D
Hydrology

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

HYDROLOGIC PROCESSES

Hydrology, in the context of streambank protection, includes the study of surface water, its movement and changes in the quantity of flow in a channel and over its banks. Surface-water hydrology, influenced by the physical characteristics of the watershed, involves the transport, storage and change in the quality and quantity of water in a stream. These attributes determine the physical character of the stream. The volume of water flowing down a stream and the duration of that flow determines the forces acting on the stream channel and, therefore, a stream's dimensional characteristics (see Appendix F, *Fluvial Geomorphology*). Consequently, all streambank projects must be based on, or take into consideration, hydrology.

Hydrologic processes can be studied on a wide range of scales from the watershed to a site-specific project location. Watershed hydrology involves the study of the size and shape of the drainage basin, including its stream-network pattern, geology, vegetation, soils and other variables that influence the movement and quantity of water flow. Human impacts, such as infrastructure, dams, flood control and irrigation practices also influence the hydrologic regime.

Stream-Flow Characteristics

Stream-Flow Hydrographs (Discharge vs. Time)

One of the tools used to evaluate stream flow at a given location on a stream is a *hydrograph.* This is a graph that tracks the rate of runoff (discharge plotted against time). V.T. Chow[1] describes the hydrograph as "an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff of a particular drainage basin." Discharge is expressed in the hydrograph as volume per unit time; that is, cubic feet per second (cfs) or cubic meters per second (cms). Discharge is plotted on the vertical (ordinate) axis, and time is plotted on the horizontal (abscissa) axis.

Annual hydrographs and storm hydrographs are the two most important types of hydrographs. Annual hydrographs plot stream flow for an entire water year. The total volume of flow tracked on an annual hydrograph is the basin yield. An example of an annual hydrograph is shown in *Figure D-1* on the following page.

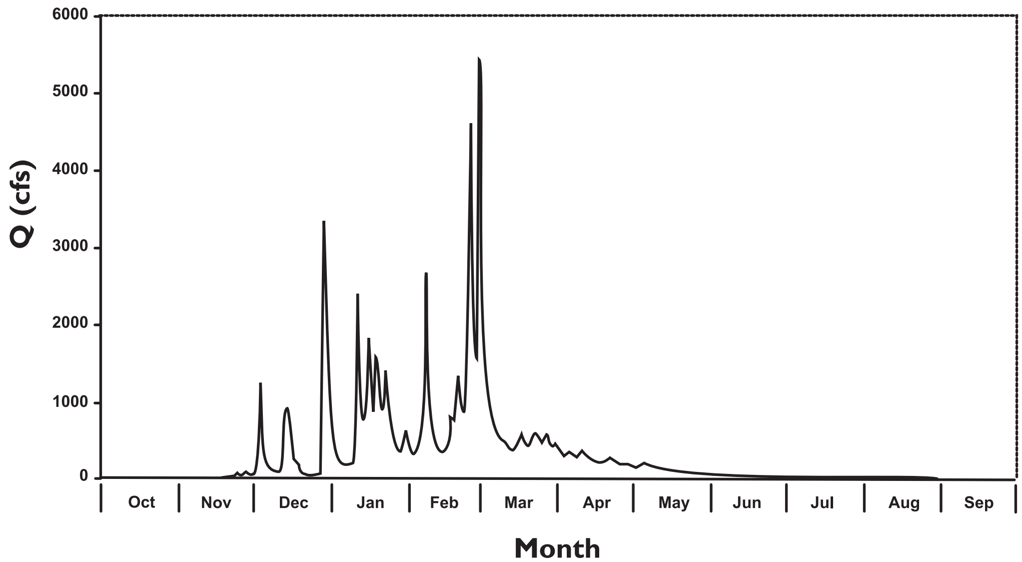

Figure D-1. Hydrograph of a storm-driven stream in western Washington.

A storm hydrograph plots discharge during a single storm event whose time units may be in days or hours. *Figure D-2* shows four components of a hydrograph during a storm. The flow volume represented in the curve segment AB is usually called "base flow" – the flow that occurs during periods of no precipitation. A stream's base flow comes from groundwater that has slowly seeped through surface soils until it reaches the channel. Segment BC on the storm hydrograph is the "rising limb," where direct runoff begins at point B, and flow volume peaks at point C. Flow then declines, as represented by Segment CD, ending at D. Segment DE represents the return to a normal base-flow discharge. The "lag to peak" is the time difference from the moment of highest rainfall intensity to the peak runoff rate and is largely dependent on pre-existing moisture conditions and soil-infiltration rates at the drainage area.

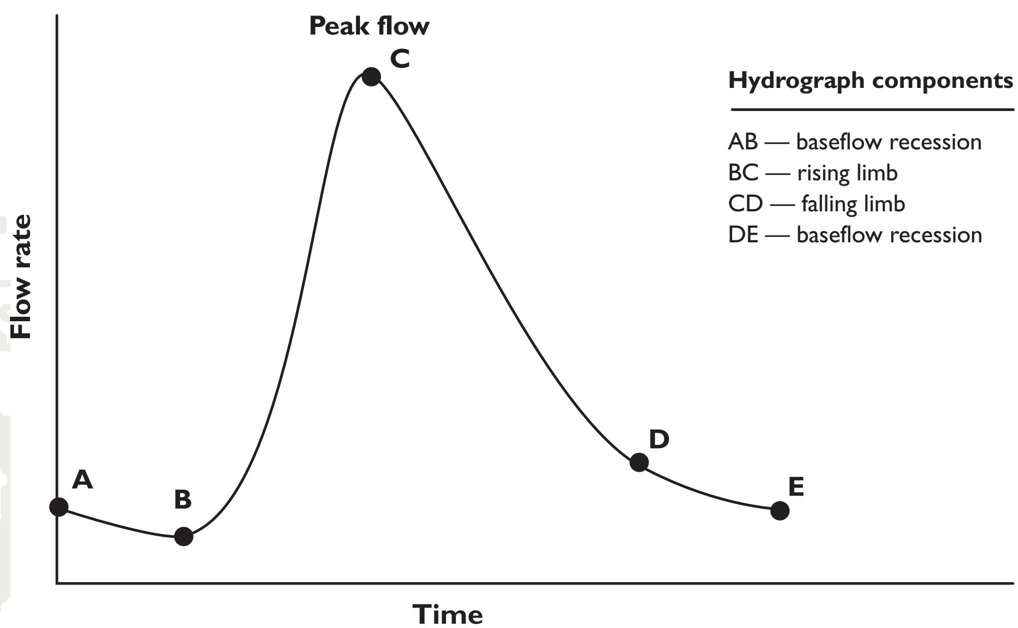

Figure D-2. Storm hydrograph (adapted from Chow, Maidmont and Mays, Applied Hydrology, p. 134, 1988, McGraw Hill)

Storm-Driven Systems

A typical storm-driven system hydrograph from a perennial stream in Washington is shown in *Figure D-3*. A stream that originates from a spring or is fed primarily from groundwater will have a very smooth hydrograph curve, indicative of relatively constant base flow. Discharge may gradually rise and fall in relation to seasonal precipitation patterns and their influence on the groundwater table. The water table recharges or rises in elevation during wet periods and falls or decreases in elevation during drier months. Seasonal changes will register with more clarity on the hydrograph farther downstream in the watershed where tributaries feed into the stream flow and the spring water or groundwater becomes a smaller percentage of total stream-flow volume. In contrast to perennial streams, ephemeral streams have extended dry periods of no surface flow in the channel, followed by intervals of abrupt or flashy discharge caused by seasonal storm events. In this case, rainfall usually becomes direct runoff and reaches the channel as overland flow. Overland flow is a thin layer of water that spreads over a wide surface or slope before it is concentrated or confined to a channel. Overland flow occurs when rainfall intensity of a given storm exceeds the soil-infiltration rate of the basin.

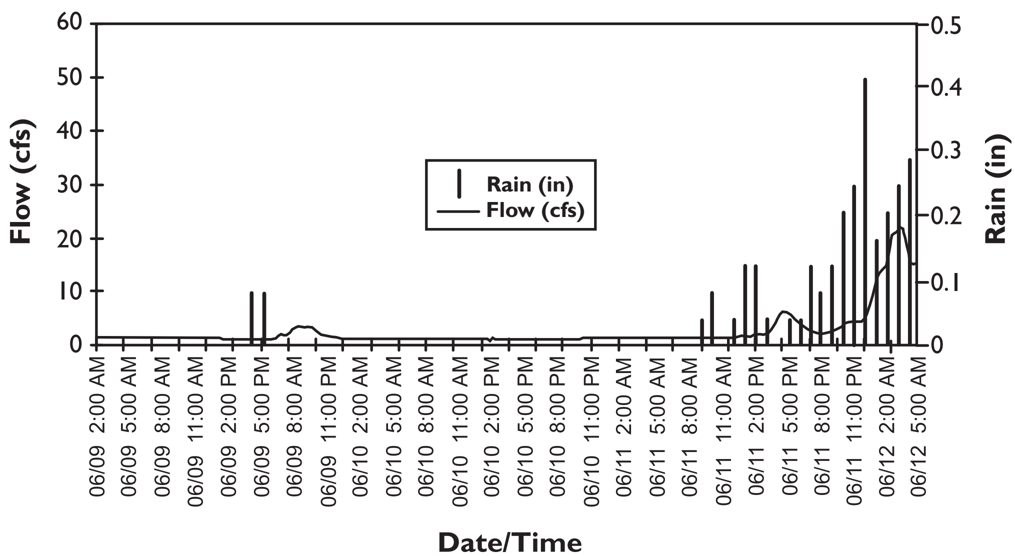

Figure D-3. Storm hydrograph of a perennial stream in western Washington.

Snowmelt-Driven Systems

In regions of the country where the majority of annual precipitation is snow, runoff from snowmelt during spring and early summer comprises the majority of basin yield. A snowmelt-driven system usually creates a smoother curve on a hydrograph (*Figure D-4*) than storm-driven streams (e.g., *Figure D-1*) because a snow pack usually supplies a steady rate of flow. However, a rain-on-snow event, where rain and snowmelt simultaneously contribute to runoff, often produces dramatic spikes in the hydrograph that may correspond with flooding. These events usually occur as a result of the ambient air temperature warming, which causes precipitation to fall as rain rather than snow, with the warmer air also contributing to the melting of the snowpack. The contribution of rain and snowmelt can also coincide with saturated soil conditions, where the ground can no longer absorb or store water, resulting in the direct discharge of overland flow to surface waters. Rain-on-snow events are frequent in the mountainous regions of western Washington and are a common cause of extreme flow conditions and flood events.

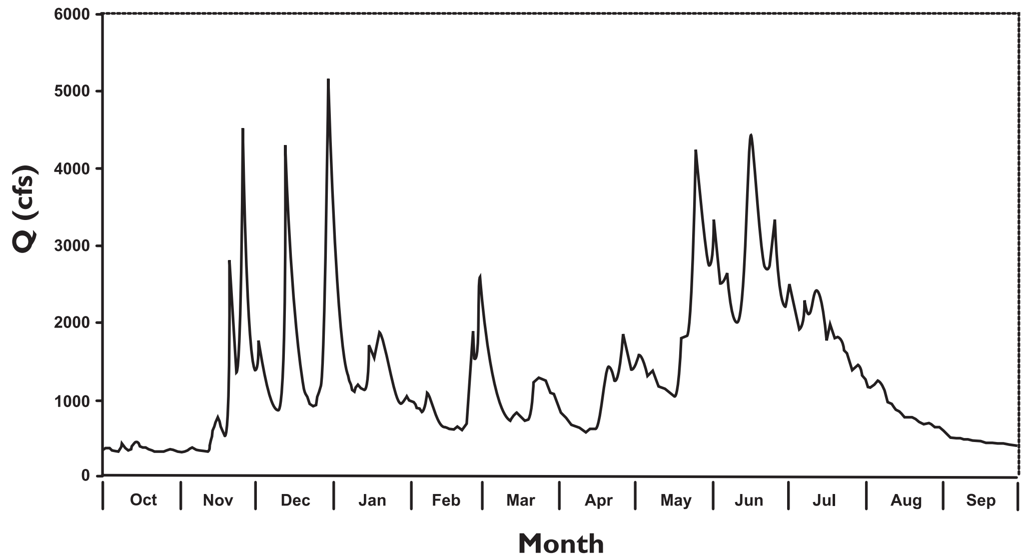

Figure D-4. Storm hydrograph of snowfall-driven stream in eastern Washington.

Gaining and Losing Stream Reaches

Typically, a drainage system's base-flow volume increases in a downstream direction; this may be defined as a *gaining* stream reach and is common throughout Washington wherever groundwater maintains the base flow. A *losing* stream reach occurs where base-flow volume decreases in a downstream direction. Losing steam reaches are most common in arid climates where the loss of water through subsurface infiltration exceeds the rate of flow in the channel. Flow diversions (as discussed in the following sections) may alter base flow and result in loss of stream flow. In some cases, the hydrology of a stream may experience both phenomena, gaining and losing flow volume as the subsurface geology and/or water use changes in the watershed.

Regulated Flow Regimes

There are few major stream drainages that are still undeveloped. Most streams are affected by some form of man-made flow regulation that impounds, diverts, augments and/or modifies their natural hydrologic regime. When examining a historic hydrologic record in a regulated stream, it is often necessary to bracket the data; that is, separate the data based on chronological events of development. For example, separating differences in the flow regime from pre-dam to post-dam hydrologic conditions is necessary to plan and anticipate future conditions. In an urban area, the different flow regimes that may have existed before and after development (e.g., accounting for the influence of impervious ground surface) should also be evaluated.

Reservoirs and Dams

Hydropower

Dams constructed to produce hydroelectric power are common throughout Washington. The effects of dams on the hydrology of a system can be dramatic. Generally, the ability of a dam to store water in a reservoir behind it lowers the magnitude of downstream peak flows. However, the rate at which the dam releases its stored water generally *increases* a river's low flow or base flow from what it was in the pre-dam era. Flows released to generate power through turbines create a sudden increase in discharge downstream from a dam and a corresponding steep rise in the hydrograph, often referred to as "ramping up." Once the demand for power is met, flow volumes are immediately reduced, causing a sharp fall in the curve. This cyclic rise and fall of flow volumes can affect the morphology of the river, change riparian-plant-community distribution and composition, and modify the physical properties of the river system by altering erosional and depositional processes downstream.

Flood Control

Dams, with their ability to store storm runoff and/or snowmelt, protect people and property from the threat of flooding. As discussed in the previous section, dams reduce the volume of peak flows and alter the frequency and duration of flood events. Other flood-control practices that affect hydrology are stream channelization and the construction of levees. Channelization practices reduce the likelihood and duration of a flood by increasing the stream's base- and high-flow velocities. Levees reduce the area of the active floodplain, which also increases the magnitude and frequency of flow in the channel. The faster the flow volume moves through the channel, the less likely the channel is to flood.

Diversions

Seasonal Irrigation Practices

Stream-flow diversions for agricultural use often reduce the overall flow volume of a stream system. Water demands for irrigation are seasonal, depending upon the crop, farming practice and climate in question. Irrigation commonly results in reduced stream flow as water is diverted away from the channel into canals and ditches. This can result in flow reductions and increased water temperatures that may be dangerous to fish.

Water Supply

Another diversion practice involves industrial and municipal water supplies. These types of diversions are used throughout the year and do not result in the seasonal flux that is typical of irrigation diversions. However, during a drought or in the driest months of the year, diversions (in total) may completely dewater a system if instream flow requirements are not identified and maintained.

Flow Augmentation

Flow augmentation is often practiced where the demand for water exceeds the natural supply in a watershed. Augmentations take water from one drainage basin and divert it to another basin, often transporting it through tunnels, aqueducts or open ditches. The discharge is often guided into a natural stream channel or directly into a reservoir. Usually, flow augmentations occur during spring and early summer runoff when water is most abundant and reservoirs are full. Therefore, a watershed system may show a dramatic increase in the magnitude, duration and frequency of peak flows if it is being augmented.

Urban Hydrology

Urbanization of a watershed has a profound impact on stream hydrology. Increased impervious surfaces are a common cause of increased peak-runoff volumes. Examples of impervious surfaces include paved streets and parking lots and roofs. Impervious surfaces decrease soil infiltration rates to zero (see *Figure D-5*[2]). As runoff volumes in urban channels increase (because water is no longer infiltrating the soil), the duration of high flows decreases (because groundwater is no longer contributing to the flow). Also, urban development causes a decrease in lag time between rainfall and runoff by increasing the hydraulic efficiency of the drainage system (water can reach the channel more swiftly when it travels over smooth, hard surfaces). Artificial channels, curbs, gutters and storm sewers increase the magnitude of flood peaks by creating smoother conveyance and decreased storage in the channel and surrounding drainage area.[2] A combination of increased peak-runoff volumes, decreased durations and hydraulic efficiency results in more "erosive work" or hydraulic force acting on a stream channel. On the other hand, when storm flows are captured in detention facilities and gradually released, storm-flow duration increases and peak flow decreases from that of developed conditions.

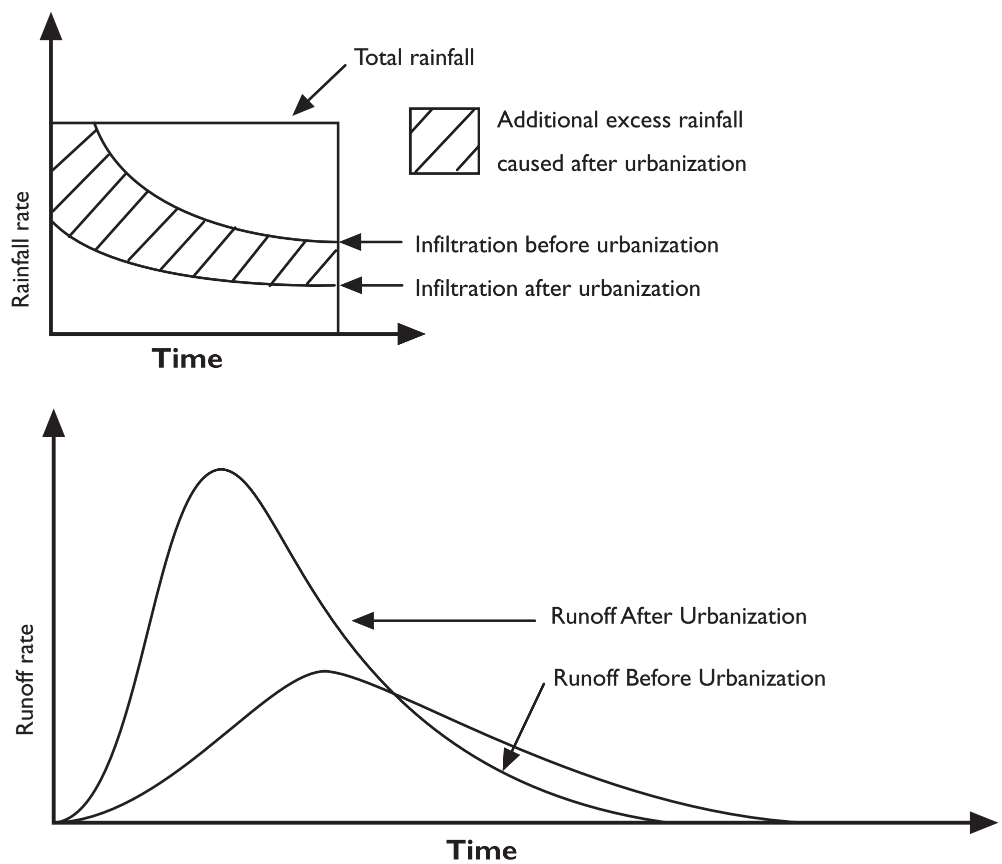

Figure D-5. Urban Hydrograph[2]

The incorporation of storm water detention basins and storm sewers greatly complicates hydrologic analysis. Urban hydrologic modeling is complex and time consuming, but essential to streambank-protection projects. Gauge data and traditional models discussed in the following sections are useful, but inadequate to do the whole job. Urban hydrologic systems often require data collection and modeling that is specific to the urban catchment under consideration.

Urbanization has the most profound impact on streams during the minor floods flows that happen fairly frequently and the least impact on streams during the major floods that happen only rarely. The following provides a general outline for hydrologic analysis of urban settings when implementing a streambank-protection project:

- determine whether the channel has responded to altered hydrology (refer to Appendix F),
- consider potential changes in watershed boundaries due to storm-sewer configurations,
- evaluate flow records with respect to level of urbanization, and
- consider future urbanization trends and possible hydrologic responses.

HYDROLOGIC ANALYSIS

Historic and Current Hydrologic Data

Hydrology at Gauged Stream Sites

The hydrologic statistics described in this section are typically derived from historic stream-gauge data. One must decide if the period of record is long enough to be statistically significant or what portion, if any, of the period of record is relevant. Gauge data usually include mean daily flows for each day. If the project site is in an urbanized or suburbanized basin, it is better to use instantaneous peak flows rather than mean daily flows for deriving statistics. Likewise, only a short period of record is usually relevant in an urban environment because rapid development and changing hydrologic conditions tends to make historic data obsolete. Therefore, segmenting the data set to best represent existing or future conditions may be necessary, but it may also leave only a small amount of relevant data to work with.

- *One-, two-, five-, 10-, 20-, 50- and 100-year flows*. These flows are the annual maximum flows that have an average return interval of the stated number of years. Their probability of occurrence in every year is the inverse of the return interval. The *annual maximum series* consists of all maximum annual flood events. For all statistics less than the 10-year event, a partial-duration series should be employed, which uses all flood peaks greater than some arbitrary base magnitude, usually the smallest number of the annual-maximum series. The recurrence interval derived from a partial-duration series is the average frequency of occurrence between floods of a given size irrespective of their relation to the year, or it is the average time between flows that equal or exceed a given base discharge.[4] For all statistics greater than the 10-year event, use either a partial-duration series or an annual, maximum-data series.
- *Mean annual flow.* This is the mean of all mean annual, daily flows over the period of record.
- *Monthly mean flow*. This is the mean generated by averaging all monthly averages for the period of record. Each month has a characteristic mean flow, which is described by this statistic.
- *Mean monthly minimum.* This is the mean of all monthly minimum flows.
- *Mean monthly maximum*. This is the mean of all monthly maximum flows.

The United States Geological Survey provides the most complete and widely used data for hydrologic analyses. USGS gauging stations are found on almost all major drainage systems and are invaluable sources of data and information. The data for most gauging stations are reported as mean daily flow. In some cases, the instantaneous maximum and minimum daily flow values are also reported. Some gauging stations are no longer in operation, so historic data may often be the best and only hydrologic data available for a particular river system.

Information on where to find hydrologic data for all USGS gauging stations as well as recent and current (real-time) hydrologic conditions for many gauging stations is available from the USGS website. The local or regional USGS office may be able to help obtain more recent data and qualifications of historic data. Other sources of potential hydrologic data are state and local agencies, tribal governments and federal agencies (e.g., U.S. Forest Service, Bureau of Land Management and Bureau of Reclamation).

Hydrology at Ungauged Stream Sites

Where gauge data are determined to be absent, insufficient or of questionable reliability, estimating hydrology can be derived through modeling or analysis of precipitation events using data from other stations in the region. It is important to understand that flow resulting from a given precipitation event does not translate to a stream flow of the same probability. For example, the flow resulting from a 10-year, 24-hour rainstorm is not the same as a 10-year flow event. Be certain that stream-flow statistics are provided, not precipitation data. If alternative statistics are presented, justification for their use should be provided.

Regional analysis for ungauged sites works only if flood-frequency characteristics of the various basins having flood records can be correlated with meteorologic or physiographic parameters. If these parameters are available, floods at ungauged sites can be estimated from the physical geography of the basin. This method assumes that, for a large region, homogeneous meteorologic and physiographic conditions exist, and individual basins in the region have flood-frequency curves of approximately the same slope.[4] If appropriate, regional regression equations can be derived and are often available from the USGS. Common regression variables include:

- basin area,
- mean basin elevation,
- annual rainfall, and
- mean channel width.

Analysis of Hydrologic Data

Interpreting a past record of hydrologic events to determine future probabilities of occurrence is known as "frequency analysis" and is often the basis for planning and designing streambank protection. The method of analysis depends upon the data that is available. If the project site is located within a reach where a record of floods exists, the data can be used directly. In the absence of a flood record, other data from neighboring stations can be regionalized and applied to the prediction of floods at the ungauged site.[3] Hydrologic analysis must derive the correct statistics of probability (described as return intervals) and/or flow duration. The references listed at the end of this appendix provide a more detailed and comprehensive methodology for statistical analyses of hydrologic data.

The most commonly applied hydrologic statistics for streambank-protection design are the following:

- *Return Intervals* - the average interval between events equaling or exceeding a given magnitude, and
- *Exceedence Probabilities* - the chance that the annual maximum event of any year will equal or exceed some given value. These values are derived from calculating and plotting a flow-duration curve. Probabilities are the inverse values of return intervals.

Flood-Frequency Analysis

Design criteria for streambank-protection projects will include hydrologic events (often referred to as an x-year flood, such as a 100-year flood) as descriptors. One common method to calculate the probability of a given flow is the Weibell Plotting Position[2]:

$$T = \frac{n+1}{m}$$

Where: **T** = return interval (years);
n = *number of years of record; and*
m = *rank (number value).*

For example, a certain water elevation for revegetating a streambank may be required for a certain number of days during the critical growing season when the plants must have sufficient soil moisture to establish themselves. To design for this criterion, the amount of flow that can be expected in the stream during this season must be known (perhaps a 0.5-year flow or a three-month average). Determination of the hydrologic regime must be completed prior to any design. Typically, other design criteria for mitigation and habitat design projects will depend upon the hydrologic values derived.

The next section provides a summary of hydrologic characteristics that must be identified as part of a streambank-protection project. If any of these characteristics don't apply or are impossible to determine given available data, it is important to demonstrate why, and then describe how the design criteria can be met without an understanding of these characteristics.

Flow Duration

In addition to the statistics above, one should consider whether or not the project requires an analysis of flow duration. Flow duration refers to the minimum or maximum number of days or hours that a given flow is exceeded for a given time period. Flow-duration statistics must be tailored to the specific nature of the project proposed. Generally, any project whose stated objectives include habitat components designed to sustain a specified life stage should be based on flow-duration statistics. However, flow-duration statistics can only be generated if gauge data are available. Additionally, flow-duration statistics should be based on data specific to the season for which the design is relevant. Note that USGS-derived flow-duration statistics are not applicable, as they are generally not seasonally specific. For example, if a design objective is to sustain sufficient flows for spawning, duration statistics should be based only on those daily-flow data collected during the time of spawning. Hydrologic analysis must include a discussion of what flow-duration data are relevant, whether or not there are sufficient data to derive flow-duration statistics and how they will be derived and applied. For further information regarding derivation of flow-duration statistics, refer to Dunne and Leopold's book, *Water in Environmental Planning*.[3]

Stage-Discharge Relation (Rating Curves)

In hydrology, the term, "stage" refers to the elevation of the water surface above some arbitrary datum. Stage is recorded at gauging stations by measuring water-surface elevations. Stage-discharge relationships are records of stage as a function of time.[4] The stage-discharge graph is called a "rating curve." A rating curve can be helpful in establishing design parameters for a project, such as where and how a given discharge will correspond with a physical attribute of the channel (e.g., an inset, low-flow channel or the bankfull stage).

Single-Event, Rainfall-Simulation Models

The temporal and spatial variations of precipitation, hydrologic abstractions and runoff form the basis of simulation models. Single-event rainfall models are designed to evaluate direct runoff by simulating individual rainfall-runoff events with an emphasis on infiltration rates and surface runoff.[5] Examples of these models include:

- the U.S. Army Corps of Engineers, HEC-1 model;[6]
- the U.S. Natural Resources Soil Conservation Service, Project Formulation-Hydrology model (Technical Release No. 20);[7] and
- the Environmental Protection Agency's Storm Water Management Model.[8]

These models simulate flood events in watersheds and river basins with no provision for pre-existing soil-moisture conditions, and simulations are limited to a single-storm event.[5]

HEC-1 develops a series of interconnected subbasins with hydrologic and hydraulic components. Components may be surface runoff, a stream channel or a reservoir. HEC-1 calculates discharge only, but stage can be indirectly calculated from user input. The result of the model is a computation of stream-flow hydrographs at the targeted location within the watershed.[5]

The objective of Technical Release 20 is to provide the user with a hydrologic analysis of flood events. This model is best applied to watersheds where peak flows are generated by thunderstorms or other high-intensity, short-duration storms. It may be used with as many as nine different rainstorm distributions over a basin with a range of land-use conditions, including various structures that interfere with floodwater conveyance, diversions and channel work.[5]

The EPA's Storm Water Management Model was originally designed for modeling urban storm water runoff and combined sewer overflow. It gives the user many options based on a description of spatial and temporal effects, including storage and/or treatment, cost estimates, and it predicts water quality and quantity values.[5]

Stream-Flow Simulation Models

Stream-flow simulation models are based on continuous stream flow within a watershed and its channels. The Hydrological Simulation Program - FORTRAN is a comprehensive package for the simulation of watershed hydrology and water quality. HSPF uses watershed-scale models for a basin-scale analysis on one-dimensional stream channels. HSPF has been commonly used to simulate hydrology in many watersheds throughout Washington. The Stanford Watershed Model serves as the basis for HSPF. It is comprised of several components, including input data such as precipitation and potential evapotranspiration. If stream flow is influenced by snowmelt, additional meteorological data are necessary. To perform calculations with the Stanford Watershed Model, known or assumed initial conditions are incorporated into the model until the time series input data are exhausted.[5] The model considers four storage zones for precipitation:

1. upper-zone storage,
2. lower-zone storage,
3. groundwater, and
4. snowpack.

Overland flow, infiltration, interflow, base flow and flow-to-groundwater storage are routed within the upper and lower zones to the watershed outlet, where discharge can be expressed as a continuous out-flow hydrograph. To apply the Stanford Watershed Model, typically three to six years of rainfall-runoff data are necessary to calibrate the various parameters, and adjustments are made until an acceptable level of agreement between simulated and recorded flows is established.[2]

HYDROLOGIC DESIGN

Hydrologic design is an integrated process that determines how hydrologic events will affect the physical components of a project. Hydrologic design is a necessary analysis for any streambank-protection project. The level of engineering and choice of structural and geotechnical materials is often based on the hydrologic regime. Hydrologic design must incorporate a much broader scope when a project may affect public safety, infrastructure, aesthetics, economics and natural stream processes.

Flow Types

Distinct flow types and durations that perform different geomorphic and biological functions result from a varying seasonal climate. The following terms are commonly used to describe flow types and are based on a river stage and its relation to physical boundaries and conditions within the channel and floodplain environment:

- low flow,
- flood flow,
- dominant discharge, and
- flow resistance.

Low Flow

A low-flow channel is often formed by base flow and may have the greatest frequency and longest flow duration. The low-flow channel is an inset to a larger, active channel and may be broken down into smaller segments with distinct geomorphic features such as riffles and pools. The stage in the low-flow channel is important to examine if the project's goals include specific revegetation and/or habitat requirements. For example, designing an adequate water depth and velocity is will be critical to the survival of fish species. Likewise, the survival of riparian plant communities and other deep-rooted species may be an integral part of a streambank-protection project that uses a range of bioengineered treatments. Vegetation needs to be planted at a proper bank elevation to make use of moist soil conditions in the low-flow channel for establishment and survival. The best, nonstatistical approximation of this value in Washington is the ordinary high water mark, which is the flow that exists when the water-surface elevation is equal to the elevation of perennial vegetation. This flow level can be determined using Manning's equation[1] or by hydraulic analysis of a surveyed cross section. (Manning's equation is explained later in this appendix under *Flow Resistance and Manning's Equation.*)

Flood Flow

Flood flows are those that exceed the capacity of the channel. Flood stage occurs when water overtops the channel banks to the floodplain surface. Incised channels, however, may contain flood-level flows. Ten-year, 50-year, and 100-year flows are common flood flows used in streambank designs. In ungauged basins, various hydrologic models or regional regression equations may be used to derive flood flows.

Dominant Discharge

Dominant discharge is the flow that produces the greatest morphological effects over an extended period of time. Conceptually, a dominant flow helps describe the flow type that controls the overall shape and function of the active channel. Consequently, dominant discharge should be used as the basis for design of channel characteristics in streambank-protection projects. However, because dominant discharge is difficult to quantify, there are two alternative flows that are commonly used as substitutes:

1. effective discharge (the discharge that transports the most bed load; it can be quantified with knowledge of the channel sediment budget and closely approximates dominant discharge); and
2. bankfull flow.

Bankfull flow is the flow that fills the channel to the top of its banks and at a point where the water begins to overflow onto the floodplain. It generally approximates the dominant discharge only in streams whose hydrology and sediment supply have not been impacted and whose channels have not been impacted by people. In such relatively pristine streams, bankfull flow can be determined from measured cross sections using Manning's equation. Some channels, however, do not have distinct banks; thus, it is hard to determine floodplain-channel boundaries critical to defining bankfull conditions. In channels that are incised or are otherwise impacted, apparent bankfull flow may significantly exceed the dominant discharge and will, therefore, be inappropriate as a design discharge.

Flow Resistance and Manning's Equation

When designing a streambank-protection project using Manning's equation, it is important to consider the relation of channel roughness to discharge. Roughness in a channel, represented by *n* in Manning's equation, refers to all those factors that increase flow resistance, including bed substrate, bank vegetation and relative channel dimensions. Manning's equation expresses the relationship of several variables that include the discharge (Q), hydraulic radius (R_h), velocity (V), the channel slope (S), cross-sectional area of flow (A) and a roughness co-efficient (n).[1] Selection of a roughness coefficient, *n*, will greatly affect the product of the equation. Manning's Equation, in terms of flow depth as it varies with flow rate Q, is expressed as:

$$Q=\frac{1.49S^{1/2}AR_h^{\;2/3}}{n}=VA$$

Roughness values (*n*) for stream channels can be approximated from reference sources such as those developed by H. H. Barnes, Jr.,[5] D. M. Hicks and P. D. Mason.[9]

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Appendix E
Hydraulics

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Within the context of streambank protection, hydraulics refers to the laws governing the movement of water within a channel and the forces generated by this movement. Hydraulic effects result in the erosion of channel banks and scour of the channel bed. This appendix describes how to calculate shear stress (erosional forces along a bank or bed) and scour depth in natural stream channels. Refer to Chapter 2, *Site Assessment* for descriptions of these hydraulic parameters and their relationship with geomorphic processes and aquatic habitat.

SHEAR STRESS

Shear stress is an important parameter in streambank-protection design. All materials used for streambank restoration and protection, whether manufactured or natural, must be able to withstand the expected shear stress, or the bank will continue to be prone to failure. Thus, in streambank-protection design, all materials and vegetation types must be chosen based on the expected shear for a given design flow (for example, the 50-year discharge) at their point of installation. Shear stress is typically measured in units of pounds per square foot (psf).

The material and vegetation types required to resist erosion may vary with location. *Figure E-1*[1] shows the theoretical distribution of shear stress on stream beds and banks on a straight section of trapezoidal channel. Based on the diagram, materials and plants capable of withstanding greater shear forces are required lower on the bank, while a lighter-duty treatment may be sufficient near the top of the bank. When designing vegetated streambanks that include temporary surface protection, such as biodegradable fabric, the designer must be sure that the shear resistance of both the temporary protection (e.g., coir fabric) and the long-term surface treatment (vegetation) are adequate to withstand hydraulic forces at that location. In addition, when making use of vegetation as the primary erosion protection, factors such as species, site aspect, shade, soil type, moisture conditions and local climate must all be considered.

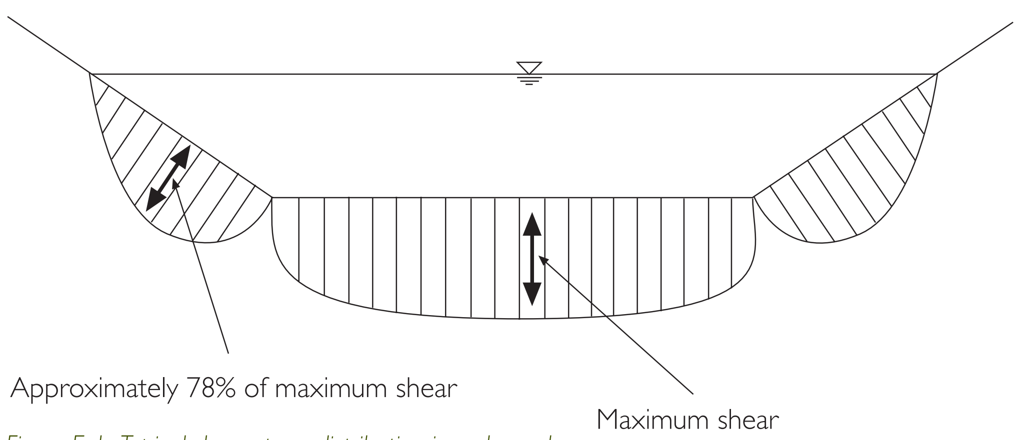

Figure E-1. Typical shear stress distribution in a channel.

Typical levels of tolerated shear stress for various erosion-control materials are shown in *Table E-1*. There is no standardized testing procedure that accounts for the effects of weather, repetitive inundation and long-duration inundation. Therefore, the values in *Table E-1* should be applied using professional judgment, and they should take into account variables unique to the project location.

Erosion-Control Materials	**Tolerated Shear Stress (psf)**
Straw with net	1.4
Coir mats and fabrics	Approx. 1-3 (varies by product)
Synthetic mats	Approx. 2-8 (varies by product)
Class A vegetation: Weeping lovegrass — excellent stand, average height 30" Yellow Bluestem Ischaemum — excellent stand, average height 36"	3.7
Class B vegetation: Kudzu — dense or very dense growth, uncut Bermuda grass — good stand, average height 12" Native grass mix (long and short midwest grasses) — good stand, unmowed Weeping lovegrass — good stand, average height 13" Lespedeza sericea — good stand, not woody, average height 19" Alfalfa — good stand, uncut, average height 11" Blue gamma — good stand, uncut, average height 13"	2.1
Class C vegetation: Crabgrass — fair stand, uncut, height 10" to 48" Bermuda grass — good stand, mowed, average height 6" Common lespedeza — good stand, uncut, average height 11" Grass-legume mix — good stand, uncut, height 6" to 8" Centipede grass — very dense cover, average height 6" Kentucky bluegrass — good stand, height 6" to 12"	1.0
Class D vegetation: Bermuda grass — good stand, cut to 2.5" height Common lespedeza — excellent stand, uncut, average height 4.5" Buffalo grass — good stand, uncut, height 3" to 6" Grass-legume mix — good stand, uncut, height 4" to 5" Lespedeza sericea — very good stand, cut to 2" height	0.6
Class E vegetation: Bermuda grass — good stand, cut to 1.5" height Bermuda grass — burned stubble	0.4
1" diameter gravel	0.3
2" diameter gravel	0.7
6" rock riprap	2.0
12" rock riprap	4.0

Table E-1. Tolerable shear stresses of various materials.[2]

ESTIMATING SHEAR STRESS

Shear equations presented in this appendix allow the designer to estimate bed and bank shear in straight stream reaches and bends. In addition, a means of estimating bank shear as a function of height on the streambank is presented. It is important that those who use the equations presented in this appendix be familiar with hydraulic-analysis methods and the concepts of shear and scour. It is recommended that hydraulic analyses be completed by a qualified hydraulic engineer or a professional with equivalent experience.

Bed Shear Stress in a Straight Reach

According to the U.S. Department of Transportation,[2] shear stress on the stream bed in a straight reach is expressed as:

$$\tau_{bed} = \gamma \, S_e \, R_h \qquad \text{(EQUATION 1)}$$

Where: τ_{bed} = *maximum bed shear stress in lb/ft*^{2} *(psf)*
γ = *the specific weight of water = 62.4 lbs/ft*^{3}
S_e = *energy slope in ft/ft (see below)*
R_h = *hydraulic radius in ft (see below)*

S_e *is the slope* of the hydraulic grade line. This slope is usually similar to the bed slope (gradient) and is occasionally replaced by bed slope in hand calculations. A standard and effective way to calculate channel slope from a surveyed profile is to base the elevation change on the elevations of the thalweg at "zero-flow points." Zero-flow points are the points in the bed that would control the pools upstream of major riffles if there were no water flowing in the channel. In a braided channel, or channels without defined riffles, the mean bed elevation should be used. The mean bed elevation should be determined from several closely spaced cross sections. The U.S. Army Corp of Engineers' hydraulic program, HEC-RAS, can output bed shear stress as well as energy slope.

R_h *is the hydraulic radius*, which is the cross-sectional area of the wetted channel (A) divided by the length of the wetted channel perimeter (P) at the design flow being considered. This value is occasionally replaced by depth of flow, y, but this should only be done when the width of the channel far exceeds the depth of the channel. As a rule of thumb, always use R_h = A/P.

Bank Shear Stress in a Straight Reach

By approximating the channel cross section as a trapezoid or rectangle, the bed shear stress can be transformed into the maximum bank shear stress. This stress acts approximately one-third of the distance up the bank (from the bed) and can be approximated by multiplying by a factor (see Figure E-1). For most channels, multiplying the maximum bed-shear estimate by a factor of 0.8 provides a conservative estimate of the expected maximum bank shear. This approximation applies only to a relatively straight reach of stream.

Using U. S. Department of Transportation's formula,[2] calculate maximum bank shear stress in a straight reach as follows:

$$\tau_{bank} = 0.8\,\tau_{bed} \qquad \text{(EQUATION 2)}$$

Where: τ_{bed} *= maximum bed shear stress in lb/ft^2 (psf)*

Note: the factor 0.8 can be adjusted for high width/depth ratios

Shear stress on the upper bank can be estimated using the following equation:

$$\tau_x = C\,\tau_{bank} \qquad \text{(EQUATION 3)}$$

Where: τ_x *= bank shear at distance x from stream bottom (psf)*
τ_{bank} *= maximum bank shear stress (psf)*
C *= coefficient from Table E-2*

Distance x (feet from stream bottom)**	Coefficient C
1.00y	0.00
0.90 y	0.14
0.80y	0.27
0.67 y	0.41
0.60 y	0.54
0.50 y	0.68
0.40 y	0.79
0.33 y	0.80
0.20 y*	0.70
0.10 y*	0.50
0.00 y*	0.00

Notes: * Although Lane's Diagram indicates zero shear at the base of the bank, for design purposes it is recommended that the maximum bank shear, as calculated above, be assumed to be present for the lower one-third of the bank height.
** *y = stream depth (ft)*

Table E-2. Coefficient C vs. depth.

Shear Stress in Bends

Flow around bends creates secondary currents that exert higher shear forces on the channel bed and banks than those found in straight sections. Several techniques are available for estimating shear stress in bends. A relatively simple and widely used method, presented by U. S. Department of Transportation,[2] estimates maximum shear stress on channel banks and bed occurring within bends. This equation, however, does not differentiate between bank and bed shear stress.

The maximum bed/bank shear stress is primarily focused on the bank and bed on the outside portion of the bend (Figure E-2). The maximum bed/bank shear stress in a bend can be calculated by:

$$\tau_{bend} = K_b \tau_{bed} \qquad \text{(EQUATION 4)}$$

Where: τ_{bend} = *maximum shear stress on bank and bed in a bend (psf)*
τ_{bed} = *maximum bed shear stress in adjacent straight reach (psf)*
K_b = *bend coefficient (dimensionless)*
$= 2.4\, e^{-0.0852(R_c/b)}$
(alternatively, K_b can be determined from Figure E-3)
where: R_c = *radius of curvature of bend (ft)*
b = *bottom width of channel at bend(ft)*

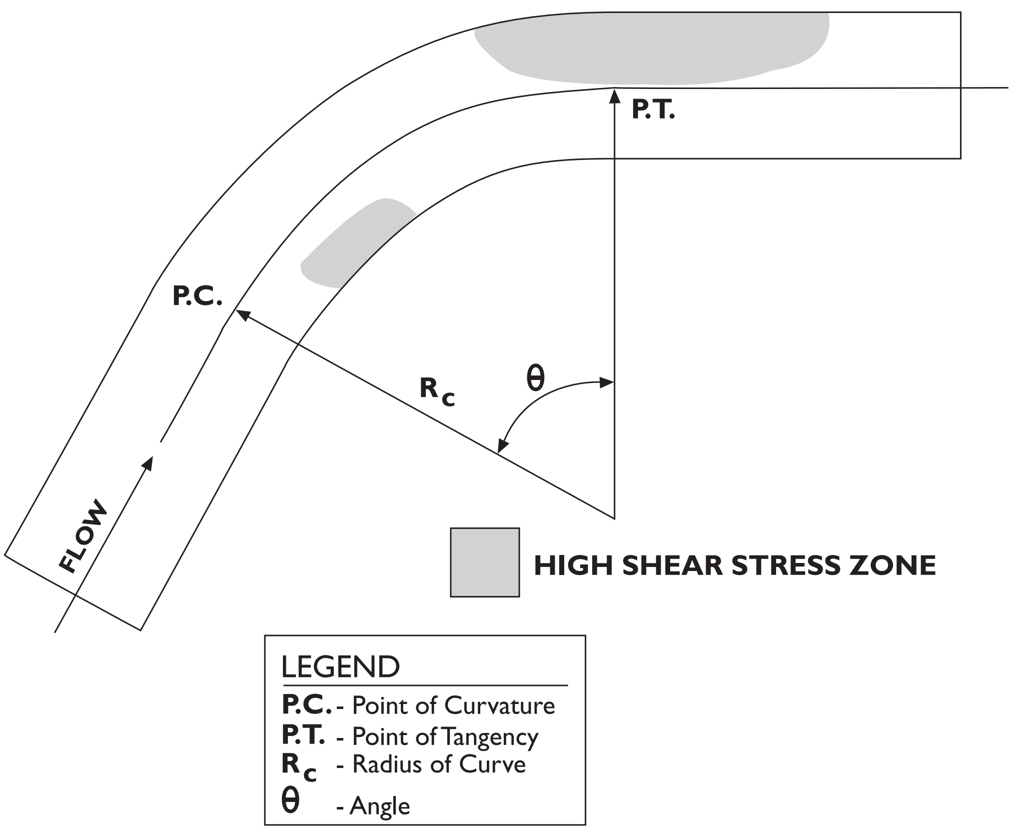

Figure E-2. Shear-stress distribution in a channel bend.

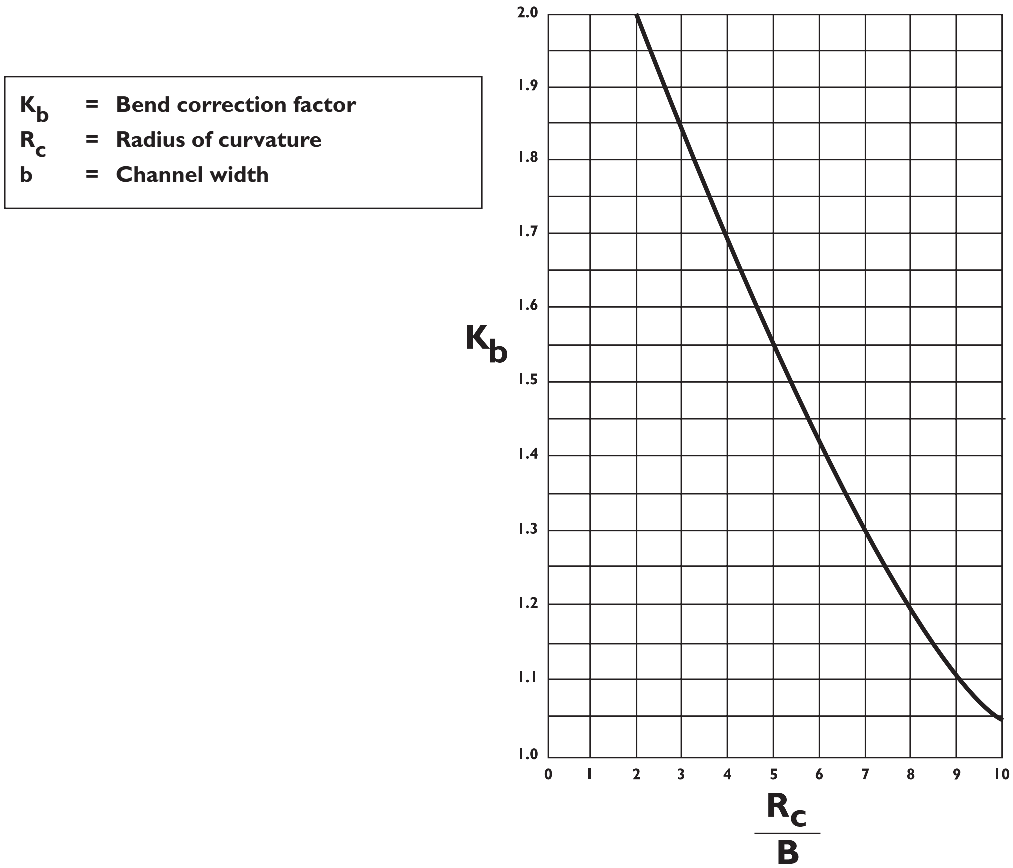

Figure E-3. Bend correction factor chart.

Analysis of the vertical distribution of shear stress on banks in bends is not well defined. Secondary currents found in bends complicate shear analysis in these regions. Equation 4 can be used as a rough estimate of shear distribution on banks in bends, but it does not account for secondary currents. It is recommended that vertical shear distribution in bends be estimated using Equation 4, with judgment based on the severity of the bend and the degree of expected super-elevation of the water surface around the bend. The water-surface elevation increases around the outside of bends as the channel banks exert centrifugal forces on the flow. This super-elevation can be estimated using the following equation[2]:

$$\Delta y = V^2 W / (g R_c) \qquad \text{(EQUATION 5)}$$

Where: Δy = *super-elevation of water surface (ft)*
V = *average velocity of flow (ft/s)*
W = *channel top width (ft)*
g = *acceleration due to gravity (32.2 ft/s^2)*
R_c = *radius of curvature of bend (ft)*

SCOUR

The importance of scour in bank erosion and in the creation of fish habitat is discussed in Chapter 2. This appendix provides methods to predict the depths of scour at embankments and instream structures. Accurate prediction of scour depth is important when designing bank toes and cross-channel structures, such as drop structures and anchoring systems. In addition, the calculation of scour depth allows the designer to predict the effectiveness of instream structures intended to induce scour.

Most of the scour equations presented here were developed to predict hydraulics phenomena associated with man-made structures, such as bridges, located within relatively large, often sand-bed, streams. There are no widely used scour equations developed specifically for use on gravel-bed streams, so the equations developed for sand-bed streams are presented in this appendix along with methods of modification and interpretation that allow their application to gravel-bed streams with larger bed material.

Calculating Potential Depth of Scour

Anticipating the maximum scour depth at a site is critical to the design of a successful bank treatment. It defines the type and depth of foundation needed. Scour depth is also useful when designing anchoring systems or estimating the depths of scour pools adjacent to in-channel structures. Determining the maximum depth of scour is accomplished by:

- identifying the type(s) of scour expected (see next section, *Types of Scour*);
- calculating the depth for each type of scour;
- accounting for the cumulative effects of each type of scour (If more than one type of scour is present, the effects of the scour types are additive); and
- reviewing the calculated scour depth for accuracy based on experience from similar streams, conditions noted during the field visit and an understanding of the calculations.

Types of Scour

Because scour equations are type-specific, the first step in determining the potential depth of scour is to identify the types of scour that occur at the project site. For instance, an equation for calculating local scour will give an incorrect depth if applied to a site affected only by constriction scour. Five types of scour are defined in Chapter 2. They include bend scour, local scour, constriction scour, drop/weir scour and jet scour.

All of the scour equations presented are empirical. Empirical equations are based on repetitious experiments or measurements in the field and, therefore, can be biased toward a specific type of stream from which the measurements were made. In general, however, empirical equations are developed with the intention to error on the conservative side if applied correctly.

The scour equations may distinguish between live-bed and clear-water conditions. These categories refer to the sediment loading during the design event. Live-bed conditions exist when stream flow is transporting sediment at or near its capacity. Under such conditions, erosion is offset by deposition, as stream flow needs to "drop" sediment in order to "pick up" new sediment. Clear-water conditions exist when stream flow is transporting sediment at a rate that is far below its capacity. Such conditions often occur downstream of dams. Because clear-water stream flow is "sediment-starved," it has the capacity to entrain and transport sediment without associated deposition. Accordingly, clear-water conditions usually produce deeper scour depths than live-bed conditions.

Local Scour

Research on scour has focused on local scour at bridge piers and abutments. If the geometry of an obstruction, such as a boulder or rootwad, can be equated to the geometry of a pier, then pier-scour equations are applicable. If the location and shape of the obstruction more closely resembles a bridge abutment rather than a pier, then scour equations for bridge abutments should be used. Obstructions that resemble bridge abutments include woody-debris installations or similar structures that are attached directly to the streambank. Equations for estimating pier and abutment scour are presented below.

Estimating Pier Scour

Numerous equations are available for predicting scour depths near piers. In general, these equations have been developed for sand-bed rivers. However, when applied to streams with larger-size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. As determined by these equations, the scour depths for gravel-bed streams may not occur to the extent predicted, or they may take quite a long time to occur. The pier-scour equation presented below includes an adjustment for bed materials that have a D_{50} of six cm or larger (D_{50} refers to the median grain size of bed material and must be expressed in millimeters) and thus is applicable to gravel-bed streams. Expert judgment should be used to adjust the calculated value, if needed, based on observed stream conditions. In addition, the results of Equation 18 (in this appendix) can be used to evaluate the results of the pier scour analysis.

When using a pier-scour equation to estimate scour near an obstruction, the obstruction must be represented as a pier. For instance, a boulder may be represented in the equation by a cylindrical pier of equal diameter. A log or rootwad may be represented as a round or square-nosed pier of the appropriate length. Note that the pier-scour equations assume that the pier extends above the water surface. When pier-scour depth is calculated for obstructions that do not extend through the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the design engineer.

One of the more commonly applied and referenced pier-scour equations is the Colorado State University Equation.[3] While the equation does not differentiate between live-bed and clear-water scour, it can be applied under both conditions.[3] In addition, the equation includes a correction factor (K_4) to adjust for bed materials of D_{50} greater than or equal to six cm.

The U. S. Department of Transportation recommends using two times the scour depth as a reasonable estimate of scour-hole top width in cohesionless materials such as sands and gravels.[3] Scour-hole top width is measured from the edge of the pier to the outside edge of the adjacent scour hole.

Colorado State University Equation for piers

$$d / y_1 = 2.0\ K_1\ K_2\ K_3\ K_4\ (b/y_1)^{0.65}\ Fr^{0.43} \qquad \text{(EQUATION 6)}$$

Where: **d** = maximum depth of scour below local streambed elevation (m)
y_1 = flow depth directly upstream of the pier (m)
b = pier width (m)
Fr = Froude number: $V / (g\,y)^{0.5}$ (dimensionless)
where: **V** = velocity of flow approaching the abutment (m/s)
g = acceleration due to gravity (9.81m/s^2)
y = flow depth at pier (m)

For the special case of round-nosed piers aligned with the flow, then:
For $Fr \leq 0.8$, $d \leq 2.4$ times the pier width
For $Fr > 0.8$, $d \leq 3.0$ times the pier width

K_1 = correction factor for pier nose shape:
For approach flow angle of attack > 5 degrees, $K_1 = 1.0$
For approach flow angle of attack ≤ 5 degrees:

square nose	$K_1 = 1.1$
round nose	$K_1 = 1.0$
circular cylinder	$K_1 = 1.0$
group of cylinders	$K_1 = 1.0$
sharp nose	$K_1 = 0.9$

K_2 = correction factor for angle of attack of flow from Table E-3
$K_2 = (\cos\theta + L/b\ \sin\theta)^{0.65}$

Where: **L** = length of the pier (along the flow line which is being directly subjected to impinging flow at the angle of attack (m)
b = pier width (m)
θ = flow angle of attack to pier (in degrees)

K_3 = correction factor for bed conditions, based on dune height, where dunes are repeating hills formed from moving sand across the channel bed. For gravel-bed rivers, the recomended value of K_3 is 1.1.

θ	L/b = 4	L/b = 8	L/b = 12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.8	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Table E-3. K_2 based on L/b and **θ** .

Bed Conditions	Dune Height (m)	K_3
clear-water scour	N/A	1.1
plane bed and anti-dune flow	N/A	1.1
small dunes	0.6 to 3	1.1
medium dunes	3 to 9	1.1 to 1.2
large dunes	≥ 9	1.3

Table E-4. K_3 based on bed conditions and dune height.

K_4 = *correction factor for armoring of bed material (scour decreases with armoring)*

K_4 range = 0.7 to 1.0
K_4 = 1.0, for $D_{50} < 0.06$ m, or for $V_r > 1.0$
$K_4 = [1 - 0.89 (1-V_r)^2]^{0.5}$, for $D_{50} \geq 0.06$ m,

where:
$V_r = (V - V_i)/(V_{c90} - V_i)$
$V_i = 0.645 (D_{50}/b)^{0.053} V_{c50}$
$V_c = 6.19\, y_1^{1/6} D_c^{1/3}$

and:
V = approach flow velocity (m/s)
V_r = velocity ratio
V_i = approach velocity when particles at a pier begin to move (m/s)
V_{c90} = critical velocity for D_{90} bed material size (m/s)
V_{c50} = critical velocity for D_{50} bed material size (m/s)
g = acceleration due to gravity (9.81 m/s^2)
D_c = critical particle size for the critical velocity, V_c (m)
y_1 = flow depth directly upstream of the pier (m)

Estimating Scour at Abutments

Like pier-scour equations, abutment-scour equations have generally been developed for sand-bed rivers. When applied to streams with larger-size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. The scour depths predicted by these equations may not occur or may take quite a long time to occur on gravel-bed streams. "Reliable knowledge of how to predict the decrease in scour-hole depth when there are large particles in the bed material is lacking."[4]

Nonetheless, the equations that are available work for sand-bed rivers, and their results yield a conservative estimate, over-predicting the scour depth on gravel-bed streams. As always, judgment should be used to adjust the calculated value, as needed, based on observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value. The results of Equation 18 in this appendix can be used to evaluate the results of the abutment scour analysis.

The Froehlich Equation presented below can be used to estimate scour at an abutment or abutment-like structure.[3] Several variables are included in the equation to describe parameters, such as the abutment shape, angle with respect to flow and abutment length normal to the flow direction. When using this equation to calculate scour for a structure such as a log jam, these parameters should be coupled with expert judgment to describe the structure as best as possible. Note that the abutment-scour equation assumes that the abutment extends above the water surface. When abutment scour depth is calculated for obstructions that do not extend through the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the design engineer.

Froehlich Equation for Live-Bed Scour at Abutments

$$d / y = 2.27 K_1 K_2 (L' / y)^{0.43} Fr^{0.61} + 1.0 \qquad \text{(EQUATION 7)}$$

Where: **d** = *maximum depth of scour below local streambed elevation (m)*

y = *flow depth at abutment (m)*

K_1 = *correction factor for abutment shape where:*

vertical abutment = 1.0

vertical abutment with wing walls = 0.82

spills through abutment = 0.55

K_2 = *correction factor for angle of embankment to flow =* $(\theta / 90)^{0.13}$

where: θ = *angle between channel bank and abutment*

θ *is > 90 degrees if embankment points upstream*

θ *is < 90 degrees if embankment points downstream*

L' = *length of abutment projected normal to flow (m)*

L' = *A / y A = flow area of approach cross section obstructed by the embankment* (m^2)

Fr = *Froude number of flow upstream of thhe abutment =* $V / (g\,y)^{0.5}$

where: **V** = *velocity of flow approaching the abutment (m/s)*

g = *acceleration due to gravity* ($9.81\ m/s^2$)

1.0 is added as a safety factor.

Clear-Water Scour at an Abutment

U. S. Department of Transportation recommends using the live-bed scour equation presented above to calculate clear-water scour at an abutment.[3]

Bend Scour

Scour occurs on the outside of channel bends due to spiraling flow, as described in Chapter 2. Bend scour removes materials from the bank toe, precipitating toe erosion or mass failure.

Field observation/measurement of scour at established bends can yield a quick indication of the magnitude of scour expected if correlated to the flows that produced the scour. A first estimate can also be obtained by assuming the scour in any given bend to be about equal to the flow depth found immediately upstream and downstream of the bend.[5] This estimate will be somewhat conservative for mild bends.

G. J. Hoffmans and H. J. Verheij presented the following equation, developed by C. R. Thorne,[6] based on flume and large-river experiments where the mean bed-particle size varied from 0.3 to 63 mm. This equation is applicable to gravel-bed streams.

Thorne Equation

$$d / y_1 = 1.07 - \log(R_c/W - 2) \quad \text{for } 2 < R_c/W < 22 \qquad \text{(EQUATION 8)}$$

Where: **d** = *maximum depth of scour below local stream bed elevation*
y_1 = *average flow depth directly upstream of the bend*
W = *width of flow*
R_c = *radius of curvature at channel centerline*

The width of flow in Equation 8 corresponds to the width of active flow. This width is subject to engineering judgement. However, it often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage. English or metric units may be used.

S. Maynord reviewed bend scour estimates for natural, sand-bed channels and presented one bend-scour equation by W. Wattanabe and a second method of his own.[7] These two equations are listed below. They are useful for predicting scour depths on sand-bed streams and for determining conservative scour depths (for comparison to other methods) on streams with coarser bed materials.

Maynord Equation

$$D_{mb}/D_u = 1.8 - 0.051\,(R_c/W) + 0.0084\,(W/D_u) \qquad \text{(EQUATION 9)}$$

Where: D_{mb} = *maximum water depth in bend*
D_u = *mean channel depth at upstream crossing (cross-sectional area/W)*
R_c = *radius of curvature at channel centerline*
W = *width of flow at upstream end of bend*

Notes:

- *Equation 9 was developed from measured data on 215 sand-bed channels.*
- *The data were biased for flow events of one- to five-year return intervals.*
- *Equation does not apply when higher return intervals occur that cause overbank flow exceeding 20 percent of channel depth.*
- *There is no safety factor incorporated into this equation; this is the mean scour depth based on the sites measured.*
- *A safety factor of 1.08 is recommended.*
- *The equation is limited to:* $1.5 > R_c/W > 10$ *(use* $R_c/W = 1.5$ *when < 1.5), and limited to:* $20 > W/D_u > 125$ *(use* $W/D_u = 20$ *when < 20).*
- *English or metric units may be used.*
- *The width of flow in Equation 9 corresponds to the width of active flow. This width is subject to engineering judgement. However, it often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage.*

Wattanabe Equation

$$d_s/D = \alpha + \beta(W/R_c)$$ (EQUATION 10)

Where:

$\alpha = 0.361 X^2 - 0.0224X - 0.0394$

$X = \log_{10} (WS^{0.2}/D)$

S = bed slope

d_s = scour depth below maximum depth in unprotected bank

W = channel top width (water surface width)

D = mean channel depth (cross-sectional area/W)

$\beta = 2/(\pi\ 1.226\ ((1/\sqrt{f}\ ) - 1.584)\ x\ )$

f = Darcy friction factor = 64/Re where Re = Reynolds number

$x = 1/\ [1.5\ \ f\ \{(1.11/\sqrt{f}\ ) - 1.42\}\ \sin\sigma + \cos\sigma\ ]$

$\sigma = \tan^{-1}\ [\ 1.5\ \ f\ ((1.11/\sqrt{f}\ ) - 1.42)] = f$

Notes:

- *Results correlate well with Mississippi River data and predicted Thorne and Abt data (1993) by about 25 percent.*
- *Limits of application are unknown.*
- *A safety factor of 1.2 is recommended with this method.*
- *English or metric units may be used.*

Constriction Scour

Constriction-scour equations were developed primarily from flume tests with the constriction resulting from bridge abutments. However, these equations apply equally well to natural constrictions or constrictions caused by installation of instream structures such as groins.

The following constriction equations are based on either live-bed or clear-water conditions. Live-bed conditions occur when the bed material upstream of the constriction is in motion. Clear-water conditions occur when the bed material is not in motion.

Live-Bed Conditions

The following equation for live-bed constriction scour was developed primarily for sand-bed streams. Its application to gravel-bed streams is useful in two ways:

1. it provides a conservative estimate of scour depth; and
2. it can, by extrapolation of the data in *Figure E-4*, provide scour-depth estimates for streams with gravel-sized bed materials.

Coarse sediments in the bed may limit live-bed scour. When coarse sediments are present, it is recommended that scour depths under live-bed and clear-water conditions (see next section) be calculated and that the smaller of the two calculated scour depths be used. As always, expert judgment should be used to adjust the calculated value as needed, based on experience and observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value.

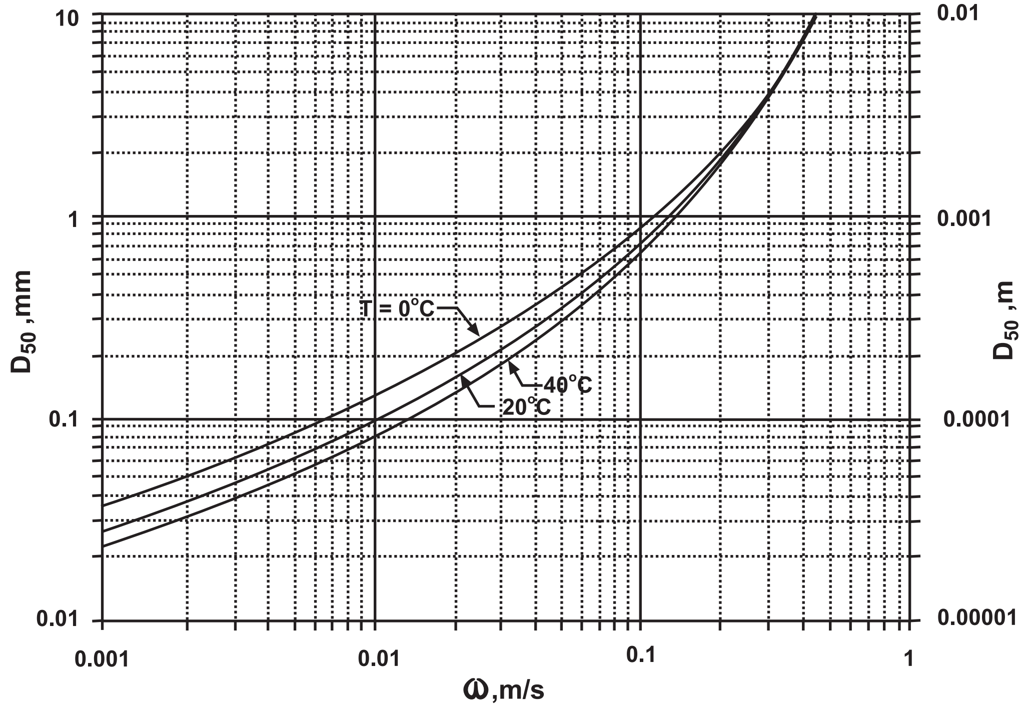

Figure E-4. Fall velocity of sand-sized particles.

Laursen Equation for Live-Bed Conditions[3]

$$y_2 / y_1 = (Q_2/Q_1)^{0.86} (W_1/W_2)^A \quad d = y_2 - y_0$$ (EQUATION 11)

Where:
- d = average depth of constriction scour (m)
- y_0 = average depth of flow in constricted reach without scour (m)
- y_1 = average depth of flow in upstream main channel (m)
- y_2 = average depth of flow in constricted reach after scour (m)
- Q_2 = flow in constricted channel section (m^3/s)
- Q_1 = flow (m^3/s) in upstream main channel (disregard floodplain flow)
- W_1 = channel bottom width at upstream cross section (m)
- W_2 = channel bottom width in constricted reach (m)
- A = exponent from Table E-5
  - where: ω = fall velocity (m/s) of bed material based on D_{50} (see Figure E-4)
  - U_* = shear velocity = $(g y_1 S_e)^{0.5}$ (m/s)
    - where: g = acceleration due to gravity (9.81 m/s^2)
    - S_e = slope of energy grade line in main channel

Note:

This equation assumes that all stream flow passes through the constricted reach. In review, coarse sediments in the bed may limit live-bed scour. When coarse sediments are present, it is recommended that scour depths under both live-bed and clear-water conditions (see following equation) be calculated scour depths be used.

U_* / ω	A	Mode of Bed Material Transport
< 0.5	0.59	Mostly bed load
0.5 to 2.0	0.64	Mostly suspended load
> 2.0	0.69	Mostly suspended load

Table E-5. Exponent "A" based on U_*/ω.

Clear-Water Conditions

The following equation calculates constriction scour under clear-water conditions. Unlike the live-bed equation presented above, this equation makes allowance for coarse bed materials.

Laursen Equation for Clear-Water Conditions[3]

$$y_2 = \{0.025\ Q_2^2/[D_m^{0.67} W_2^2]\}^{0.43},\ d = y_2 - y_0 \qquad \text{(EQUATION 12)}$$

Where: d = *average depth of constriction scour (m)*
y_0 = *average depth of flow in constricted reach without scour (m)*
y_2 = *average depth of flow in constricted reach after scour (m)*
Q_2 = *flow in constricted channel section* (m^3/s)
$D_m = 1.25D_{50}$ = *assumed diameter of smallest nontransportable particle in the bed material in the constricted reach (m)*
W_2 = *channel bottom width in constricted reach (m)*

Drop/Weir Scour

Two equations are presented here for estimating scour depths for flow pouring over a vertical drop structure. *Figure E-5* shows the typical configuration of such structures. The equations were developed to estimate scour immediately downstream of vertical drop structures and sloping sills.

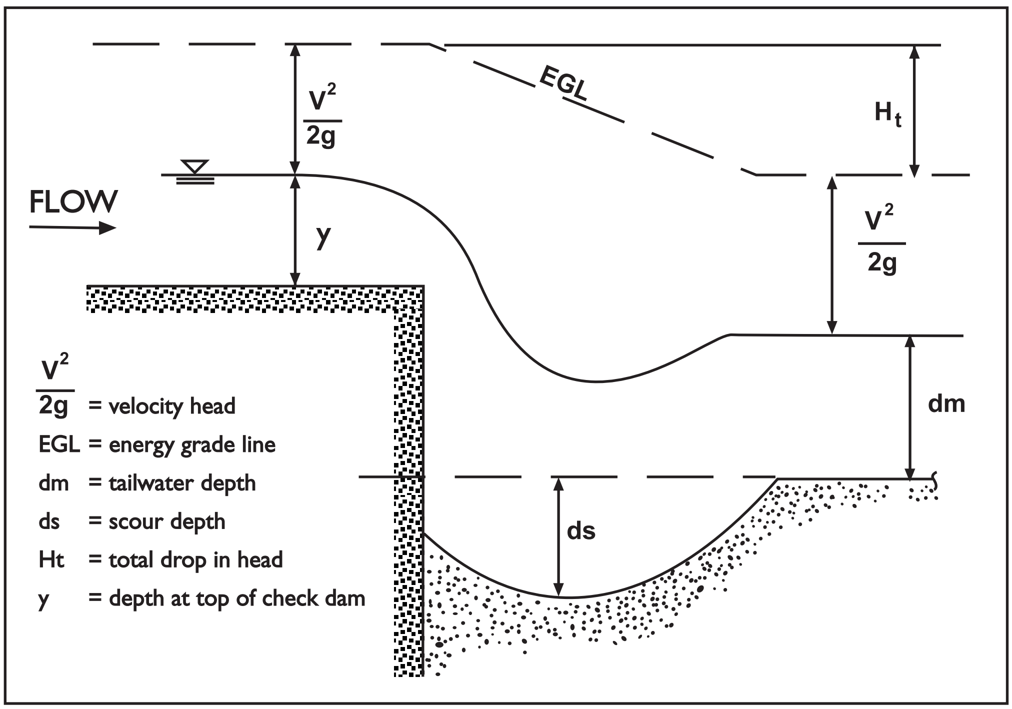

Figure E-5. Schematic of a vertical drop caused by a drop structure.

True vertical drop structures typically include weirs and check dams constructed of materials able to maintain sharp, well-defined crests over which stream flow spills. Drop structure and weirs constructed of logs and tightly constructed rock can create hydraulic conditions associated with vertical drop structures. Structures constructed of loose rock usually form a sloping sill.

Equation 13 is recommended for predicting scour depth immediately downstream of a vertical drop structure and for determining a conservative estimate of scour depth for sloping sills.[8] Equation 14 specifically addresses sloping sills constructed of rock. When designing check dams, weirs, grade controls and similar structures, it is recommended that the designer use these equations as needed (using professional judgment) to estimate expected scour depth immediately downstream of the structure.

U.S. Bureau of Reclamation Equation - Vertical Drop Structure[8]

$$d_s = KH_t^{0.225}q^{0.54} - d_m \qquad \text{(EQUATION 13)}$$

Where:
- d_s = *local scour depth (below unscoured bed level) immediately downstream of vertical drop (m)*
- q = *discharge per unit width ($m^3/s/m$)*
- H_t = *total drop in head, measured from the upstream to downstream energy grade line (m)*
- d_m = *tailwater depth immediately downstream of scour hole (m)*
- K = *1.9 dimensionless*

The depth of scour calculated in Equation 13 is independent of bed-material grain size. If the bed contains large or resistant materials, it may take years or decades for scour to reach the depth calculated in Equation 13.

Laursen and Flick Equation - Sloping Sill[9]

$$d_s = \{ [4 (y_c/D_{50})^{0.2} - 3 (R_{50}/y_c)^{0.1}] y_c \} - d_m \qquad \text{(EQUATION 14)}$$

Where:
- d_s = *local scour depth (below unscoured bed level) immediately downstream of vertical drop (m or ft)*
- y_c = *critical depth of flow (m or ft)*
- D_{50} = *median grain size of material being scoured (m or ft)*
- R_{50} = *median grain size of stone that makes up the grade control, weir or check dam (m or ft)*
- d_m = *tailwater depth immediately downstream of scour hole (m or ft)*

Jet Scour

Although jet scour is a phenomenon associated with streams, it is not typically a component of streambank or instream structure design. In special cases where jet scour may be desirable (or unavoidable) and analysis is necessary, the designer should consult a hydraulic design manual such as Simons & Senturck[10] for guidance.

Check Method - U.S. Bureau of Reclamation Method

A method developed by the Bureau of Reclamation provides a multipurpose approach for estimating depths of scour due to bends, piers, grade-control structures and vertical rock banks or walls.[11] The method is usually not as conservative and possibly not as accurate as the individual methods presented above.

The Bureau of Reclamation method computes an "average" scour depth by applying a systematic adjustment (**STEP 2** on page E-23) to the results of three regime equations: the Neil Equation, a modified Lacey Equation and the Blench equation (**STEP 1** below).[11]

STEP 1

Neil Equation

Obtain field measurements on an incised reach of the river (i.e., a reach that does not flow overbank except at very high discharge) from which bankfull discharge and hydraulics can be calculated.

$$y_n = y_{bf}(q_d / q_{bf})^m$$ (EQUATION 15)

Where: y_n = *scoured depth below design-flow level which is adjusted in Step 2 to yield predicted scour depths*
y_{bf} = *average bankfull flow depth*
q_d = *design-flow discharge per unit width*
q_{bf} = *bankfull flow discharge per unit width*
m = *exponent varying from 0.67 for sand to 0.85 for coarse gravel*

Note: Units can be metric or English

Modified Lacey Equation

The Lacey equation was modified with the Blench method of zero bed-sediment transport. An incised reach is not required for this application. With one noted exception, units can be metric or English.

$y_L = 0.47\ (Q/\ f)^{.33}$ (EQUATION 16)

Where: y_L = *mean depth at design discharge*
Q = *design discharge*
f = *Lacey's silt factor* = $1.76\ D_{50}^{0.5}$
where: D_{50} = *median grain size of bed material (must be in mm)*

Blench Equation

For zero bed sediment transport factor (clear-water scour):

$y_B = q_d^{0.67}\ /\ F_{bo}^{0.33}$ (EQUATION 17)

Where: y_B = *depth for zero bed-sediment transport*
q_d = *design flow discharge per unit width*
F_{bo} = *Blench's zero bed factor, from Figure E-6*

Note: Units can be metric or English.

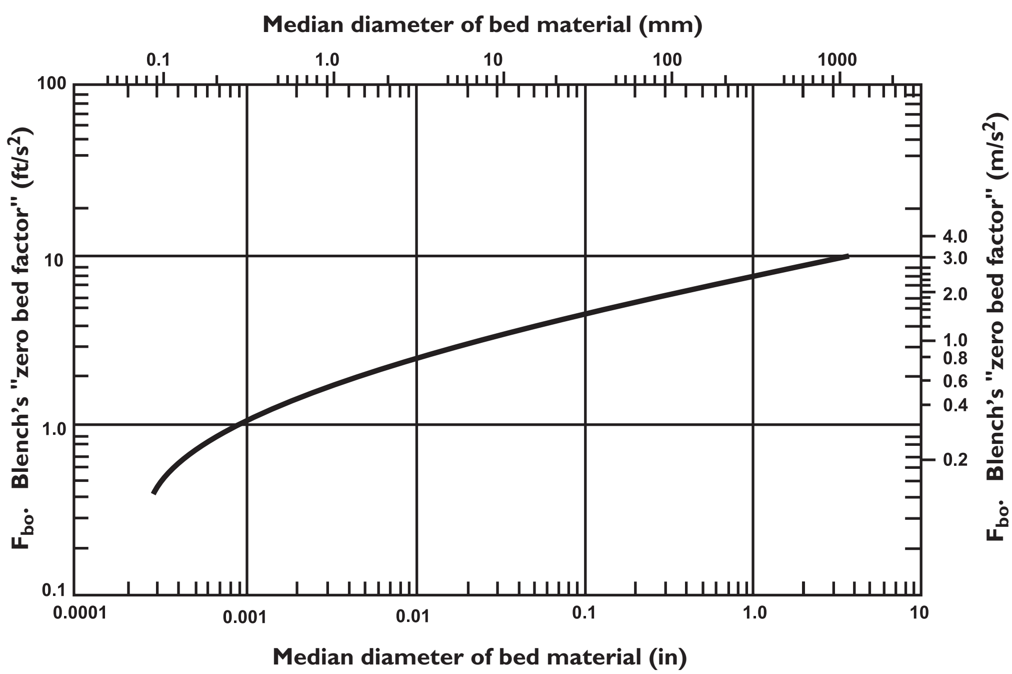

Figure E-6. Chart for estimating F_{bo}.

STEP 2

Adjustments to Neil, Modified Lacey and Blench results:

$$d_N = K_N y_N \qquad \text{(EQUATION 18)}$$
$$d_L = K_L y_L$$
$$d_B = K_B y_B$$

Where: d_N, d_L, d_B = *depth of scour from Neil, Modified Lacey and Blench equations, respectively*

K_N, K_L, K_B = *adjustment coefficients for Neil, Modified Lacey and Blench equations as shown in Table E-6.*

Condition	Neil - K_N	Lacey - K_L	Blench - K_B
Bend Scour			
Straight reach (wandering thalweg)	0.50	0.25	0.60
Moderate bend	0.60	0.50	0.60
Severe bend	0.70	0.75	0.60
Right-angle bend	-	1.00	-
Vertical rock bank or wall	-	1.25	-
Nose of piers	1.00	-	0.50 to 1.00
Small dam or grade control across river	0.40 to 0.70	1.50	0.75 to 1.25

Table E-6. Adjustment coefficients based on channel conditions.

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Fluvial Geomorphology

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Appendix F
Fluvial Geomorphology

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Fluvial geomorphology is the study of landform evolution related to rivers. Although most streambank-protection projects do not require an intensive, watershed-scale, geomorphic analysis of the project reach, any project that potentially affects natural river processes will require a basic understanding of the fluvial geomorphology of the system in question.

BASIC CONCEPTS IN FLUVIAL GEOMORPHOLOGY

Scale

The variables affecting stream systems, such as climate, geology, vegetation, valley dimensions, hydrology, channel morphology and sediment load, have different causal relationships with one another, depending upon the time scale of analysis.[1] Over thousands of years, climate and geology have driven all other variables. Climate change is one of the most obvious and ongoing types of disturbance mechanisms affecting stream channels. However, it is a complex phenomenon and cannot be accurately assessed over a short period of time. Over short time scales (one to 10 years), most variables become independent. Discharge and sediment load become the only dependent variables.[2] At this scale, some disturbances caused by human activities can be assessed. For example, overgrazing can affect hydrology and sediment load, potentially causing channel erosion and incision. Defining the temporal scale of observation, therefore, is key for assessing relationships between various attributes of fluvial systems.

Equilibrium

A basic concept in fluvial geomorphology is that stream channels tend toward an equilibrium state in which the input of mass and energy to a specific system equals the outputs from the same system.[3] A corollary to this condition is that the internal forms of the system (such as channel morphology) do not change in the transfer of mass and energy. The term "stream-channel equilibrium" refers to the relative stability of the channel system and its ability to maintain its morphological characteristics over some period of time and range of flow conditions. In reality, perfect equilibrium does not exist in natural streams. However, natural streams do tend to develop channel sizes and shapes that accommodate their own typical discharge levels and character and quantity of sediment supplied by the watershed. These streams are said to be in a state of approximate equilibrium.[3,4]

Streams respond to minor system alterations (such as a change in hydrologic regime due to human activity) by modifying their size, shape and profile. Geomorphologists describe two altered states of equilibrium that account for this temporary instability in a channel system.[3,5]

1. *Steady-state equilibrium* occurs when short-term fluctuations in a given variable occur throughout the channel system; but the longer-term, constant mean value of the variable is maintained. An example of steady-state equilibrium occurs when channels adjust to scour and fill associated with seasonal flooding. It is important to note that the time scale of observations is critical for defining an equilibrium state - if the time scale is too short, the mean value of the variable in flux will not be accurately determined.
2. *Dynamic equilibrium* occurs when short-term fluctuations in a given variable occur around a longer-term mean value that is also changing. An example of dynamic equilibrium occurs when a stream adjusts to a slow change in base level (the level below which a stream cannot erode - the ultimate base level being sea level). In this instance, the stream undergoes a complex pattern of erosion, deposition, changes in sediment load and renewed incision as it adjusts to the new base level.

Regime Theory and Channel Geometry

Prior to extensive use of equilibrium principles by geomorphologists, hydraulics engineers used the concepts of equilibrium in *regime theory*.[3] Regime theory is based on the tendency of a stream system to obtain an equilibrium state under constant environmental conditions. It consists of a set of empirical equations relating channel shape to discharge, sediment load and bank resistance. The theory proposes that dominant channel characteristics remain stable for a period of years and that any change in the hydrologic or sediment regime leads to a quantifiable channel response (such as erosion or deposition). Stream reaches that are "in regime" are able to move their sediment load through the system without net erosion or deposition and do not change their average shape and dimensions over a short time period.[6] By definition, regime theory is not applicable to streams located in landscape positions where overall erosion and deposition is the natural process (such as alluvial fans, deltas, or headwater source areas).

Regime theory formed the basis for a large body of work in fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes.[7] According to R. D. Hey,[6] the nine measurable variables used to define equilibrium channel geometry are:

1. average bankfull channel width (w),
2. average bankfull depth (d),
3. maximum depth (d_m),
4. velocity (V),
5. height (Δ) of bedforms,
6. wavelength (λ) of bedforms,
7. slope (S),
8. meander arc length (z), and
9. sinuosity (*P*).

These characteristics may be considered dependent variables for stream reaches that are in regime.

The six independent variables that control changes in channel dimension and shape are:

1. discharge (Q),
2. sediment load (Q_s),
3. size of bed material (D),
4. bank material,
5. bank and floodplain vegetation (riparian and/or upland species), and
6. valley slope (S_v).

With the exception of discharge, vegetation and bed-material transport (which may vary over time), the independent variables remain constant when a stream channel is in regime. Changes in any of these independent variables may result in a new channel geometry that represents a stable morphology in a new equilibrium state.

Geomorphic Thresholds

Short-lived states of disequilibrium often result when a geomorphic threshold is exceeded. A geomorphic threshold, as defined by S. A. Schumm,[5] is "a threshold of landform stability that is exceeded by intrinsic change of the landscape itself, or by a progressive change of an external variable." The classic example of a geomorphic threshold is the attainment of critical shear stress in a channel during increasing discharge. When critical shear is exceeded, sediment motion is initiated and sediment transport ensues.

Both extrinsic and intrinsic geomorphic thresholds exist. An extrinsic threshold is exceeded by application of an external force or process, such as a change in sediment supply or discharge. Progressive change in the external force triggers an abrupt, physical change in the system. Examples of forces relating to extrinsic thresholds are climatic fluctuations, land-use changes and base-level changes. An intrinsic threshold is exceeded when system change occurs without a change in an external variable; the capacity for change is intrinsic within the system and can be considered the system's natural variability. An intrinsic threshold might be reached when a torturous meander bend becomes unstable, resulting in a meander cutoff and subsequent reduction in sinuosity.[8]

The most significant controls on channel stability over a period of years or decades are flow regime vegetation and sediment supply. If any of these controls changes (either progressively or suddenly), the channel may cross a threshold and undergo change. Channel avulsion, the formation of a new channel across the floodplain and channel degradation, the general lowering of channel-bed elevation, are two common types of channel changes involving geomorphic thresholds.

Channel avulsion and degradation/incision are not the only ways in which streams respond to the unique combination of drivers and controls acting upon them. On the horizontal plane there is lateral migration (meandering), channel widening, channel narrowing and avulsion. On the vertical plane, rivers incise and aggrade.

Channel Avulsion

Channel avulsion is a common response occurring when a stream has reached a geomorphic threshold. An avulsion is a major change in channel direction, location or form, usually initiated by a large flood. Avulsions often result from scour and headcutting into the floodplain. They occur in numerous types of channels. Anastomosing channels, which have multiple, active threads, cohesive banks and low migration rates, tend to avulse as the channel threads age and lose transport efficiency. Braided channels, which have high sediment loads, may avulse under two conditions:

1. as backwater conditions occur upstream from a constriction (e.g., aggrading bar or bridge), an overflow may occur (often on the outside of a bend); or
2. as overflow into a side channel or abandoned oxbow occurs, headward erosion and stream capture may develop.[9]

Meandering channels may avulse due to insufficient sediment transport, which results in channel aggradation and further loss of channel capacity. Aggradation increases the frequency of overbank flows and avulsion potential. Topographic variability on the floodplain surface can also concentrate overbank flows in certain areas and create further avulsion potential. Avulsion potential is also increased if floodplain roughness is relatively low compared to the active channel roughness, which is common in areas where the floodplains have been cleared for agriculture. Finally, all channels are prone to avulsion if they become perched relative to their floodplain. This is common in alluvial-fan environments or along relocated channel segments.

Channel Degradation

Degraded channels (also called entrenched, eroded, or incised channels) occur when sediment-transport capacity exceeds sediment supply, causing a lowering of the channel bed. Stream channelization, land use that increases runoff or concentrate high flows, or a lowering of base level are all potential causes of channel degradation. The process of degradation often begins when channel stability reaches a threshold condition; the threshold is then crossed, and bed degradation occurs, often followed by channel widening as streambanks erode.[10]

Because the response pattern of incised channels is remarkably similar throughout a variety of stream environments, incised-channel evolution models are useful for tracking land-form development through time. S. A. Schumm, et al., used such a model to develop a channel-evolution sequence for a stream in Mississippi.[11] The model assumed that the base level for the channel did not change and that land use in the watershed remained relatively constant. The model (see *Figure F-1*) described five channel reach types (Types I to V) whose conditions ranged from disequilibrium (Type I) to a new, dynamic equilibrium (Type V).[10]

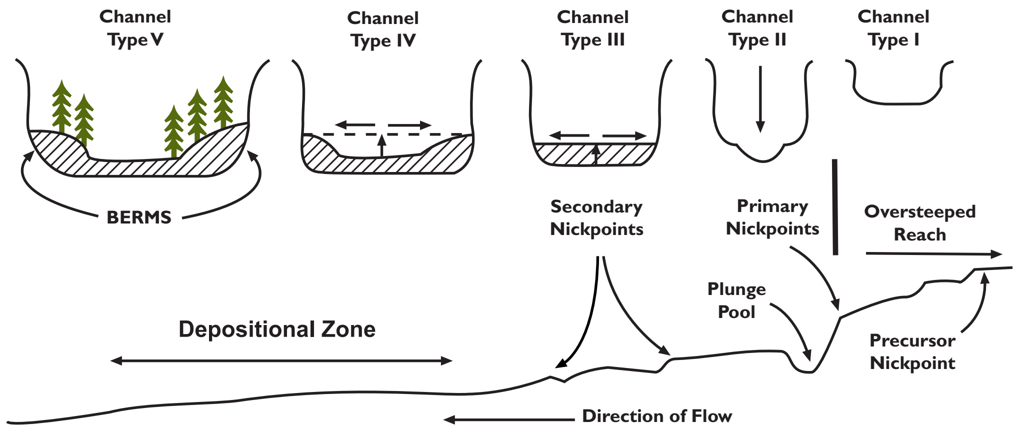

Figure F-1. Diagram of a channel evolution model.[10]

SEDIMENT-TRANSPORT PROCESSES

The sediment-transport process begins with the erosion of soil and rock in a watershed and transport of that material by surface runoff. The transport of sediment through a river system to the ocean or closed basin consists of multiple erosional and depositional cycles, as well as progressive physical breakdown of the material. Many sediment particles are intermittently stored in alluvial deposits along the channel margin or floodplain and ultimately re-entrained via bank and bed erosion. Total sediment loads consist of suspended load (the fine-grained fraction transported in the water column) and bedload (the coarse-grained fraction transported along the channel bed). The transport of sediment through the stream system depends on the sediment supply (size and quantity) and the ability of the stream to transport that sediment supply.

Sediment-Transport Processes and Aquatic Habitat

The caliber, volume and transport dynamics of sediment exerts a major control on channel form and geomorphic processes that create and sustain aquatic habitat in all river systems. Sediment caliber dictates what geomorphic features and associated habitat types (e.g., sand bed vs. gravel bed) will be characteristic of a given channel. Sediment volume can affect the stability of a channel, causing channel aggradation if the volume delivered is in excess of the transport energy available and causing channel degradation if the volume is insufficient. Sediment volume may also affect channel pattern and slope, with high volumes of coarse sediment resulting in relatively steep slopes, high width/depth ratios and braided channel patterns.[5]

Some degree of sediment mobility is critical for the ecological health of a stream system. Most Pacific Northwest aquatic organisms have evolved within dynamic stream systems, in which pools, bars and other habitat features are continually reworked and reformed. Physical habitat is created and sustained through processes such as the maintenance of pools and riffles, the formation of transient bars, side channels, and backwater areas, the deposition of spawning gravels, and the flushing of fines from bed substrate.

Sediment sorting through selective transport creates spawning habitat and quality habitat for benthic organisms, which in turn are food for aquatic species such as fish. The maintenance of pool-riffle sequence morphologies and the effective sorting of bed materials exemplify balanced conditions of sediment caliber and transport energy that serve to generate and maintain quality aquatic habitat.

Stream Features Maintained by Sediment Transport

Riffle-Pool Sequences

Riffles and pools are often the dominant bedforms in coarse-grained channels. In alluvial channels, pools are created by erosional processes on the outer part of river bends and below instream obstructions. Riffles are associated with straighter, often higher-gradient areas and are characterized by shallow, faster flow. Pools tend to scour at high flow and fill at low flow, whereas riffles may scour at low flow and fill at high flow.

Channel Bars

In both meandering and braided streams, channel bars are ubiquitous features representing sediment deposition and storage in the channel. Bar formation is a result of local reductions in sediment transport capacity. Bars are present in steambeds composed of silt, sand, gravel and cobble, and they occur on the inside of bends (point bars), along channel margins and within the active channel flow. Channel bar terminology includes a substantial and inconsistent array of names that has not yet been standardized in the literature. Channel bars that divide channels and divert flow are responsible for the initiation and maintenance of the braided channel pattern. Channel bars represent temporary sediment storage in the stream channel. Channel bars also represent the incipient floodplain that may become established if additional sediment is deposited on the bar and vegetation takes hold.

VEGETATION AND WOODY DEBRIS

Both upland and riparian vegetation affect the geomorphology of stream channels. Vegetation plays a key role in stabilizing streambanks dissipating energy and in maintaining a stable channel form. The growth of riparian vegetation in or near the channel augments floodplain formation as vegetation increases hydraulic roughness reduces erosion and promotes sedimentation. Upland vegetation slows hillslope erosion, and both upland and riparian vegetation contribute woody debris to the stream system. The role of large woody debris in channels is now recognized as a critical factor affecting geomorphology in forested environments and as a potential component of channel design.[12,13]

Coarse or large woody debris in streams represents large roughness elements that divert flowing water and influence the scour and deposition of sediment in forested streams throughout the world. Large woody debris in stream channels results from trees that fall on banks or hillslopes. Processes that initiate tree fall include windthrow, bank erosion, channel avulsion, tree mortality, mass wasting and land-use practices such as logging.[14] The introduction of large woody debris into the channel affects both channel form and process by:

- creating steps in the longitudinal profile of the streambed, thus dissipating energy aiding in formation of both pools and riffles and increasing sediment storage;[14]
- improving fish habitat by increasing types and sizes of pools[15] (pools associated with woody debris may be deeper and have more depth variability than free-formed pools[16]);
- forming channel bars[17] and creating suitable sites for spawning (this influence has not been extensively studied); and
- promoting sediment deposition along the active channel and floodplain, which provides sites for riparian-vegetation colonization, the growth of forested islands in the channel and forest floodplain development.[18]

Overall, the geomorphic effects of woody debris vary with stream size. In low-order streams (first and second order), woody-debris elements are large relative to the stream and may cause significant channel migration or widening and sediment storage. In high-order streams (fifth order), where woody-debris elements are small relative to the channel, woody-debris accumulations may increase channel migration and the development of secondary channels,[14] although islands formed as a result of large woody debris may actually increase stability.[16]

A bibliography of literature addressing the role of wood in aquatic systems and riparian areas has been assembled by researchers in the United States, United Kingdom and Russia. It is available on-line at http://riverwood.orst.edu/html/intro.html.

ASSESSMENT METHODOLOGIES

Baseline Geomorphic Analysis: Evaluation of Existing Conditions and Historic Change Where Restoring Historic Configuration is Appropriate

The most important components of geomorphic analysis include:

- assessment of past channel change,
- determination of causes of channel change, and
- assessment of ongoing channel adjustments.

Streambank protection will likely be unsuccessful if the driving forces of channel adjustments are not recognized and addressed. Consequently, streambank-protection projects designed to mimic or alter natural channel processes require an understanding of the causative agents of change.

Characterizing Existing Channel Conditions

The initial characterization of the project reach should be based on plotted bed and bank profiles and maps or aerial photographs that show channel planform. The project reach should be described in terms of channel slope, pattern, sinuosity and access to its floodplain. Infrastructure controls should be identified and their geomorphic relevance indicated, such as fixed-bed elevations (pipelines, weirs, bridge aprons) or channel or floodplain encroachment (roads, culverts, development, bridges).

Channel Slope

Channel slope is defined as the vertical fall of a stream over a given distance. It is typically reported as a percentage (ft/ft) or as feet of drop per mile (ft/mile). Channel profiles (elevation vs. distance plots) depict slope trends on a stream system. The most accurate means of determining the slope of the channel bed is by surveying the channel thalweg elevation (the deepest point in the channel bed) over a given distance. Alternatively, longitudinal profiles may be obtained from the Federal Emergency Management Agency if a hydraulic model has been developed for flood-insurance studies. Channel profiles determined from topographic maps may be accurate in some situations, but may not be detailed enough, since contour lines generally reflect the water surface rather than the channel bed and, for smaller streams, may actually represent the canopy cover.

Channel slope is always measured in terms of the channel distance, rather than the valley distance, and can be calculated by the following equation:

$$S=(E_2-E_1)/D$$

Where: S = *channel slope*
E_2 *and* E_1 = *channel-bed elevations at two points along the thalweg*
D = *channel distance between* E_2 *and* E_1.

A more accurate representation of channel slope will be attained if survey points are located from the top of one riffle to the top of another riffle (thereby including the entire channel unit), rather than between a riffle and a pool. The longer the survey length, the more accurate the slope calculation, unless a significant valley control is crossed.

Channel Planform

Channel planform is the condition of a stream as seen in map (aerial) view. In streams with meandering patterns, planform is quantitatively described in terms of sinuosity by the equations:

$P = D_c / D_v$ *or*
$P = S_c / S_v$

Where: P = *sinuosity*
D_c = *channel length*
D_v = *valley length,*
S_c = *channel slope*
S_v = *valley slope.*
Channel length is measured along the channel thalweg or, if necessary, the channel centerline.

Other parameters that describe channel planform are the wavelength, amplitude, belt width, bankfull width and radius of curvature of an individual meander bend (*Figure F-2*). Collectively, these planform characteristics can be compared to historical conditions in order to assess channel behavior over time.

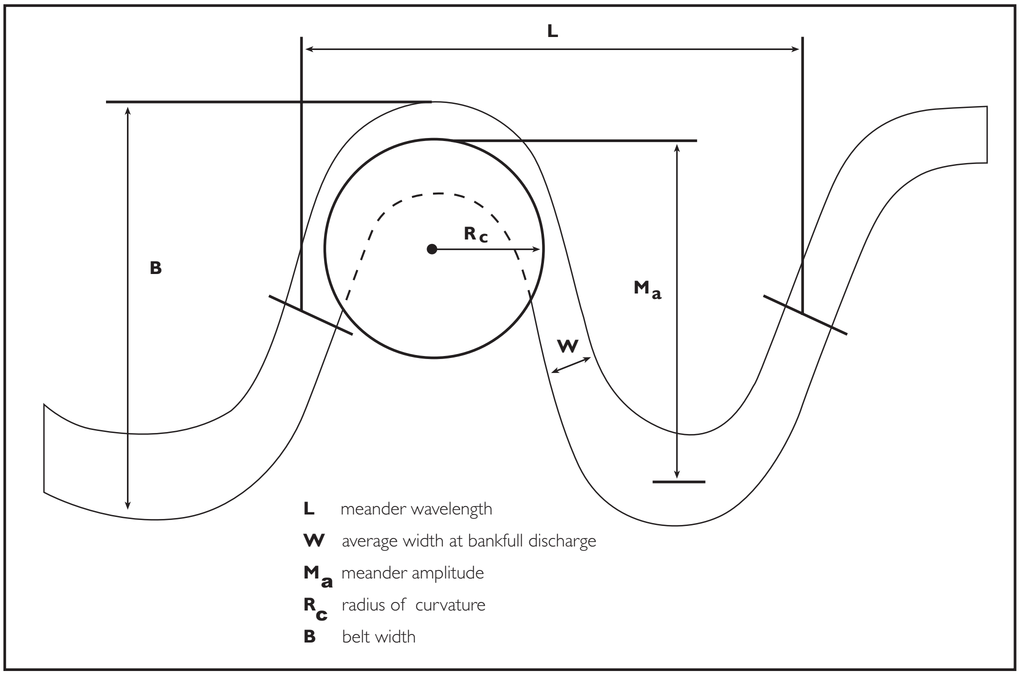

Figure F-2. Channel planform characteristics.

Channel Cross Section

Channel cross section reflects the two-dimensional view of the channel, typically viewed in the downstream direction (*Figure F-3*). Points collected from a surveyed cross section should at a minimum contain floodplain elevation, top of bank, bank toe, bankfull depth lower limit of vegetation, water surface elevation and thalweg. Typical dimensions measured from a channel cross section include top and bankfull width, bank height, bank slope and channel depth. By convention, the right and left banks reflect the sides of the channel as viewed in the downstream direction.

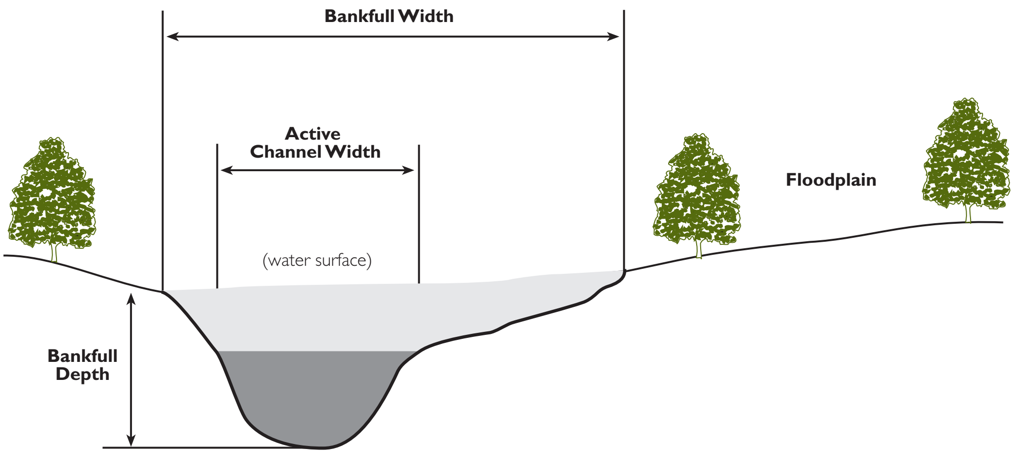

Figure F-3. Channel cross section.

Pools and Riffles

Pools and riffles generally occur at relatively constant spacing in alluvial streams. A pool-riffle sequence is a dynamic response of the channel to a large-scale, nonuniform distribution of three variables: velocity, boundary shear stress and sediment.[19] L. B. Leopold, et al., determined that riffle spacings were consistently on the order of five to seven times the channel width (*Figure F-4*).[4] This empirical deduction is consistent with a theoretically predicted spacing of 2π (6.28) times the channel width determined by R. D. Hey.[20] Hey and C. R. Thorne further substantiated the correlation between width and riffle spacing, predicting riffle spacing as:

$$z = 6.31w$$

where z = the distance of riffle spacing, and
w = bankfull width.[21]

This definition of riffle spacing is based on work in Great Britain on gravel-bed rivers with single-thread channels and a mix of straight, sinuous, and meandering planforms. The coefficient of determination for this data set is 0.88, and the overall range of riffle spacing for the majority of sites is between four and ten times the channel width. The original assertion for riffle spacing made by Leopold, et al., then, still hold after almost forty years of observation and measurement.[4] Hey and Thorne's prediction[21] may be more site-specific and, therefore, not universally applicable to alluvial streams found in various landscapes and climate zones.

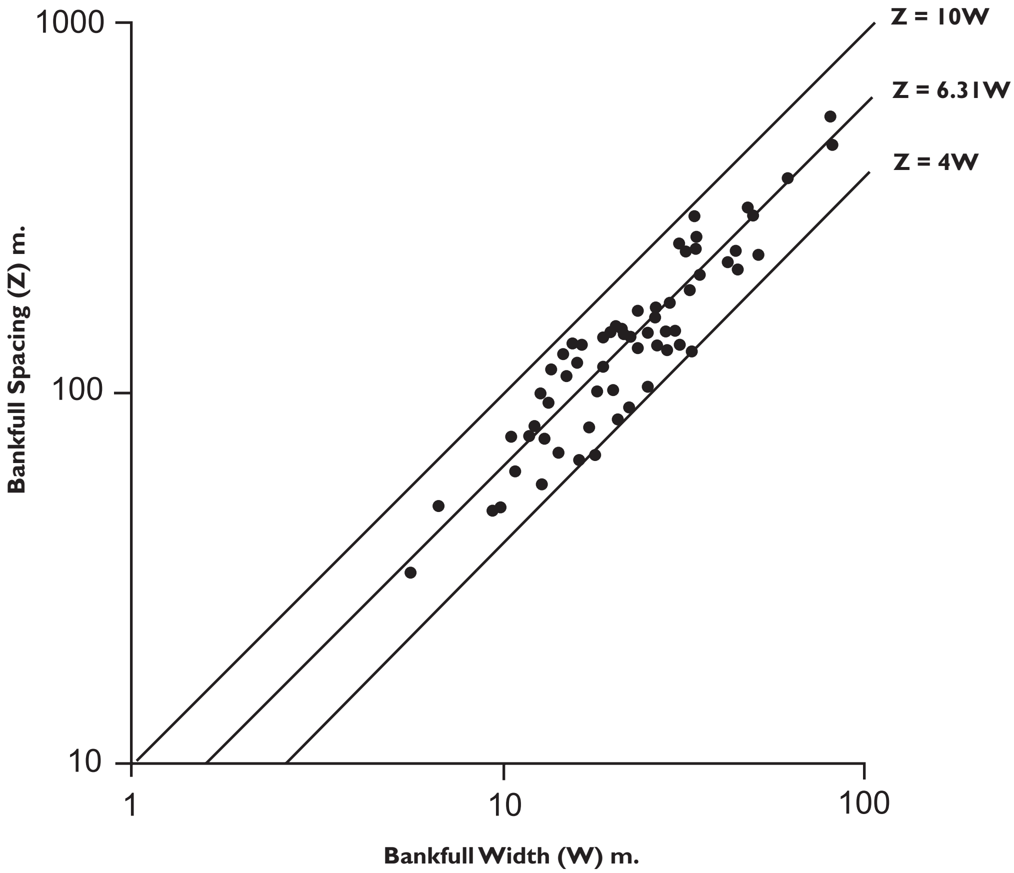

Figure F-4. Riffle spacing as a function of bankfull width.

Channel Classification

A classification of subreaches can aid in visualizing and describing the project site, although classifications on their own provide limited application for channel restoration designs.[19] Early classification systems were based on channel planform patterns (e.g., those developed by Leopold and M. G. Wolman[22]), including meandering, braided and straight channel patterns. Later classification systems were also based on channel cross-sectional geometry, longitudinal profile, patterns and size/composition of bed material (e.g., those developed by D. L. Rosgen[23]). Other recent classifications attempt to link channel process, form and stability.[24,25,26] Finally, D. R. Montgomery and J. M. Buffington's classification[27] is based on a hierarchy of spatial scales that reflect different geomorphic processes and controls on channel morphology. This system (which includes geomorphic provinces, watersheds, valley segments, channel reaches and channel units) provides a useful means for comparing channels at increasingly finer spatial scales.

Rosgen's classification system[23] is the most extensive and widely applied. This system divides streams into eight major types based on number of active channels, presence of a floodplain, width/depth ratio and sinuosity. Each major type is then subdivided, based on the channel slope and dominant type of bed and bank materials. To date, this system for stream classification is probably the most comprehensive and useful, provided that practitioners have a strong geomorphological background.

It is important to note that most classification systems are based on the existing channel morphology of a stream in dynamic equilibrium, a rare occurrence especially in disturbed or urban watersheds. Therefore, a classification system must be used with the understanding that fluvial systems are constantly adjusting and evolving in response to changes in slope, hydrology, land use and sediment supply. Furthermore, classification systems are rarely appropriate as the basis for a channel or streambank design.

Assessing Historic Channel Change

Aerial Photography

When available, sequential photos of a stream channel over the last 100 years provide a historical record of channel planform changes. This information, coupled with hydrologic data from stream gauges, is extremely valuable for understanding how the particular channel responds to floods. An evaluation of historic channel change may reveal previous channel conditions that provided quality habitat or channel stability, which may then be used as the basis for project objectives. However, an aerial photo provides a snapshot in time, and channel stability cannot be inferred from a photo. The stream may have been responding to significant changes in the watershed – there is no reason to assume that a past morphological form will be stable under current hydrologic and landscape conditions *unless* everything has stayed the same (not usually the case).

Aerial photographs for areas in the western United States are available beginning in the 1930s typically and are recorded in a database maintained by the U.S. Geological Survey Earth Science Information Center (the USGS will search for historical photography at ***1-888-ASK-USGS***). Access to maps produced by USGS can be found at **www.usgs.com**. Aerial photographs of your region can be obtained from the Washington State Department of Natural Resources, the Washington State Department of Transportation, the Federal Bureau of Land Management, the U.S. Forest Service, the U.S. Army Corps of Engineers and the Natural Resources Conservation Service.

Ground Reconnaissance

Field observations provide valuable information regarding flood history and channel response. This information is especially valuable when combined with hydrologic data regarding flood-recurrence intervals - for example, the effects of recent 10-year or 25-year recurrence-interval flows might be directly observed in the field. Primary flow direction can be significantly different for a two-year event versus a 10-year event. Ground assessment of stream channels may include observable flood impacts, such as abandoned channels, natural channel cutoffs or the accumulation of woody debris on mid-channel bars. Many geomorphic channel features can be roughly dated according to the age of riparian vegetation that is present. For example, an abandoned side channel with 10-year-old cottonwoods present may represent the impacts of a flood documented 10 to 11 years ago. Ground reconnaissance is an essential part of a geomorphic assessment and can provide useful information on the geomorphic effects of large flows in a particular channel reach.

Application of Results

For pristine streams degraded by low-probability floods, the data retrieved from the historic baseline survey can provide a basis to restore the channel to its historic configuration. This process includes recreating channel conditions characteristic of preflood conditions in order to improve habitat conditions and promote geomorphic function. For streams impacted by long-term changes in hydrologic or sediment transport conditions (e.g., downstream of a dam or in an urbanizing watershed), restoration to a historic configuration may not be appropriate.

Advanced Geomorphic Analysis: Achieving Geomorphic Stability Where Historic Configuration is Inappropriate

Alluvial streams are highly dynamic and responsive to changes in hydrology, slope or sediment load. Historically, engineering projects have dramatically destabilized stream channels by imposing unnatural and inappropriate channel cross sections, slopes, discharges and sediment-transport regimes. The destabilization of streams occurs when the balance between transport energy and sediment supply is altered. If a project is designed to modify hydrologic or hydraulic regimes, sediment-transport continuity should be a primary project objective.

Geomorphic stability occurs when the channel is adjusted to convey flow and sediment without undergoing net erosion or deposition. Successful bank-protection projects promote that balance and provide for optimal channel function and aquatic habitat. One of the most significant challenges in streambank-protection projects is defining this state of channel equilibrium and directing the project to promote long-term channel stability. In the context of geomorphology, this assessment requires an evaluation of current channel conditions, an assessment of historic changes that may have resulted in channel destabilization, a determination of the mechanism and causes of destabilization and an estimation of conditions required to promote sediment-transport continuity.

Channel Stability

The assessment of channel stability relates the current sediment-transport capacity of the channel to the existing sediment supply. Excessive transport capacity results in channel degradation, which is commonly indicated by geomorphic features such as headcuts (steep breaks in channel profile), human activities such as extensive channel armoring, or bank oversteepening and gravitational failure. Channel degradation can result in a floodplain surface becoming high enough above the channel that it is no longer inundated by the current hydrologic regime (see *Figure F-5*. The formation of such a perched floodplain, or terrace, disconnects that surface from the water table and affects the establishment and survival of riparian vegetation. Other effects include unstable banks due to:

- oversteepening, bank instability due to groundwater discharge;
- increased shear stress because of low-probability flows being contained within the channel within the channel; and
- loss of wetland/floodplain habitat and backwater areas.

Figure F-5. Channel Degradation. An example of channel instability in a degrading channel.

This process is often coupled with the progressive formation of a new floodplain surface within the incised channel. Excessive sediment supply is generally evidenced by aggradation such as pool infilling, loss of channel capacity, overbank deposition, channel widening and extensive channel-bar development. Sediment-transport evaluations, such as incipient motion and sediment-continuity modeling, assess the mobility of sediment in a given system and can analyze reach stability.

A geomorphic assessment of the reach where the streambank-protection project is intended will provide some understanding of the causes and effects of channel change through time. This assessment includes quantifying historic changes via repeat bed profiles, maps, as-built bridge-survey data and sequential aerial photographs. Potential causes for geomorphic channel change include alterations in hydrology or sediment load, the occurrence of large floods and human activities such as urbanization and channelization. After completing the geomorphic assessment, the next step is to estimate geomorphic parameters that will provide for channel stability under project conditions. These steps, in combination with hydraulic analyses, then lead to the definition of design elements such as channel slope, planform and cross-sectional geometry.

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CREDITS

Figure F-5. Source: Inter-Fluve, Inc.

Appendix G
Biological Considerations

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Appendix G
Biological Considerations

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

It is necessary to know as much as possible about the life-cycle needs of fish and wildlife in order to predict the impacts of a streambank-protection project, to design for the minimum impact and to plan for the mitigation of unavoidable negative impacts. What happens in the water directly affects fish, of course, but what happens in the area along the bank (riparian area) also directly affects them. The riparian area is also where other wildlife live; numerous bird species, mammals (large and small), insects and amphibians all spend part or most of their lives in areas adjacent to water.

Salmonid fish species are emphasized in this appendix. Salmonids discussed here are all species of Pacific salmon, char (known as Dolly Varden and bull trout), steelhead, rainbow trout and cutthroat trout. It is reasonable to believe that, if we take care of the habitat needs of salmonids, we will satisfy the needs of many wildlife species as well. This is assuming that such care involves restoring and protecting natural stream conditions and processes such as velocity, diversity, ample hiding cover, shade, overhanging vegetation, access to sloughs and the presence of backwater habitat adjacent to faster flow.

While much has been written about the life cycles of salmonids, less has been written about their specific habitat needs, and even less has been written about the impact of streambank disturbance on the species' habitats. While the amount of data regarding the habitat effects of bank-protection activities is lacking, we can make logical and defensible assumptions about their effects based on the specific habitat needs of various fish species. There are certain habitat needs that are common to all species of salmonids. This information is presented first by general habitat needs at each life stage: egg/alevin, fry, smolt and adult. A description of specific needs for each species follows the general description.

GENERAL HABITAT NEEDS OF SALMONIDS

The Salmonid family includes a number of fish species that have similar body structure and life cycles. Salmonid species include salmon, char (known as Dolly Varden and bull trout) and trout. Salmonids hatch in freshwater streams, but most migrate from those streams as they mature. Some species spend their entire lives in freshwater (nonanadromous), while other species migrate to saltwater (anadromous) where they spend the majority of their adult lives (see *Figure G-1*).

Most salmonids return to the freshwater stream where they began their own lives to lay their eggs in a nest (redd), which they dig with their tails in the gravel of a streambed. (There are some exceptions, such as steelhead trout, which may spawn in a stream that is not their stream of origin.) The eggs incubate in the gravel for weeks or months, then hatch into a form called "alevins" (hatchlings whose yolk sacs are still attached). They may live for some time in the gravel streambed, but they eventually emerge as very small fish called "fry." They stay in freshwater for a certain length of time, depending upon the species. At some point, the anadromous species begin their migration downstream to the ocean, all the while undergoing a physiological change to adapt to saltwater. Fish that are undergoing this change are called "smolts." After a number of years in the ocean, the anadromous fish mature and return to their river of origin as adults to lay and fertilize their eggs, thus completing the cycle. Some salmonid species die after spawning, while others survive to spawn again.

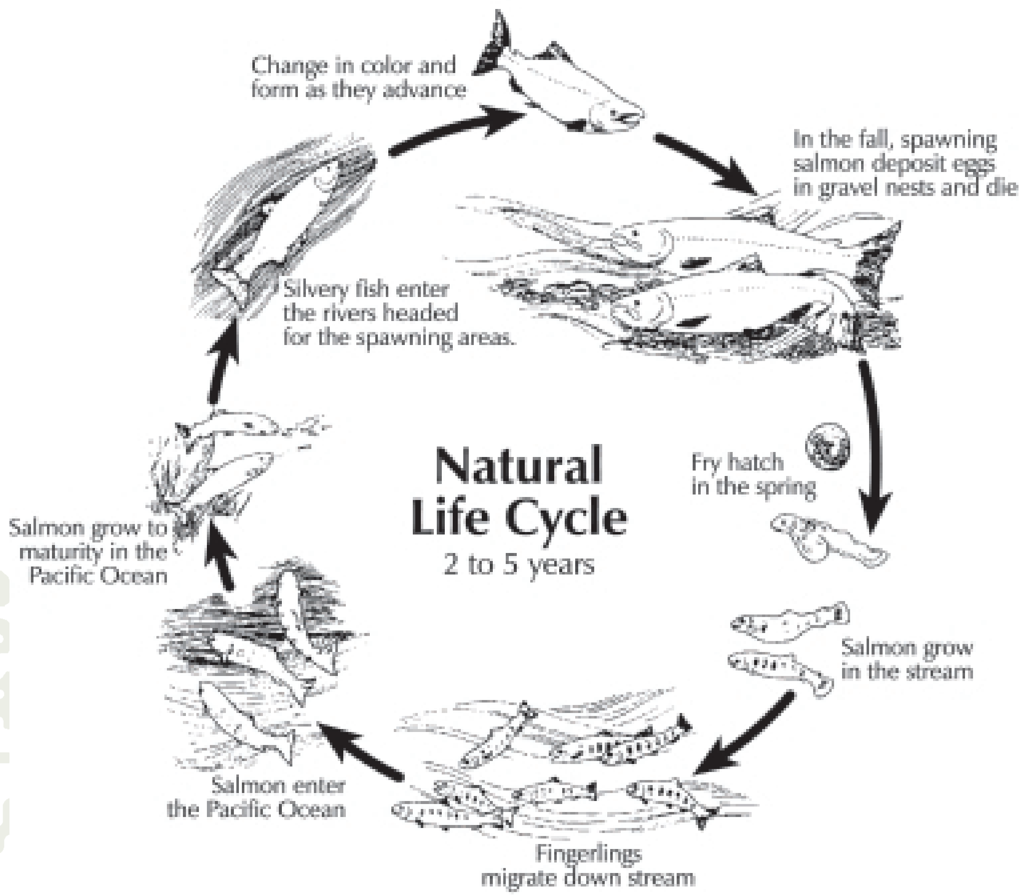

Figure G-1. The life cycle of anadromous salmon.

Salmon, char and trout use different freshwater habitats for different stages of their lives. These life stages are described in general terms as follows:

Adults

Adult salmonids need access to upstream spawning areas with minimal obstacles that could cause delay. If they are returning from saltwater, they need frequently spaced holding habitats from the river mouth upstream to the spawning areas. Holding habitats include deep-water pools and near-shore scour pools with dense cover in the water and above the water. They also need deep, midchannel pools adjacent to spawning areas, large woody debris and bank vegetation, all of which serve as refuge during spawning. The velocity breaks provided by scour pools create much-needed resting sites as well. Because some species enter freshwater in the spring and summer and hold for several months before spawning, they need well-oxygenated, cool, deep holding pools where harassment by predators and other forms of stress are minimized. Access to river braids, side channels and upwelling sloughs is needed during spawning season for species that use such areas.

As mentioned earlier, most salmonid species die after they spawn, and there is increasing evidence that their carcasses add significant amounts of nutrients to streams where they spawn and to the surrounding uplands (where eagles, bears and other predators carry them for feeding). Entire riparian ecosystems depend to varying degrees on the nutrients provided by salmon carcasses. Sufficient debris and backwater areas are needed to capture these carcasses.

Eggs/Alevins

Eggs and alevins need stable gravel and cobble substrate at just the right size for their particular species. They need substrate that is not compacted and is low in fines (small particles of clay, silt and sand less than 0.85 mm in diameter) to allow adequate flow of well-oxygenated water within the gravel spaces. Complex habitat is needed in the form of boulders, logs, log jams, sticks, rock ledges, etc., to sort gravels and dissipate energy while keeping the channel form relatively stable. Even minor increases in the depth of scour may significantly reduce embryo survival. Eggs and alevins prematurely scoured out of the substrate are unlikely to survive. Eggs and alevins deeply buried by shifting substrate may suffocate or may not be able to emerge from the gravel. The natural function of floodplains should be preserved so that high water can flood, thereby minimizing bed scour in spawning areas. High flows are needed periodically through side channels to clean up the gravel, move debris along and generally refresh the spawning area.

Stream or habitat alterations that concentrate flow in the main channel or in a portion of the channel cross section can cause the loss of spawning habitats or affect the stability of the bed and, therefore, survival of eggs and alevins. For example, projects that make a streambank smooth tend to cause a concentration of flow along the bank. This can cause a change in cross-sectional shape that eliminates an on-site spawning riffle. The resulting high-velocity thread may periodically scour a downstream spawning riffle.

Juveniles/Presmolts

The juvenile life stage is especially affected by bank-protection and flood-control activities. Juveniles depend on cover for protection from predation. They also depend on rearing habitats, including resting and feeding stations. Juveniles that are larger in size by the fall will survive the winter and ocean life stages in greater numbers than smaller juveniles. Instream cover may be useful to segregate species and visually reduce aggressive interactions, thereby promoting fish growth and survival. All salmonid juveniles require high-quality rearing habitats with enough food and vegetation resources to support prey. Water velocity and cover are the primary variables governing microhabitat selection by juvenile salmonids in summer.

Movement during the winter into low-velocity microhabitats with good cover is common among many stream-dwelling, juvenile salmonids. Winter cover can consist of large rock rubble with large interstitial spaces; large and small, complex woody debris; undercut banks with submerged vegetation; and deep pools and off-channel areas. Off-channel rearing habitat in floodplain channels is also important winter habitat. Bank-protection activities may preclude the future development of new off-channel rearing habitats by fixing the channel in its current location. Channel degrading or flood-control activities may severely limit access to off-channel winter habitat.

Smolts

The specific habitat needs of smolts are not well known. There is reason to believe that cover plays a critical role in smolt survival. In most Pacific Northwest rivers, smolt out-migration occurs primarily in spring, often during freshet conditions (i.e., during higher river flows caused by rain or melting snow). Smolts migrate downstream primarily at night. During the time when these fish are not moving, they need a safe place to hold and feed, presumably in low-velocity water with good cover. Vegetative cover and velocity breaks high on the bank, even if used only during freshets or floods, may be very important habitat for migrating smolts. It is assumed that approximating a natural, well-vegetated bank at out-migration water levels will produce smolts in better physical condition (well fed and physiologically ready for the sea) than a smolt migrating through a channelized (hard-sided) river. As anadromous smolts travel downstream and enter saltwater, they go through complex physiological changes that enable them to live in saltwater. This transition requires exacting water-quality conditions and habitat features, details of which are beyond the scope of this document.

FISH HABITAT USE DURING FLOODS - FLOOD REFUGE

All adult and juvenile fish need a way to hold in the stream or on the floodplain during flood events. Refuge materials may be provided by relict river channels and sloughs, lakes and ponds, log jams and other large and small pieces of wood, large rock rubble, and riparian vegetation. There may be little in the way of flood-refuge materials left in diked and riprapped river sections. For juveniles dislodged from their winter locations by flood flows, it may not be possible to get back upstream to suitable wintering habitat. Each successive, high-water event increases the chances that these fish will be swept out of the river. Eggs, alevins and presmolts that are prematurely washed to sea during high flows do not survive in significant numbers.

During floods, fish may move to areas with more cover or areas with slower stream flow within a river to minimize the flood's impact on them. Water velocity and depth are important factors in determining refuge suitability. Chinook and steelhead tend to use large-boulder and cobble habitat, whereas undercut banks and instream debris are preferred by coho and cutthroat trout. Fish that live near the edge of the river may respond to floods by moving laterally within the river to stay close to the shoreline regardless of the flow. Log jams that may otherwise be high and dry on gravel bars and banks may become very important refuge during floods. Research has shown that, during floods, brown trout and nonsalmonid species seek areas outside the low-flow channel with depths and velocities similar to what they are accustomed to at lesser flows.

Fish may move laterally for a number of reasons. Fish may move into temporarily flooded areas of the stream margins to feed. They may feed on terrestrial animals such as small insects, amphibians, birds and even small mammals. Juvenile brown trout have been found feeding at higher than normal rates during floods. Fish may move to slower-flowing water to avoid being swept away. By moving to shallower areas, fish are less susceptible to predation by larger fish. However, in these shallower areas they become more susceptible to predation by birds and mammals, so cover is essential.

HABITAT NEEDS OF PACIFIC NORTHWEST SALMONIDS BY SPECIES

Chinook Salmon

Chinook salmon behavior and habitat needs in freshwater are complex and may differ from one stream to the next. Habitat requirements may vary among sizes of streams and seasons. In any given river, there may be races of fish that return as adults in the fall, some in the spring and others in the summer. The juveniles of these various races also differ in their behavior and habitats.

In large rivers, young chinook are frequently seen near the water's margins. They move to deeper water as they grow. In the Skagit River in western Washington, chinook are found most frequently in backwater areas and along natural bank lines, less frequently next to armored banks, and even less frequently near sand bars. According to U.S. Army Corps of Engineers studies on the Sacramento River in California, the least-preferred habitat for chinook is riprap revetments.

Chinook generally spawn in the fall and winter, and the fry emerge in mid- to late spring. Habitat needs of chinook during the summer change as fish grow and as water flows change. In small mountain streams, summer habitat is most often provided by undercut banks where water velocities are less than 20 cm/s and depths are 20 to 80 cm. In large rivers, chinook use quiet-water scour pools associated with logs and roots at the edge of the channel. As fish become larger, they select faster and deeper habitat farther from the banks. Age-zero chinook (fry less than a year old) can tolerate faster and deeper water than can steelhead of the same age. Juvenile chinook occupy feeding stations that allow them to hold position in water with a low-velocity, usually near the stream bottom, but near high-velocity flow. This allows fish to dart into faster current to prey on drift insects and then return to the slower water to rest. In turbid, glacial rivers, they frequently hold behind boulders. In larger rivers, chinook most often can be found at depths of 30 to 100 cm where velocities are less than 50 cm/s. They are found on the margins of sand bars, closely associated with woody debris, even debris as small as a pencil.

In British Columbia, researchers reported the numbers of yearling chinook were positively correlated with rock size, water depth and velocity during freshet flows in June, but were found in lower-velocity zones in September. In late summer on riprap banks, chinook were found more often around larger rock than smaller rock. In late winter, they may be found more around large riprap than small riprap. Near riprap, the near-bank velocity has a large effect on yearling chinook distribution; they hold in low-velocity zones associated with large rocks, but the low-velocity zone needs to be near a high-velocity zone.

In winter, chinook are consistently very near the surface, away from the large steelhead located near the bottom of deep pools. Chinook generally are not found in riffles in the winter. In rivers, chinook can make extensive use of off-channel areas with slow-moving water. Age-zero chinook move into winter cover when water temperatures fall and stream flows rise. Winter cover for fish of this size usually consists of large rubble and cobble with large, interstitial spaces. During very cold weather, nearly all chinook live among rock piles in the stream or river. When cobble is added to undercut bank areas, chinook use these undercut areas much more than before. Juveniles can survive damage from harsh, ice-scouring conditions if they can enter substrate crevices. Fine-sediment filling of these crevices makes them unusable by chinook. In large rivers, juveniles often use sloughs and backwaters for winter habitat, especially areas fed by warmer spring water.

Steelhead and Rainbow Trout

Steelhead spawn in the spring, and the fry emerge in late spring to early summer. Steelhead may stay in freshwater two or three years before becoming smolts and migrating to the ocean. Steelhead are mostly found in faster water and riffles. They are often concentrated in riffles and glides around wood. In cobble and boulder beds with no wood, cobbles will be used by all sizes of trout more often than large boulders. Steelhead are also found in deeper pools near obstructions. In larger rivers, steelhead may be found near the bottom in 15 to 20 feet of depth in the lee of obstructions that serve as holding and feeding stations.

When threatened by a predatory fish, recently emerged fry hide in the gravel, while older individuals take refuge in cover, such as woody debris. When in the presence of coho, steelhead segregate themselves and occupy the lower third of the water column and riffles. Age-zero steelhead use the shallowest and slowest water. Larger steelhead use the deeper and faster water.

Microhabitat selection by steelhead and rainbow trout varies among fish sizes and seasons. Fish of the same size use very different habitats in the summer and winter. In summer, rainbow trout prefer the same dense, vegetative shade that cutthroat trout do. For steelhead, overhead cover may not be as important; instead, they may need fast, shallow-water habitat with large-particle substrate, such as cobbles and boulders. All size classes prefer to hold close to the bottom.

Steelhead begin to change their preference for habitat in the fall as conditions change from summer to winter. Winter cover may be far more important than summer cover. In fall and winter, steelhead relocate as water temperatures drop if suitable habitat is not available. Both juveniles and adults prefer slower and deeper water than they do in summer. This movement to slower, deeper water in the winter may culminate in juvenile fish taking refuge in the substrate during very low temperatures. Steelhead in winter tend to seek out cover around boulders, rubble and log jams; at low temperatures, age-zero steelhead are most often found amongst and under rubble and cobble having substantial interstitial spaces.

Numbers of age-zero steelhead in small streams are lower at riprap sites than at other types of habitat. In a British Columbia study, numbers of steelhead yearlings and older fish increased with larger rock size and increased water depth and flow during June high-flow conditions and September lower flows. They appear to prefer higher-velocity water (or at least access to it), near big rocks in deeper water. They establish feeding stations near large riprap at the toe of the bank. Age-zero steelhead were found in greater numbers at sites with larger riprap than with smaller riprap. When boulders were added to riprap banks, the number of age-zero steelhead in summer decreased, while yearlings and older fish increased.

Cutthroat Trout

Cutthroat trout make extensive use of small streams. Cutthroat are present in most small streams, together with coho salmon and steelhead. Cutthroat can exist as resident fish, spending their entire lives in freshwater, or they can follow the anadromous life cycle. Both forms of cutthroat can exist in the same watershed. Anadromous cutthroat tend to spawn in the small headwater tributaries of larger streams and live in freshwater from one to six years before they become smolts. Cutthroats tend to spawn higher in a watershed than coho, and they rear near their spawning areas.

After emergence, fry quickly drift downstream into low-velocity margins, backwaters and side channels adjacent to the main channel. In the absence of competition by other species, such as coho, they may remain in these margins throughout summer. Because of their larger size and predatory nature, coho drive age-zero cutthroat from pools and margins into riffles. The cutthroat stay there until decreasing water temperatures and increasing flows in the fall drive them into winter habitats. In the spring, migratory age-one cutthroat begin their downstream movement to the main stem of the stream. In the fall, at the onset of freshets, there is often an upstream movement back into the tributaries.

In small streams, cutthroat prefer dense, vegetative shade in summer. Pool habitat is very important. They are often found in deep pools, with larger fish in deeper pools, in lateral scour pools along deeply undercut banks and around submerged objects. They can be found in large numbers in pools with and without wood and in riffles and glides with wood. Cutthroat like backwater-slough habitat with slow water and plenty of good cover, such as log jams and overhanging vegetation.

Winter habitat for adults and subadult prespawners are deep holes, undercut banks and debris piles. Off-channel pools and side channels are also important winter habitat.

For those smolts that are anadromous, their migration occurs in spring, primarily at night. Smolts may spend considerable time in estuaries during their first summer. Most move back into the freshwater in the fall to winter over, and cutthroat subadults may return from saltwater in the fall to estuaries and freshwater in order to feed. Anglers often fish for them from the shore, around log jams and other woody debris. In streams, these fish may be found in deeper pools around cover such as wood. They may occupy the same winter habitat as larger presmolts.

In a study of small streams, the total weight of all cutthroat living along shorelines with riprap was less then along similar shorelines with no riprap. In large streams, the number of large cutthroat increased at riprap sites, as opposed to along shorelines without riprap.

The Chars known as Dolly Varden and Bull Trout

Fish belonging to the classification known as "char" are differentiated from other salmonids by their small scales and light-colored spots on their skin. Dolly Varden and bull trout are the only native char in Washington. Both Dolly Varden and bull trout occur in coastal and Puget Sound streams; however, only bull trout are known to occur east of the Cascades. Both can be present in the same watershed in western Washington. Char have a number of different, complex life cycles. Some are life-long residents of headwater streams, while others spend their adulthood in the main river or in lakes but ascend into small, headwater streams for spawning and juvenile rearing. Some are anadromous, some are not.

As adults, char feed primarily on other fish. It may be that a vigorous population of char requires an abundant forage fish such as mountain whitefish, various salmonid species and sculpins. Adult growth can be very rapid in saltwater and reservoirs. In saltwater, they feed on surf smelt, herring, sandlance, and pink and chum salmon smolts.

Char can live 10 to 15 years. Those adults that remain in freshwater live in pools in winter, spring and early summer. They hold in deep pools, long runs with cover, undercut banks and log jams. If a pool gets too shallow, they may move into whitewater around large boulders and surface turbulence.

Spawning is initiated at stream temperatures that are colder (usually below 9 degrees Centigrade) for char than for other salmonids. Spawning habitat for char is farther upstream than for any other anadromous fish. In western Washington, 95 percent of Dolly Varden and bull trout spawn above an elevation of 300 meters (984 feet) or in streams with very cold temperatures similar to high-elevation streams. Many stretches of streams at higher elevations flow down steeper gradients, and this washes away gravel and cobble of suitable size for use by spawning char. However, suitable gravel and cobble may persist in stream stretches at higher elevations where the gradients are less steep or where large logs and log jams form and maintain deep pools. It's in these places that char generally find patches of suitable gravel and cobble in which to spawn, as long as the stream temperature remains within an optimal range for char. Where side channels and wall-based channels exist, logs and log jams can be very important to char.

Shortly after spawning, adults often move back down the river and can be found in the quiet water of deep pools and long, slow runs. During winter, fish that have spawned may feed very little and show little growth. However, those that associate with spawning salmon feed on drift eggs and retain their body condition. After spawning, anadromous adults migrate downstream throughout fall and winter to enter the estuary in the spring. They remain in the estuary until early to midsummer, when they go back upstream to spawn again. Upstream movement can be very fast, often during low-light conditions at dawn and dusk. Once at the spawning ground, they may remain in the same pool or area for several months. All char spawn in the fall.

Eggs and juvenile char require very cold water. Optimal water temperature for incubation is 4 degrees Celsius. Juveniles optimally rear in water 4 to 10 degrees Celsius. Nursery areas for char are near the spawning areas. Rearing habitat can be highly variable. Newly emerged fry are very secretive and are closely associated with large substrate such as large cobbles, boulders and large woody debris. In Oregon, bull trout were most often observed over sand and gravel-sized substrate, independent of stream size and season. They are usually associated with the deepest and largest pools. Juveniles can use stream margins and side channels for rearing. When char are around large rocks, they often seek cover in crevasses between the rocks during daytime, emerging after dark. When juveniles are with other species, they hide in heavy cobble and debris jams. Char can sometimes be found in large numbers in side channel habitats near heavy cover, much like coho off-channel habitat. Boulders and cobbles provide cover in high-gradient sections, and large wood does the same in lower-gradient sections.

Juveniles remain in their natal streams until age two. Those with a resident life history strategy will remain in their natal stream for their full life cycle. Some (adfluvial) will move to large reservoirs, while others (fluvial) will migrate to larger mainstem reaches to rear. Other sub-adults may move out of headwater streams and become anadromous. These anadromous smolts migrate in the spring to live at river mouths and nearby beaches.

Char are very susceptible to changes in land use. Char populations can be limited by increased water temperature, scouring from increased stream flows and insufficient large woody debris. Bank-protection projects that remove trees and overhanging cover in the upper-watershed nursery areas can be particularly damaging to char. Projects that remove log jams and other debris will change or eliminate pools, greatly affecting adult holding sites and juvenile rearing.

Coho Salmon

Coho salmon juveniles are consistently associated with cover. In small streams, they are most often found with cutthroat in deep-shaded pools with wood debris. They are found at undercut banks with overhanging vegetation and around and under logs, stumps and sticks. Coho densities increase with increasing amounts of wood in riffles, glides, pools and side channels. Increasing roughness can create pools and velocity diversity, both of which attract coho. Coho use cover when it is present in pools, but they'll still use the pool even if cover is absent; they simply go deeper for protection. When there is overhanging cover, coho move around more than when the only shade is formed by higher vegetation such as trees. If woody debris is removed from streams, there is a reduction in the density and total production of coho.

Coho prefer a variety of habitats throughout the year. Fry in the spring are found in all habitats, but are primarily at the channel margins. Their densities are greatest in backwater pools and off-channel areas. As they grow, they shift into deeper habitats. In winter, they again shift into areas such as beaver ponds and off-channel habitats with the lowest velocities and turbulence during freshets. Coho populations are limited by total pool volume in the summer. Low stream flows can greatly decrease coho survival. Coho occupy a wide range of habitats in summer, including pools, side channels, beaver ponds, glides and the edges of riffles. When threatened by a predatory bird, coho seek cover. Recently emerged fry hide in the gravel substrate to escape a predatory fish, while larger fry seek woody-debris cover. At lower flows, overhead shade is very important as hiding cover.

Coho tend to be found at middle depths in the main body of pools. Coho select a lower position in the water column when the only cover is water depth. When in streams with yearling steelhead, coho are found higher in the water column, with steelhead deeper or in riffles. Conversely, when sharing waters with younger steelhead and Dolly Varden, age-zero coho are usually in deeper water than these fish. Coho select feeding stations based on water velocity and food supply; the greatest amount of insect drift is in higher-velocity water. They feed primarily on terrestrial insects.

During fall freshets, coho juveniles seek the quiet water of off-channel habitats. Cover may be much more critical for coho in winter than in summer. The most suitable winter habitat for coho combines low flow velocity, shade and three-dimensional complexity. Colder water and increased stream flow may trigger this shift into winter habitat. Many coho must winter over in streams and in main-stem habitats rather than their preferred off-channel areas. In streams, they prefer areas of deep pools and undercut banks with lots of wood, perhaps because of the low flow velocities in pools and in the lee of obstructions. Juvenile coho are generally absent in main channels lacking cover. Where sloughs are limited, coho are very dependent on structural complexity and cover to survive. Survival in winter is strongly correlated with habitat complexity and the amount of woody debris. In winter, at lower temperatures, coho feed less and move closer to low-velocity areas and cover such as logs and upturned rootwads. In very cold weather, they appear to bury themselves in the cover structure, being almost comatose.

Wood provides protection from predators and provides lower flow velocities that help to keep fish from being displaced downstream during freshets. As the water flow increases, fish accumulate in the back eddies behind cover structures and swim against the eddy. At maximum flows, they are found close to cover structures; otherwise, they are either flushed out or they swim away. During daylight, at high flows, fish hold position in the lee of an obstruction. The smallest fish may be the most susceptible to being swept away. There may be a decline in the juvenile coho population in streams after freshets. After freshets, higher numbers of coho remain in stream sections with accumulations of wood than in other habitat types.

Riprap provides very poor habitat for coho. In both small and large streams, coho numbers decrease at riprap sites. Riprap does not provide winter habitat for coho. Bank- and pool-alteration activity can have severe impacts on coho populations. Removing overhead shade also has negative effects.

Chum Salmon

Chum typically emerge from the gravel at night and immediately migrate downstream to the estuary. Most migration occurs at night, although increased turbidity can lead to daytime migration. Chum show a greater tendency to migrate during the daylight in years when pink salmon are present. They also change their vertical distribution when pinks are present.

Chum may actively feed while migrating downstream, especially at night. Some delay migration to feed and have extended freshwater rearing (two to four months). Rearing can occur in backwater sloughs, off-channel habitat, and in quiet backwaters and eddies typically used by coho. Chum may be seen in the shallow margins of sand bars closely associated with both large and small (pencil-thin) wood debris. They may be seen immediately adjacent to the river bank during daytime. In British Columbia's Fraser River, chum are distributed randomly across the river. In smaller streams, chum migrate in the stronger currents in the middle of the stream.

Due to their limited freshwater residence, there may be very little impact of bank protection on chum salmon fry. Bank protection may limit their ability to find cover during their daytime layovers. Secondary impacts of bank-stabilization activities, such as a change in species composition, may have a significant impact on juvenile chums.

Pink Salmon

After emergence from the gravel, pink salmon migrate quickly downstream to saltwater. They school up soon after emergence, travel as a school and, when attacked, do not hide in the substrate as do other salmonids. They spend less time in freshwater than other salmonids. A rapid exodus from freshwater to saltwater may be necessary for their survival. Coho, and, to a much less extent Dolly Varden, can be significant predators on pinks.

There may be behavioral differences between pinks found in small and large rivers. Schooling may be more common in large rivers and estuaries; however, in small rivers and streams, migration may occur as individuals. In small, coastal rivers, migration occurs at night, and nearly all fish may make it to saltwater in one night. Those that don't complete the migration in one night usually finish the trip the second night. In longer rivers where the spawning areas are greater distances upstream, migration may also occur during the daytime, particularly in the lower reaches of the river. Migrating pink salmon may be found anywhere in a river, from the surface to the bottom and from shore to shore, but they generally concentrate in the fastest flowing water.

Due to their limited freshwater residence and speedy migration, there may be very little impact of bank protection on pink salmon. Just as with chum salmon, secondary impacts of bank-stabilization activities, such as a change in species composition, may have a significant impact on juvenile pinks.

Sockeye Salmon

Most sockeye juveniles rear for a year in freshwater, usually in lakes. The vast majority of sockeye in Washington are lake-inlet spawners and simply move downstream to the lake immediately after emergence. Some sockeye are lake-outlet spawners and migrate upstream to the lake after emergence. After emergence, they may be swept downstream. When they are sufficiently big and strong, they seek out the shoreline and migrate along the bank back upstream to the lake in which they will continue to mature. There is limited rearing in streams; instead, they move quickly to a lake and reside there for a year or more. Lake-rearing juveniles are pelagic (living in open, deeper water), and bank-protection projects probably have little impact on them.

There are also stream-spawning sockeye in systems with no lakes. Their rearing habitats in these situations are not well known. Some biologists speculate that in large river systems, sockeye juveniles may act like coho, seeking deep river braids, off-channel sloughs, beaver ponds or other slack-water areas which act like small lakes. They have been found in winter in nonfreezing springs, spring ponds, creeks and side-channel sloughs. In some systems without lakes, juveniles may migrate directly to the estuary at age zero (younger than one year) and stay to grow in the tidewater sloughs.

Smolts usually migrate to the ocean in schools, often at night, swimming faster than the current. Smolts migrate near the surface in the main channel rather than in the quieter, near-shore area. They have been sampled migrating in the same midchannel locations as steelhead and yearling chinook. In the Columbia River, they can travel at rates of 40 kilometers per day.

Juvenile sockeye do not appear to be often associated with near-shore areas for any part of their freshwater life. Therefore, there is probably little overall impact of bank-protection projects on sockeye stocks. Barriers to access into river sloughs may have a large impact on sockeye that rear in rivers. Secondary impacts of bank-stabilization activities, such as a change in species composition, may have a significant impact on juvenile sockeye.

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Planting Considerations and Erosion-Control Fabrics

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Appendix H

Planting Considerations and Erosion-Control Fabrics

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Successful revegetation of streambanks and floodplains requires an understanding of natural fluvial processes, such as sediment deposition, hydraulic scour, inundation and drought associated with falling water tables. These processes are distinct to riparian zones, and riparian vegetation is well-adapted to these processes. Because the dynamics of the riparian zone require that vegetation be highly specialized to survive, planting strategies and plant materials developed for traditional landscaping or reforestation projects may not be well suited to the streambank environment.

This appendix provides a framework for revegetation planning and implementation based on riparian and fluvial processes and to provide instruction on the use and installation of erosion-control fabrics to stabilize the planting area. It also serves as a more detailed reference for the biotechnical and structural techniques described in Chapter 6, *Techniques* that require live vegetation for proper functioning. These techniques including *Herbaceous Plantings, Woody Plantings, Soil Reinforcement, Coir Logs* and *Bank Reshaping*. Other techniques that may also incorporate revegetation include *Roughness Trees, Riprap, Log Cribwalls, Manufactured Retention Systems, Riparian-Buffer Management* and *Floodplain Roughness*.

PLANTING CONSIDERATIONS

The list of steps shown below is the recommended sequence for most riparian revegetation plans. Each step in the sequence is discussed in more detail in this appendix.

1. conduct a site review;
2. identify site constraints;
3. develop design criteria;
4. select plant-material types (e.g., woody, herbaceous, bare-root, seed, potted);
5. select plant species;
6. determine planting density and layout;
7. schedule timing of plantings;
8. consider site-preparation requirements;
9. determine planting techniques; and
10. define procedures to monitor and maintain project (see Appendix J, *Monitoring Considerations*).

Site Review

A vegetation site review consists of collecting specific, vegetation-related data at a project site for use in development of a revegetation plan. A site review should include the specific project reach and a functional reference site, preferably in the same or a nearby watershed with similar site conditions. Use the reference site as a tool to aid in the design of a planting plan for the project area. At a minimum, the information below should be collected:

- *Plant Distribution/Colonization* - note the distribution of dominant woody and herbaceous species (including weeds) relative to river stage, hydrology and shade and which plants are colonizing freshly deposited soils. Look for and identify any good sources for local cutting collection and/or plant salvage.
- *Shade* - observe and note how canopy cover will affect light availability for new plants.
- *Lower Limit of Perennial Vegetation* - determine the lowest bank elevation that will support perennial vegetation. This is most accurately determined on gradually sloping banks, where an easily observed continuum exists, ranging from unvegetated channel to annual plants to perennial plants. If possible, how this elevation relates to river discharge should be noted.
- *Depth to Groundwater* - ideally, this is determined using test pits or monitoring wells; but, in the absence of such tools, it is often estimated using the elevation of late-summer base flow.
- *Soils* - describe existing soils on different bank and channel features such as bars and overbank-deposition areas. Note the soil texture (e.g., sandy, rocky, clay, organic). Note whether soils are well-drained (gravelly or sandy) or poorly drained (clay or organic), dry or wet, friable or highly compacted by livestock or heavy-equipment operation. Look for cut banks that identify soil profile by depth. Are shallow soils or till present? Additional information that can be helpful but is not often collected includes soil pH, salinity and nutrient status. This information can be obtained by sending a sample to a soil lab or by testing it with a home soil test kit.
- *Human/Wildlife Use of the Site* - note whether there is existing or a potential for human and animal foot traffic, recreational river use, grazing, deer and elk browsing, beaver activity, or other potential impacts to vegetation and soil.
- *Hydrology* - check to see if portions of the site periodically flood. If so, attempt to determine how often and for how long. Look for physical indicators of high flow, such as sediment deposition, woody debris and trash.
- *Geographic Characteristics* - determine the elevation, slope and aspect of the site. Plant species harvested for revegetation projects that come from high elevations on the slope may not grow well at low elevations. Some species are more adapted to steep slope conditions and provide greater resistance to slope erosion than others. South-facing slopes are much drier than north-facing slopes.

Site Constraints

Early in the revegetation-planning process, it is important to identify potential factors that may limit successful revegetation. While site constraints for plantings are often biological or physical site factors, less obvious constraints are related to project budget and management or to the scheduling of construction activities. Often, recognition of site constraints early in the planning process can lead to a creative solution that not only may increase plant survival but also simplify construction and possibly save money.

Below are some possible site constraints, many of which are specifically related to natural riparian processes.

- weed competition;
- heavy shade;
- over-compacted soils;
- overly drained soils;
- poorly drained soil;
- deep summer water table;
- shallow soils/bedrock;
- high amounts of sediment deposition;
- large flood events expected soon after planting;
- potential ice flows/damage;
- poor native-species availability;
- soil compaction due to heavy foot traffic (human or animal);
- construction-sequencing conflicts;
- livestock, deer and elk grazing/trampling/browsing;
- heavy beaver damage;
- incompatible mowing and pruning activities (a common problem at golf courses and near power lines);
- rodent problems;
- extended inundation;
- high soil salinity (a common problem in arid areas that are irrigated);
- dam-influenced hydrology;
- tide-influenced hydrology;
- limited site access; and/or
- insufficient maintenance budget.

Design Criteria

While not necessary for all projects, it is recommended that revegetation planning begin with development of design criteria. Design criteria are specific guidelines that quantify desired performance attributes to meet objectives. For further discussion of design criteria, refer to Chapter 4, *Considerations for a Solution*. A general revegetation guideline or objective might be "to provide habitat" or "to provide erosion control," whereas a design criterion might be "to provide overhanging shrub cover along 50 percent of bank within three years." Design criteria for vegetation should specify requirements for habitat needs, size of material, species diversity and erosion control.

Plant-Material Types

Plant-material type refers to the form in which the plants will be when obtained and planted into a particular project site. Examples of plant-material types include cuttings, seed, containerized, bare-root stock, and ball and burlap stock. They are further classified into herbaceous and woody plant categories. Base the selection of specific woody or herbaceous plant-material types on design objectives or design criteria, site conditions, and site constraints. Most projects tend to use a combination of woody and herbaceous plant-material types.

Woody Plant Material

Woody plants, which include both shrubs and trees, are widely used in bank-protection projects to provide bank stability, habitat and aesthetic appeal. Their roots tend to be strong and deep, mechanically reinforcing soils by adding tensile strength.[1] Large riparian trees contribute large, woody material to streams, and all woody plants provide good shade and cover to streams. On many streams, undercut tree and shrub roots provide excellent fish habitat, especially the roots of mature cedar, hemlock and spruce. Multiple, flexible shrub stems dissipate stream energy and encourage sediment deposition rather than scour. Common, woody types of plant material are briefly discussed.

Cuttings

Cuttings consist of harvested stems of dormant shrubs and trees. They are capable of developing both roots and shoots if planted in proper conditions. For the best chance of success, cuttings should be harvested during the dormant season, preferably fall or spring,[2] and planted within days of collection. By far, the most commonly used and successful cuttings are those taken from a variety of willow (*Salix* spp.). Other species commonly used in Washington with good success include red-osier dogwood (*Cornus stolonifera*) and black cottonwood (*Populus trichocarpa*). Species that are less commonly used but root well from cuttings include salmonberry (*Rubus spectabilis*), elderberry (*Sambucus* spp.), Pacific ninebark (*Physocarpus capitatus*), mallow ninebark (*Physocarpus malvaceous*), black twinberry (*Lonicera involucrata*), Nootka rose (*Rosa nutkana*) and spirea (*Spiraea* spp).[3,4]

Keep in mind that not all of the species listed above are appropriate in live-stake applications due to their relatively small, flexible branches, but they are appropriate as components of fascines and brush layers. Few other riparian shrubs or trees native to Washington reliably and consistently root from cuttings. Cuttings are popular in bank-stabilization projects because they are inexpensive and can be collected in long lengths capable of accessing deep (10- to 12-foot) water tables. Whether installed as live stakes, fascines, or brush mattresses, cuttings provide excellent erosion control and bank stabilization. More detail on cuttings is provided later in this appendix under *Planting Techniques*.

Containerized

Containerized plants are nursery-grown plants established from seeds or cuttings and planted in any one of dozens of different sizes and shapes of containers. They are distinguished from most other types of plant materials on the basis of their well-developed soil/root mass, allowing planting to occur throughout much of the year, provided adequate water is available. If installed plants are irrigated, they can be installed in the dry summer months, which is an advantage when construction occurs during summer low-flow months. Another distinct advantage of containerized plants, especially in contrast to cuttings, is that many riparian woody (and herbaceous) plant species native to Washington State can be obtained in this form. Conifers such as cedar, spruce and hemlock are usually acquired as containerized plant material.

Although conventional landscaping nurseries typically provide containerized plants in one-, two- or five-gallon containers, some native-plant nurseries make use of a much wider array of containers that are better suited to streamside conditions. For example, a deep but narrow container known as a tubeling or plug has dimensions of approximately one inch wide by six inches deep. The greater depth-to-width ratio of the container provides the plant with better resistance to pullout caused by flowing water and better access to deep, moist soil than conventional nursery containers. Other innovative containers include, but are certainly not limited to 14-inch-deep treepots®, PVC pipe four to six inches wide by one to two feet long, biodegradable burlap "socks" and biodegradable coir (coconut-husk fiber) containers.

Bare-Root

Bare-root plant material is a type of nursery-grown, woody plant-material widely used in riparian restoration. Woody plants in the bare-root form consist of rooted plants sold with the soil removed and packaged with damp sphagnum moss or sawdust and sold in bundles. Bare-root plant material generally requires smaller planting holes than comparatively-sized containerized plants because you don't have to make room in the hole for soil packed around the roots. Although often much less expensive (one-tenth the cost of container stock), bare-root plants can be less forgiving and more delicate during the planting stage and may not survive if stored or planted incorrectly. Bare-root plants are becoming increasingly available, both in number and species diversity, at native-plant-material centers, nurseries and local conservation districts. Locally collected material is harder to find, but some nurseries can accommodate special requests with advance notice. The main limitation of bare-root plants is their narrow planting window (late winter/early spring dormant season). Bare-root plantings may be successful even when planted later into the spring if well watered through the summer.

Ball and Burlap

The mainstay of the landscaping industry, ball-and-burlap plants consist of mature trees and shrubs ranging from six to 12 feet tall. Plants are shipped from nurseries with their roots "balled-up" and wrapped in burlap and wire. Their large size makes ball-and-burlap plants less susceptible to animal grazing and weed competition, and it adds an element of structural diversity to a revegetated area. However, ball-and-burlap plants are considerably more expensive than other forms of plant material and their large size and relative bulk make handling difficult, requiring guy wires and staking for stability during the first one to two years after planting.

Salvaged

Another type of woody plant material consists of salvaged or transplanted plants. Ideally obtained on-site, salvaged shrubs and trees are those that otherwise would be destroyed or disposed of during the construction phase of a bank-reconstruction project or another nearby construction project, but are instead salvaged and replanted at the site to add biological, economic and aesthetic value. The size of plants that can be salvaged depends upon what's growing at the site, the types of heavy equipment available and the scope of the project. If carefully coordinated, excavators or tree spades can effectively transplant a large number of seedlings, saplings and sometimes mature shrubs and trees. In addition to great cost savings (provided equipment and transportation costs are low), salvaged plantings can provide immediate benefits to bank stability, structural diversity, cover and aesthetics compared to smaller forms of plant materials. Their large root mass may also make them resistant to flood flows.

When salvaging plant material, keep in mind that the larger the plant being transplanted, the lower survival rate it will have. The root systems on large plants are more likely to get damaged during the process, and the damaged root system may not be capable of supporting the relatively large, above-ground portion of the plant during the first growing season following transplant. Pruning woody stems and branches may help reduce drought stress. According to the Thurston County Master Gardener Foundation,[4] native plants that are easily salvaged include:

- vine maple (*Acer circinatum*),
- bigleaf maple (*Acer macrophyllum*).
- red alder (*Alnus rubra*),
- beaked hazelnut (*Corylus cornuta*),
- Oregon ash (*Fraxinus latifolia*),
- Indian plum (*Oemleria cerasiformis*),
- Pacific ninebark (*Physocarpus capitatus*),
- Douglas fir (*Pseudotsuga menziesii*),
- cascara (*Rhamnus purshiana*),
- Nootka rose (*Rosa nutkana*),
- clustered rose (*Rosa pisocarpa*),
- red elderberry (*Sambucus racemosa*),
- snowberry (*Symphoricarpos albus*), and
- western red cedar (*Thuja plicata*).

Seed

On some sites, there may be interest in experimenting with western red cedar using direct seeding, as discussed in the Soil Rehabilitation Guidebook.[5] Otherwise, seeding of woody species is not a recommend means of establishing vegetation at a bank-protection site.

Herbaceous Plant Material

Herbaceous plants consist of grass and grass-like plants including rushes, sedges, ferns, legumes, forbs and wildflowers. They are characterized by fine-textured roots that grow between six and 24 inches deep, depending upon plant species, soil type and site hydrology. In contrast to woody plants, most herbaceous plants tend to form dense cover over the soil surface, although some species tend to be more clumped. Their fine mats of roots and dense cover combine to provide excellent soil reinforcement and protection from surface soil erosion. Unlike some woody species, the flexible stems of herbaceous plants bend or flatten under flood flows, providing high-flood conveyance.

Containerized

Nursery-grown herbaceous species are widely available in containers that are similar to those described under the previous discussion on *Woody Plant-Material Types*.

Bare-Root

Emergent, wetland, herbaceous plants such as bulrush (*Scirpus* spp.) are available in bean-sized, bare-root fragments. Easy to install and far less expensive than containerized plants, streambank plantings of bare-root herbaceous plants are appropriate if covered with erosion-control fabrics to prevent flood flow wash-out. Like woody bare-root stock, herbaceous bare-root stock must be planted in their dormant season (late winter to early spring) and may require supplemental irrigation.

Salvaged

Salvaged sod, if available, is an outstanding type of herbaceous plant material. It has a dense soil/root mass that is relatively resistant to erosive forces; it establishes quickly; it's cost effective, and it makes use of materials that would otherwise be discarded. Salvaging and transplanting sod requires an excavator or other specialized, heavy equipment.

Seed

Seed is the most common type of herbaceous plant material because it is relatively inexpensive; and, if planted properly, it can quickly establish itself as a short- or long-lasting ground cover. In reconstructed streambanks, seed is generally installed by hand or with a mechanical seeding device, and it is covered with a temporary erosion-control fabric to protect the seed from wash-out during flood events. Seed is also available in preseeded erosion-control mats. This product may be beneficial on steep slopes where it would otherwise be difficult to place seed. However, preseeded mats are relatively expensive, and their use often results in spotty vegetative cover. Seed can also be applied using hydroseeding methods; however, hydroseeding is not recommended for streambanks because it offers little protection against flowing water. Some suggestions for selecting the most suitable mix of seed are discussed later in this appendix under *Planting Techniques*.

Prevegetated Mat

Similar to salvaged sod in terms of its advantages, another interesting type of herbaceous plant material is a prevegetated coconut mat that resembles conventional turf sod. The mats are characterized by dense root systems that quickly penetrate into the soil once installed. The coconut mat provides temporary erosion control until the vegetation gets established. Available from some Washington native plant nurseries, these products can be a low-risk (but expensive) means to quickly establish herbaceous cover.

Plant-Species Selection

All streambank- and floodplain-revegetation projects should use, and are often required to use, native plants naturally occurring in the project area. Unlike introduced species, native plants are genetically adapted to the local climate, compete well for survival on native streambank soils, and they are resistant to local insect infestations. Choosing native plants grown with seed or cuttings collected from sites in similar, local watersheds will preserve the genetic integrity of the local stock and will have the highest likelihood of success. There are over 40 native-plant nurseries in the state of Washington.[6]

Species for each chosen plant-material type (e.g., herbaceous seed or woody cuttings) should be selected with an emphasis on the following:

- suitability for anticipated climate, hydrology, elevation, soils and site constraints of planting site;
- reasonable availability in desired quantity (either from nurseries or a local source);
- probability of successful establishment (based on best available experience or information);
- desired growth form or shape and size (as specified in design criteria); and
- ability to achieve desired plant diversity (as specified in design criteria).

Planting a variety of species ensures the highest likelihood of project success. Monocultures are susceptible to total failure when exposed to disease or unfavorable site conditions. Consider planting a mix of fast- and slow-growing plants, deciduous and evergreen. Remember to use information gathered in project- and reference-site characterization during species selection. *Table H-6* (located at the end of this appendix) provides a list of native species one might consider using on streambank-stabilization projects. This list is not exhaustive, but it does provide helpful information to consider during the plant selection process. Consult plant guides or native-plant nurseries for further information on specific plants. As with any purchase, when choosing a source of plant material, assess the quality of the plants; cheaper is not necessarily better.

When choosing plants for a disturbed streambank, consider each plant's role in forest succession. Pioneer species such as red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), willow (*Salix* spp.) and salmonberry (*Rubus spectabilis*) are naturally tolerant of extreme, adverse conditions, such as low soil-nutrient status, moisture stress (with the exception of salmonberry), and full sun and wind exposure. Alternatively, some desirable conifers, such as western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*), form late-succession forests and establish best under shady, relatively protected conditions.[3] Plantings such seedlings in direct-sun locations often fails. Success may be substantially improved at the location if seedling planting is delayed until a nearby shrub and/or tree layer develops a canopy, offering at least partial shade.

Plant Density and Layout

Plant densities for reconstructed streambanks are often determined on a "plant per linear foot" basis if planting on a narrow strip along the water's edge, or on a "feet on center" basis if planted on larger or wider areas. *Table H-1* provides general guidelines concerning recommended densities for different types of plant materials. Remember that these recommendations are only a starting point for planning and may need to be increased or decreased depending upon such factors as project budget, erosion-control requirements, probability of survival and anticipated time to maturity.

Plant Material Type	Planting Density (highly site dependent)
Cuttings	Rows of 1 per 1 or 2 linear ft (rows 2-3 ft apart)
10-cubic-inch herbaceous plantings	2 ft on-center (10,890 plants per acre)
10-cubic-inch containerized shrub	3 ft on-center (4,840 plants per acre)
10-cubic-inch containerized tree	10 ft on-center (435 plants per acre)
1-gallon rooted willow container	5 ft on-center (1,742 plants per acre)
5-gallon cottonwood container	10 ft on-center (435 plants per acre)
1.5-inch--diameter stem, ball-and-burlap tree	20 ft on-center (109 plants per acre)
Seed mix	Seeding rate depends upon species

Table H-1. Recommended densities for plant materials.

It should be noted that a small increase in planting density can increase the number of plants per acre substantially. For example, decreasing plant spacing from five feet on-center to three feet on-center increases plants per acre from approximately 1,792 to 4,840. *Table H-2* provides planting-density equivalencies.

ft on center	sq. ft per plant	plants per acre
1	1.0	43,560
2	4.0	10,890
3	9.0	4,840
4	16.0	2,722
5	25.0	1,742
10	100.0	435
15	225.0	193
20	400.0	109
25	625.0	70

Table H-2. Planting density equivalencies.

After densities for plants are determined, the layout or distribution of plants across a site must be decided. The simplest approach is to distribute plants uniformly across appropriate hydrologic planting zones, evenly distributing different species at a specified spacing. Such an approach is most likely to result in uniform coverage and allows for easy installation and monitoring (especially several years later after vegetation gets thicker). This approach may not, however, optimize fish and wildlife habitat and aesthetics. Instead of focusing on even distribution, an alternative planting approach is to base the planting layout on the size and type of material, the individual plant species habits, and the habitat needs of fish and wildlife. For example, low-growing shrubs and/or herbaceous plantings might be distributed uniformly across a certain zone such as a streambank, while tall shrubs are clustered near pools to provide fish cover. When planting a number of varieties in the same area, it is often best to group similar plants together in clusters rather than interspersing all species equally. This mimics many natural plant distributions, which tend to be more aesthetically pleasing. Plants that tend to form thickets, such as salmonberry (*Rubus spectabilis*), may be planted close together. Plants that tend to grow as solitary individuals, such as many tree species, may be planted further apart.

When planting the floodplain or riparian zone above the top of the bank, future maintenance requirements should also be considered. Grasses and weeds surrounding new plants often need to be mown or otherwise suppressed for three years or more to minimize competition until the plant is firmly established. New plants often need supplemental water during the first year (and sometimes through the second summer) following planting. Maintenance will likely be easier if plants are grown in distinct clusters or bands because the plants themselves will be easier to find, and the area requiring the use of hand-held tools to suppress weeds can be narrowed to within and immediately outside of the cluster or band. Weed suppressors that operate on a larger scale, such as mowers, can be used between plant clusters if necessary. Heavy mulch between plants within the cluster or band will suppress weeds and conserve moisture so as to minimize the necessary frequency of maintenance. However, mulch is not generally recommended in areas subject to frequent flooding. Maintenance issues are of a lesser concern when planting the streambank itself because the desired outcome there is generally uniform coverage, which will likely happen if the newly planted vegetation is simply left alone.

Timing of Plantings

Each plant material type has a specific planting window of survival, based on its biological needs as summarized in *Table H-3*. It should be noted that, in riparian areas, timing of flood flows or wet site conditions may prevent or limit site access during otherwise acceptable planting periods.

Plant-Material Type	Recommended Planting Period
Seeding	Spring/fall is best; summer seeding needs irrigation
Dormant cuttings	Spring/fall is best; possibly winter or early summer
Containerized/rooted plantings	Spring/fall is best; summer plantings need irrigation
Bare-root plantings	Late winter/early spring only
Salvaged trees/shrubs	All year, but dormant season (November to March) is best; irrigate and prune summer transplants
Salvaged sod	All year; irrigate summer/fall transplants
Ball-and-burlap trees	Spring/fall is best

Table H-3. Recommended planting window.

Site Preparation

Because of the natural fluvial processes that occur in streambank planting areas, some site-preparation strategies used in upland forests, grasslands and landscaped areas are of questionable value. For example, techniques used to control competing vegetation in uplands, such as weed mats and mulch, may not be appropriate on streambanks subject to frequent flooding because they collect debris or are washed away during flood flows. In addition, along a streambank, deep-rooted shrubs and adjacent shallow-rooted grasses may not compete against each other as they do in upland plantings. Streambank grasses grow in the spring when surface moisture is available; but woody plants, once established, draw their water from deeper in the ground, rendering them better able to survive periods when surface soils are dry. During the establishment period, however, weed and grass suppression surrounding newly planted native plants may be critical to plant survival, especially when planted in heavily vegetated areas such as pastures and meadows, or in areas dominated by aggressive, noxious weeds, such as reed canary grass and blackberries.

Soil fertilizer that is regularly applied in uplands may not be appropriate in streambank zones for several reasons. First, many riparian species naturally thrive in relatively sterile soil, characterized by high sand and gravel/cobble content and may already be adapted to low-nutrient sites or obtain their nutrients in association with stream flow. Second, surface applications of fertilizer may be washed away by flood flows and add excess nutrients to the aquatic system before plants can absorb them. Third, weeds may be more competitive on fertilized sites than on typical alluvial sites that are dominated by low-nutrient, sandy and gravelly soils.

If soil amendments or supplements such as compost, topsoil or fertilizer are to be used, they should be organic products with slow-release characteristics, and they should not be applied to the surface of the soil. Rather, they should be mixed into the rooting zone with existing soils. Amending existing soils and physically incorporating these amendments into the rooting zone increases their retention under flood flows and may encourage deeper rooting than if amendments are simply placed on the soil surface.

An amendment that may be worth considering in droughty sites, at least on an experimental basis is "water crystals." Water crystals are synthetic polymers added to the rooting zone that can improve moisture retention and thereby allow plants to better withstand drought.

Note that additional site preparations, including fencing and weed control, may be required to address any identified site constraints.

Planting Techniques

Proper treatment of plant material, including storage and planting techniques, is critical to the success of a bank-protection project that incorporates vegetation. All plants used on site should have a healthy, vigorous appearance, free of dead wood and disease. Care should be taken to properly store plants prior to planting, protecting them from sun, wind and physical abuse. The appropriate planting technique in streambank settings depends upon the type of plant material, as shown in *Table H-4*. If planting is to be done in an area that's heavily vegetated, such as a pasture or meadow, remove vegetation from at least a three-foot-diameter circle where the new plant will be set to minimize competition. All plants should be watered immediately after planting to eliminate air pockets and to ensure that moisture around the root ball is at or near field capacity. More details on planting techniques are provided later in this section. *Figure H-1* shows typical installation details for woody plants (located at the end of this appendix).

Plant-Material Type	Planting Techniques
Seeds	Hand broadcast or mechanically seed under erosion-control fabric. Lightly compact seeded soil.
Dormant cuttings	Depends upon application; see details below.
Container/rooted plantings	Hand plant or use mechanized planting tools.
Bare-root plantings	Hand plant.
Salvaged trees/shrubs	Transplant with backhoe, excavator, tree spade or by hand.
Salvaged sod	Transplant with excavator or specialized equipment.
Ball-and-burlap trees	Plant with crew and backhoe or by hand; stake with guy wires.

Table H-4. Planting techniques.

Developing Seed Mixes

Seed mixes are a combination of grass and grass-like plant species intended to provide both short- and/or long-term cover, depending upon the specific project. Some suggestions follow:

- More species are not necessarily better. Select three to five species with a range of seed sizes that are biologically suited to your site.
- Do not specify hard-to-find or unavailable species.
- To the extent possible, use locally collected seed.
- Select seed containing a low percentage of weeds.

- Select at least one proven, quick-establishing species. This may justify use of short-lived non-native cover crops, such as annual rye, alfalfa or winter wheat. Or try a sterile hybrid such as regreen or a native, dry-site species, such as slender wheat grass, that provides good short-term erosion protection but will eventually be replaced by a species more tolerant of moist soils. Short-lived species are particularly appropriate when vegetation established by seed is expected to provide only short-term erosion control until native herbaceous and woody plants get established. Short-lived species will provide less long-term competition.

- More seed is not necessarily better. Instead, focus on getting good seed-to-soil contact by firmly compacting seeded streambank areas with excavator tracks, an excavator bucket or a contractor's compacter. Imprints left in the soil by tracked equipment during construction can help to collect seed and rainwater and provide a moist microclimate for seed germination.

- Have a seed supplier help determine seed rate and purchase seed in pounds of pure live seed (also referred to as "PLS lbs.").

- Experiment with different species, and monitor results.

- After applying a simple seed mix containing three to five species, add diversity by separately seeding a wildflower mix in scattered locations across the seeded area.

- To maximize survival, seed should be planted during the correct planting season as recommended by the seed supplier. To provide erosion control during the winter months, seed must sprout and root well prior to the start of the winter dormant season. A straw mulch can increase the likelihood and rate of seed germination, even if the straw later washes downstream. Erosion-control fabrics can be used in conjunction with or in place of straw mulch to prevent straw and seed from washing downstream.

- Where the potential for natural recruitment of native vegetation is high, lightly seeding the area may be more effective than heavily seeding. This will limit competition for the native vegetation.

Collection, Harvest and Installation of Cuttings

Live cuttings are the most common type of plant material used on reconstructed streambanks. At the end of this appendix, in the section entitled *Additional Sources of Information*, many on-line and published planting guidelines are listed. Some additional tips related to collection, storage and installation are described below:

- Best survival occurs with dormant collection and plantings, but anecdotal reports suggest that successful establishment is sometimes possible from cuttings planted in early summer and early fall, especially if leaves and branches are stripped from the plants and cuttings reach the water table or are irrigated.

- Collect cuttings from healthy vigorous stock. Collect cuttings from male and female plants, if applicable. One- or two-year-old wood is generally better than older wood, and cuttings taken from the center and bottom of the plant will frequently root better than those taken from the outside edges. A general rule of thumb is to take no more than 1/20 of an individual plant.[4] When harvesting cuttings, don't clearcut the source area.

- Cuttings should be at least one half inch in diameter, 12 to 18 inches long, and include two or more nodes (buds). One (or more) nodes is for the roots of the new plant and one (or more) is for the leaves. Some plants have very long sections between nodes and so your cuttings may need to be longer the 18 inches. Longer cuttings may also be necessary depending upon planting site conditions (e.g., deep water table) and application (e.g., brush layers and fascines versus live stakes). Experiment with a variety of cutting diameters, since literature on the most successful stem diameter is not consistent and varies depending upon species under consideration.[4] Cutting diameters less than one half inch may be necessary for some species (e.g., *Symphoricarpos* spp. and *Spirea* spp.).

- When harvesting cuttings, mark the base of each cutting with a clean, diagonal cut, and make sure the base of each cutting is inserted into the ground. Upside-down cuttings rarely survive.

- Cuttings should be kept moist, relatively cool and shaded until planting. Even on a cold day, exposure to direct sunlight will stress them. The literature suggests that soaking cuttings (at least that portion of the cutting that will be underground) in water for 24 hours or more prior to planting improves survival. This is also an excellent, temporary, on-site storage method. Water should be changed daily. Cuttings will be most successful if harvested and planted in the same day.
- If cuttings cannot be installed within days of collection, consider long-term storage (up to several months) under cool, damp, dark conditions (refrigeration).
- Never plant cuttings into dry soils.
- If the site is not irrigated, the bottom of the cutting must reach a depth where the soil is permanently damp. The literature is not conclusive on what percentage of the cutting should extend above ground. One quarter is often recommended (especially for arid areas), no more than one half, but experiment with variations and monitor results. When planted, at least one node should be buried and one node left exposed to establish roots and shoots, respectively.
- Ensure good stem-to-soil contact by installing in compacted soils. The stake must fit tightly in the planting hole, leaving no air space.
- Be creative with planting techniques; refer to the discussion in Chapter 6 that addresses *Woody Plantings* for more discussion on specialized planting techniques.

Installing Containerized Plant Materials

The success of planting techniques for containerized plants depends in large part upon the specific container size and dimension, making generalizations difficult. For example, narrow "tubeling" containers can be planted through erosion-control fabric with minimal fabric cutting, but larger containers require cutting fabric strands that can potentially weaken the fabric. On particularly erosive sites, the advantages of larger material should be weighed against the potential for compromising fabric strength and integrity. Depending upon the situation, planting holes can be hand dug with shovels and dibble bars, or with a variety of mechanical equipment including augers, excavators and backhoes. The planting hole should be roughly twice the diameter of the container. Loosen and uncoil circling or twisted roots. All container plants need to have the top of the soil/root mass planted flush with or slightly higher than the soil surface and have a suitable backfill material firmly compacted around the root mass. A trough or low soil berm around the planting hole may be used to retain water. However, care should be taken to keep the trunk base dry. Irrigation is recommended in many cases, but is generally not required for dormant-season plantings. If using mulch, avoid letting the mulch come in contact with the stem.

Planting Bare-Root Materials

For best success, bare-root plants must be planted during the later winter/early spring. If irrigation is available, the planting season may extend into late spring and possibly early summer, but survival may be low. Roots should be fresh and plump, not dry and withered. Store bare-root plants in a cool, shaded environment with roots covered by moist (but not soggy) mulch or sawdust. Roots must be kept moist and protected from sun and wind exposure at all times. Greater success may result from soaking the root system in a bucket of water over night prior to planting. Installation requires hand planting with attention to detail, including digging a broad and deep enough planting hole to accommodate roots without cramping, making a firm cone of soil in the hole, spreading the roots over the cone, positioning the plant at the same depth or slightly higher than it was grown in the nursery and backfilling firmly with a good growing medium. If circumstances dictate, create a trough or low soil berm around the planting hole to encourage retention of water. However, care should be taken to keep the trunk base dry. Irrigation is recommended during the first, and sometimes second, growing season following planting, but may not be needed if seasonal, natural precipitation or moist soil conditions are anticipated. If using mulch, avoid letting the mulch come in contact with the stem. As in the case of large, containerized plants, bare-root trees and shrubs planted through erosion-control fabric require that the fabric strands be cut, thereby weakening the fabric. For this reason, on particularly erosive sites, the advantages of bare-root stock over cuttings should be weighed against the potential for compromising fabric strength and integrity.

Planting Salvaged Materials

Heavy equipment such as a backhoe, excavator or tree spade is advised. While storage and/or transport of salvaged materials is possible, the increased handling, especially for woody materials, tends to increase cost and reduce survival rates. Salvage is best implemented when the following sequence can be followed:

1. prepare the planting site (including digging holes if needed);
2. salvage plants, remove the soil from around their roots and transport them in moistened burlap or plastic bags with moist (but not soggy) leaves or mulch packed around their roots; and
3. install the salvaged plants in moist soil immediately.

Minimizing transport of salvaged materials is key to their success and survival. Make sure the roots stay damp; they will dry out in seconds if exposed. If the plants will be stored before replanting, they can be transported and stored as ball-and-burlap plants. Transfer the plant from the ground with the dirt around its roots still intact onto a strip of burlap placed alongside the plant. Tie the burlap around the root ball with twine, keeping the dirt intact. To properly store the newly created ball-and-burlap plants, cover the root balls with moist mulch or sawdust. Following planting, irrigation is always advised, and pruning of woody stems and branches may help reduce drought stress.[4]

Dormant-season salvage is best (November through March), but if irrigation is available and the risk of somewhat lower survival is acceptable, salvage can take place even in dry or hot seasons. Salvaging plants is most successful if plants are collected and planted on wet, cloudy days so that roots are less likely to dry out.

Installing Ball-and-Burlap Plants

Nurseries that supply these types of trees and shrubs can provide excellent planting guidelines. Remember, the large size of the planting hole and the potential for guy wires to collect flood debris limit the application of this plant material type on streambanks. These problems may be less of a concern on floodplains.

Maintaining the Restoration Site

Where establishment of native vegetation is critical to the long-term stability of the bank, planting is just the beginning. A commitment needs to be made to maintain the site until the plants get established, generally considered to be a period of three years. Young trees and shrubs are very susceptible to drought, competition with other vegetation for moisture, light and nutrition, and browsing/trampling by livestock and wildlife. During the first three years following planting, inspect the area every few months (perhaps more during the dry season) to identify problems and implement repairs/modify management strategies, as needed.

If planting was done in a pasture or otherwise heavily vegetated site, vegetation surrounding the plant should be periodically removed or mown down to maintain the original three-foot-diameter open area surrounding each plant. Mowing twice a year during the first three growing seasons is generally recommended - once in the spring and once in midsummer. On sites where reed canary grass grows, a third mowing in the fall right down to the ground is sometimes recommended to reduce the amount of grass that comes back up the following spring. Consult your local or state noxious weed control board for more information concerning noxious-weed control and removal.

Livestock fences should be inspected and maintained to prevent livestock access to the planted area. Even small numbers of livestock or short-duration grazing can severely reduce plant survival. Although nonpalatable species may not be impacted by grazing, they are subject to other impacts such as trampling.[7] Temporary or permanent fences may also be needed in areas subject to heavy foot and pet traffic such as at parks.

Aluminum foil, arbor guards or plant protectors made of photobiodegradable plastic tubing may be needed to protect plants from being girdled by rodents, a common problem in pastures and meadows. Plastic-tube plant protectors offer the additional benefits of shielding plants from direct sun and wind exposure; they retain moisture, creating a humid microclimate, and they protect plants from mowers. Other types of barriers or repellents may be needed to protect plants from deer, elk and beaver during the plants' critical period of establishment. Planting species capable of stump sprouting or suckering from roots (identified in *Table H-6* by a "†") will reduce long-term grazing impacts.

Drought is a particular hazard to young plants due to their smaller tissue mass and less-developed root system. Plants that are not planted deeply enough to reach the zone of saturation will need to be watered regularly throughout the dry season until the fall rains. The need for watering will vary depending upon site conditions and the depth to which vegetation was planted. Watering heavily and infrequently, as opposed to frequent shallow watering, encourages deep root growth, which increases drought tolerance. In general, plants should be watered for at least the first growing season, and watering should only be stopped when the plants develop root systems capable of reaching a depth where the soils are permanently moist. This normally occurs by the end of the second growing season.[7]

EROSION-CONTROL FABRICS

This section of the appendix reviews erosion-control fabrics (also called rolled erosion-control products), including discussions on fabric types, selection considerations, costs and installation considerations. This section is applicable to several bank-protection techniques discussed in Chapter 6, *Techniques*, including *Soil Reinforcement, Woody Plantings, Herbaceous Plantings, Bank Reshaping,* and *Coir Logs*.

When to Use Erosion-Control Fabric

Erosion-control fabric should be used on bank-protection projects under the following conditions:

- where loose soils on a protected bank can be eroded during anticipated high flows;
- when shear stresses on banks at flows less than or equal to the design flow are between approximately 0.5 psf and 5.0 psf;
- where initially stable, but ultimately deformable bank-treatment techniques have been selected;
- when plant materials, such as seed and tubelings, need protection from the force of flowing water; or
- when performance thresholds of the selected fabric are not exceeded during design flows. (If thresholds are exceeded, other means of protection may be required.)

Fabric Types

For the purposes of this discussion, erosion-control fabrics are grouped into one of two broad categories, degradable or nondegradable. Degradable fabrics provide erosion protection for approximately one to five years and include biodegradable products made from natural fibers and photodegradable synthetic products. Nondegradable fabrics are typically made from synthetic materials and are resistant to decay for at least 10 years after installation.

Degradable Fabrics

In an order of increasing strength or resiliency, degradable fabric types include straw, jute, coir and a few types of synthetic fabrics. Straw and jute are excellent for uplands but are generally not resilient enough for streambanks and floodplains. Coir and, to a lesser extent, photodegradable synthetics fabrics are the most applicable for streambank-stabilization purposes.

Coir fabric is a relatively inexpensive fabric ($1.00 to $3.00 per square yard) made of coconut-husk fibers. It is available in either a blanket-like, nonwoven fabric or a stronger, longer-lasting woven type. *Nonwoven coir fabric* consists of fiber strands sandwiched between two thin layers of cotton, jute or photodegradable netting and lasts between one and two years in most climates, although the photodegradable netting has been observed to last up to five years.[8] *Woven coir fabric* is commonly used in streambank reconstruction because it is available in wide and long rolls (16' x 165' or 4m x 50m); it's strong, and it provides erosion protection for two to four years, depending upon site conditions. The biggest drawback of woven fabric is the open area between woven strands, which may allow loss of fine-textured soil particles. Where such loss may be detrimental to a project's success, such as when employing the *Soil Reinforcement* technique described in Chapter 6, woven fabric is often used as an outer layer over a nonwoven or finely woven inner fabric. A few suppliers have recently made available a degradable product that integrates both an inner, nonwoven layer and a stronger, woven layer. Such a fabric combines the best characteristics of both and is still relatively cost-effective ($2.50 to $3.50 per square yard).

Factors that directly affect the decay of degradable fabrics include ultraviolet radiation, microbial decay and physical abrasion. Even at a single site, the degree to which any one of these factors contributes to fabric decay varies substantially. Factors that may increase fabric longevity include constant inundation, dense vegetative cover and, in arid locations, burial under fine sediments. Fabric degradation rates may be increased by frequent wetting and drying, humid climates, scour from a mobile bedload or physical abrasion from foot traffic. Degradation rates of woven coir fabric are discussed in more detail in Miller, et al.[8]

A fundamental concept related to the use of degradable fabrics is that the fabric will provide initial, surface erosion protection; but, by the time fabric decays (one to five years, depending upon the product), vegetation will be sufficiently established to stabilize streambank soils. This relationship between fabric decay and plant establishment underscores the importance of selecting an appropriate fabric and the necessity of an aggressive revegetation plan.

Nondegradable Fabrics

Nondegradable fabrics, by nature of their synthetic materials, are often considered less desirable along natural streambanks than degradable fabrics. In addition, nondegradable fabrics can be more expensive and harder to work with than degradable fabrics. Yet, they are a cost-effective substitute for "hard" bank-protection measures such as riprap, and they are generally very compatible with plantings. Common types include:

- two-dimensional biaxial grid ($2 to $3 /yd^2): strong and inexpensive, but requires the use of inner fabric to prevent loss of fines through the fabric openings. The Natural Resources Conservation Service uses this material in its soil reinforcement system.[9]
- two-dimensional blankets: comprised of synthetic fibers bound between synthetic netting ($3 to $5 /yd^2). Not widely used on streambanks.
- three-dimensional, multilayered woven fabric ($7 to $8 /yd^2): a high-performance fabric with a pyramid-like matrix. Expense limits its use.
- composite fabric with three-dimensional, synthetic-fabric matrix integrated with nonwoven coir ($3 to $5 /yd^2): a relatively cost-effective, high-performance fabric that works well on streambanks.

Selection of Fabric Types

The first choice in fabric selection is between degradable and nondegradable types. Usually this is based on design criteria for deformable vs. nondeformable protection and fabric performance relative to a range of bank shear stresses at a site (see *Table H-5*). Guidelines and sources that can help determine the appropriate fabric are listed below:

- As a very general and conservative guideline, shear stresses greater than one to two psf require nondegradable synthetic fabrics.
- Manufacturers provide performance data for their products. However, consider that some fabric-securing methods may have a lower erosion resistance than the fabric itself. Also, information provided by different suppliers may be reported in different units or result from different types of tests. Generally, manufacturer-reported performance data is liberal and not necessarily legitimate in application.
- Although not a direct indicator of field performance, comparisons of manufacturer-provided "wet" or "dry" tensile strength (commonly reported as test ASTM-4595) is a good measure of absolute fabric strength at the time of installation. Tensile strength of degradable fabrics deteriorates rapidly under many site conditions.
- The Texas Department of Transportation has a website, www.dot.state.tx.us/insdtdot/orgchart/cmd/erosion/sect2.htm,[10] that compares soil loss from different fabrics under a range of flows (with specified shear stress values) based on data collected in an outdoor flume. This source also provides comparative data on vegetation growth in different fabrics.

Fabric Type	Roll Dimension	Tensile Strength lb./in. (dry)	Permissible Velocity (ft./sec.)	Permissible Shear (ft./sec.)	Comments
Degradable, Nonwoven Coir	6-8 x 60-90 ft.	80 x 60	6	0.50	Available with stronger, photodegradable netting.
Degradable, 700 g/m^2 Woven Coir	2,3 or 4 x 50m	120 x 80	14	1 to 2	Specify seamless fabric in 3m, 4m widths.
Nondegradable, 2-D Synthetic Blanket	7 x 90 ft.	220 x 145	20	5.5	Specify seamless fabric in 3m, 4m widths.
Nondegradable, 2-D Biaxial Grid	8 x 60 ft.	n/a	-	n/a	Requires inner fabric to prevent loss of fine soil.
Nondegradable, 3-D Synthetic Matrix	8 x 90 ft.	260 x 180	25	10	May limit planting of most woody plant materials.
Nondegradable, 3-D Synthetic/Coir	6.5 x 55 ft.	n/a	n/a	2.25 to 8	May be the ideal synthetic fabric for streams.

Table H-5. Fabric specifications and typical costs.

Other factors that guide fabric selection include cost, risk of failure and available fabric-roll dimensions. In some cases, a project stakeholder may prefer that no synthetic fabrics or staking materials be used on a particular site, in which case degradable fabrics or a more resilient, nonfabric-based treatment will be required. Actual field experience with a variety of fabrics will also dictate fabric preferences; some are easier to handle, while others are more difficult to plant or stake through. One important detail in fabric selection is to ensure the product has no seams; this is especially true for three- or four-meter-wide coir fabrics.

Fabric-Installation Guidelines

Although many manufacturers provide installation guidelines, these should be viewed with caution, as they may not be suitable for the intended use. To that end, some important concepts related to fabric installation and layout are discussed below. *Figure H-2* (located at the end of this appendix) shows typical fabric installation details.

Fabric Orientation

Fabric can be placed in a variety of configurations relative to the streambank, including placing roll lengths parallel, perpendicular or at an angle to the direction of the stream flow. General guidelines for fabric orientation exist, but a range of options should be considered during the design phase to ensure that the most easily constructed, cost-effective and resilient layout of fabric is used.

Staking

Numerous types of stakes are commonly used to secure fabrics. Metal stakes of any sort, including six- to eight-inch metal "U" staples and more hefty rebar stakes (often with one end bent into an "L" or "U" shape to fasten fabric securely to the ground) seem incompatible with the concept of degradable, erosion-control fabrics, although they may be appropriate where synthetic fabrics are used. A variety of commercially developed, biodegradable pegs and stakes are available as alternatives. Wooden stakes, often stocked by local lumberyards, may also be appropriate in some instances; however, they may not secure fabric tightly to the ground, and the fabric might easily lift off of straight stakes.

An excellent and more resilient alternative to all of these is 18- to 24-inch-long, wedge-shaped stakes made by cutting 2 x 4s diagonally. Narrow enough at the base to fit through woven coir fabric strands and wider at the top, these stakes pull fabric tightly as they are driven deeper, drastically reducing the chance of fabric lifting off the top. Once buried in a trench, the chance of stake pullout is slim, and the strength of the staking system will equal or exceed the strength of the fabric, provided they are spaced on three-foot or smaller intervals.

Deeply driven live willow stakes are sometimes used to make up a portion of the stakes needed to secure the fabric. Prior to root and shoot development, live stakes have the same disadvantages of wooden stakes in that, being straight rather than tapered, fabric may not be tightly secured to the ground and can easily lift off depending on how far they protrude from the ground. However, once established, the roots and shoots of the plant will secure the fabric better than wedge-shaped stakes. As growth is not guaranteed, live stakes are generally uniformly dispersed among other types of stakes and make up no more than one third of the required number of stakes used to secure the fabric.

Trenching

A fundamental component of erosion-control-fabric installation in difficult sites is to use trenching and buried staking to secure fabric edges. When using fabric up to three meters wide, sufficient tension can often be achieved without the need for surface stakes on the exposed fabric surface by staking all fabric edges in trenches. Trenching, especially on the upstream edges of fabric, also provides the benefit of burying the leading edge, which is a critical interface. Fabric edges parallel to flow may also be trenched in a variety of configurations for maximum erosion protection. A trench should be a minimum of six inches deep, then backfilled with common fill or topsoil, compacted and seeded.

Fabric Overlap

Another concept in fabric placement that must be carefully evaluated is the overlapping of fabric edges. It is often sufficient to simply "shingle" an upstream fabric edge over a downstream one and stake as needed. However, for extra reinforcement, it may be better to bury and stake the upstream edges of downstream fabric rolls in a key trench, then backfill the trench and place the downstream edge of the upstream fabric roll over the trench. A similar technique may be applied to edges parallel to stream flow.

Transitions

A potential weak point of any fabric-based streambank treatment is the transition between adjacent bank-treatment types, treated and untreated areas, or between fabric edges and existing infrastructure, such as bridges and culverts. If adequately designed and installed, transitions should not be a problem, but they will require that special consideration be paid to the orientation of fabric rolls and construction sequencing.

Construction Oversight

Even the best of designs will fail if not properly installed. Minor lapses in attention by installation workers or supervisors can lead to improper fabric tension, poor staking techniques and the overlapping of fabric edges in the wrong direction. Any of these conditions can lead to increased fabric vulnerability during high flow events.

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Trees					A	B	C	D	E			
Grand fir	Abies grandis	NOL	100-250	l-h	•	•	•			sn-pt sh	deep taproot; many lateral branches	best conifer for soil-binding roots; prefers deep, well-drained, alluvial soils; seedlings are shade tolerant; drought tolerant
Noble fir	Abies procera	NOL	90-250	m-h	•	•	•			sn		
Douglas maple	Acer glabrum var. douglasii	FACU†	10-25	l-m	•	•	•			sn-pt sh	deep lateral	found along canyons, rocky cliffs, forest openings on mountain slopes, moist but well-drained streambanks, floodplains, avalanche tracks; requires well-drained soils
Big-leaf maple	Acer macrophyllum	FACU †	80-100	l	•	•	•			sn-pt sh	deep, wide	good soil-binding properties; grows in a variety of soils but seldom in saturated soil; fast growing; flood tolerant
Red alder	Alnus rubra	FAC †	40-80	l-m		•	•	•		sn-pt sh	shallow, strong, lateral, spreading, fibrous	does well on disturbed sites in a variety of soils; fast grower; high survival from pull-ups"; tolerates drought, flooding, or brackish conditions; relatively short-lived (60-70yr); subject to windthrow, broken crowns, ice damage; west of Cascades only
Sitka alder/ Slide alder	Alnus sinuata	FACW †	25	m-h			•	•		sn-pt sh		moderate flood and deposition tolerance; does well on disturbed sites and alluvial floodplains in rocky or gravelly soil; prefers some shade or north-facing aspect
Pacific madrone	Arbutus menziesii	NOL	50-90	l-	•	•				sn	deep tap root, wide, tenacious	evergreen; drought and salt-spray tolerant; sensitive to air pollution; found along coast on rocky sites or coarse-textured soils; slow grower; west of Cascades only
Water birch	Betula occidentalis	FACW	20-50	l-m			•	•		sn-pt sh	shallow to deep, spreading	moderate flood and deposition tolerance; east of Cascades only

Table H-6: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	**Scientific Name**											
Trees					**A**	**B**	**C**	**D**	**E**			
Paper birch	Betula papyrifera	FACU	60-70	l-m	•	•	•			sn-pt sh	deep	fast growing; prefers sandy loam but tolerates poorly drained soils; tolerates periodic flooding and drought, acid soils; does well on disturbed sites
Pacific dogwood	Cornus nuttallii	NOL	10-65	l-	•	•	•			pt sh-sh		prefers deep, well-drained soils high in nitrogen; found in open to fairly dense mixed forests; west of Cascades only
Oregon ash	Fraxinus latifolia	FACW	60-80	l-			•	•	•	sn-pt sh		prefers flat, loamy soil; tolerates standing water early in growing season; west of Cascades only
Western crabapple	Malus fusca	FAC+ †	15-40	l-		•	•	•		sn-pt sh	shallow, spreading	forms dense thickets; does well in a variety of soils and near salt water, sloughs and estuaries; prefers acid soils; tolerant of prolonged soil saturation; west of Cascades only
Sitka spruce	Picea sitchensis	FAC	100-230	l		•	•	•		sn-pt sh	shallow-moderate, dense	tolerates flooding; found on alluvial floodplains, marine terraces, recent glacial outwash, avalanche tracks and old logs or mounds in boggy sites; subject to blowdown in areas of high water table; west of Cascades only
Lodgepole pine	Pinus contorta var. latifolia	FAC-	100- 120	m-h	•	•	•	•		sn		widespread range from bogs to dry mountain slopes; not coastal
Shore pine	Pinus contorta var. contorta	FAC-	45-60	l-m	•	•	•	•		sn	deep, wide	highly adaptable; found in dunes and bogs to rocky hilltops and exposed outer shorelines; coastal; tolerates salt and low-nutrient soils
Ponderosa pine	Pinus ponderosa	FACU-	150-200	l-m	•	•				sn		dry, gravelly soils; drought tolerant once established; mainly east of Cascades

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name				A	B	C	D	E			
Trees												
*Black cottonwood	Populus trichocarpa	FAC †	100-200	l-m		•	•	•		sn	fibrous, shallow-deep and widespread, extensive	fast grower; susceptible to root rot, windthrow; tolerates seasonal flooding; grows well in a variety of soils
Quaking aspen	Populus tremuloides	FAC+	30-80	l-h		•	•	•		sn	shallow, extensive, invasive, spreading roots send up shoots	forms dense groves; moderate drought and salinity tolerance; fast growing; prefers sandy loams
Bitter cherry	Prunus emarginata	FACU	40-60	l-m	•	•	•			sn	spreading; root system sprouts new growth	prefers well-drained slightly alkaline soils; establishes easily on disturbed sites; can form thickets; may be poisonous to livestock
Douglas fir	Pseudotsuga menziesii	NOL	75-300	l-m	•	•	•			sn-pt sh	tap-modified tap; shallow-deep and widespread	good soil-binding roots; fast grower; needs good drainage; does best in deep, moist, sandy loams; poorest in gravelly soils; potential for windthrow in thin or disturbed soils
Oregon white oak	Quercus garryana	NOL	75	l-	•	•	•			sn	deep tap root	typically found on gravelly outwash prairies and floodplains; slow growing
Cascara	Rhamnus purshiana	FAC-	25-35	l-		•	•	•		sn-sh	moderately deep tap root	good soil-binding qualities; grows well on disturbed sites; prefers loamy soils, shaded southern aspects and swampy clearings; sensitive to air pollution
*Peachleaf willow	Salix amygdaloides	FACW		l-			•	•	•	sn	fibrous	deposition and flood tolerant; moderate salinity tolerance; found on streambanks in plains and foothills; east of Cascades only
*Pacific willow	Salix lasiandra	FACW+ †	20-40	l-m			•	•	•	sn	fibrous, moderately deep and widespread	flood and deposition tolerant; grows well on sandy, gravelly, or loamy soils; found on riverbanks, floodplains, lakeshores, wet meadows; often standing in quiet, shallow river backwaters; generally found in pure stands

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Trees					A	B	C	D	E			
*Scouler willow	Salix scouleriana	FAC †	10-40	l-m		•	•	•		sn-pt sh	fibrous, moderately deep and widespread	flood, drought and deposition tolerant; moderate salinity tolerance; prefers gravelly soil; does not grow in standing water
Pacific yew	Taxus brevifolia	FACU-	15-45	l-h	•	•	•			pt sh-sh	deep	very slow growing; prefers loamy soils under canopy of large trees; foliage is poisonous to cattle and horses
Western red cedar	Thuja plicata	FAC	150-210	l-m		•	•	•		sn-sh	shallow, widely spreading	tolerates seasonal flooding and perennially-saturated soils; seedlings require some shade; tends to be wind-firm except in very wet sites; prefers loamy soils
Western hemlock	Tsuga heterophylla	FACU-	120-180	l-m		•	•			sn-sh	shallow-moderate	does best on deep, moist, well-drained soils; requires high organic content in soil; thrives in dense shade; seedlings are often dried out by full sun; susceptible to windthrow
Shrubs/ Groundcover												
Vine maple	Acer circinatum	FACU+ †	15-25	l-m	•	•	•	•		sn-sh	fibrous, moderately deep, spreading	needs canopy shade or lots of moisture; excellent soil-binding qualities; prefers sandy loam; mostly west of Cascades
Serviceberry	Amelanchier alnifolia	FACU	6-25	l-h	•	•	•			sn-pt sh	deep, spreading	edge-loving; very drought tolerant; thicket forming; prefers loamy soils but found on dry gravelly and rocky sites, rich to poor soils, moderately acid to alkaline soils; good stabilization value
Kinnikinnik	Arctostaphylos uva-ursi	FACU-	1	l-h	•	•	•			sn	fibrous, shallow, dense, extensive, highly branched	slow grower; evergreen; likes dry stony soil; tolerates salt spray; prefers slightly acidic soil
Tall Oregon grape	Berberis aquifolium	NOL	3-10	l-	•	•				sn-pt sh	deep	slow grower; thicket forming; grows in variety of soils; found in drier (often rocky) sites than B. nervosa; evergreen

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					A	B	C	D	E			
Low Oregon grape	Berberis nervosa	NOL †	2	l-m	•	•				pt sh-sh		slow grower; thicket forming; good on slopes; grows in a variety of soils; evergreen; west of Cascades only
*Red-osier dogwood	Cornus stolonifera	FACW †	6-20	l-m			•	•	•	sn-sh	shallow, strong, lateral, fibrous	excellent soil-binding qualities; thicket forming; grows in a variety of soils; takes full sun if has lots of moisture; tolerates seasonal flooding
Hazelnut	Corylus cornuta	NI †	5-20	l		•	•	•		sn-pt sh	extensive, branching	grows well in a variety of soils but intolerant of saturated soil
Black hawthorn	Crataegus douglasii	FAC †	3-20	l		•	•	•		sn	shallow to deep, spreading	excellent soil and streambank stabilizer; moderate deposition tolerance; thicket forming; well adapted to disturbed sites; prefers deep loamy soils; resistant to beaver; not favored by deer/elk
Salal	Gaultheria shallon	NOL †	3-15	l-m	•	•				sn-sh	fibrous, shallow, dense	slow to establish; grows in a variety of soils but prefers shade and rich soil; tolerates salt spray, low nutrient soils; good soil binding qualities; thicket forming
Ocean spray	Holodiscus discolor	NOL †	6-15	l	•	•				sn-pt sh	fibrous, moderate depth, spreading	found on open sites (woods, thickets, clearings, logged areas, ravine edges, coastal bluffs, steep slopes); grows well on disturbed sites in a variety of soils including gravelly and rocky soils
Trumpet honeysuckle	Lonicera ciliosa	NOL	vine	l-	•	•				sn-pt sh	shallow to moderate	
*Black twinberry	Lonicera involucrata	FAC †	3-15	l-		•	•	•		sn-sh	fibrous, shallow, spreading	takes full sun if has lots of moisture; tolerant of shallow flooding early in growing season; prefers loamy soils; fast growing; good soil-binding characteristics

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					A	B	C	D	E			
Mock azalea	Menziesia ferruginea	FACU+	2-7	m-		•	•			pt sh-sh		found in moist conifer woods with acid humus, slopes and streambanks, edges of coastal sphagnum bogs
Sweetgale	Myrica gale	OBL	2-7	l-				•	•	sn		found in freshwater wetlands, bogs and lakes, upper fringes of salt marshes and tidal flats; thicket forming
Indian plum	Oemleria cerasiformis	NOL †	5-15	l-	•	•	•			sn-sh	fibrous, shallow, spreading	prefers shade; grows well in a variety of soils: west of Cascades only
Oregon boxwood	Pachystima myrsinites	NOL	1-3	l-m	•	•	•			sn-sh		found on shallow, gravelly clay and silt loam; prefers light to deep shade, moist atmosphere; evergreen
Mock orange	Philadelphus lewisii	NOL	3-12	l-h		•	•	•		sn-pt sh	spreading, fibrous	fast vigorous grower; grows well in loamy to rocky, poor soils
*Pacific ninebark	Physocarpus capitatus	FAC+ †	6-13	l-m		•	•	•		sn-pt sh	fibrous, shallow, lateral	needs good drainage; excellent soil binding qualities; grows well in a variety of soils; mostly west of Cascades
*Mallow ninebark	Physocarpus malvaceous	NOL	2-6	l-m	•	•				sn		tough, tenacious shrub; prefers sandy to silty clay loam, dry canyon bottoms, rocky slopes; thicket forming; east of Cascades only
Choke cherry	Prunus virginiana	FACU	10-20	l-	•	•	•			sn-pt sh		moderate salinity and drought tolerance; tolerates slightly saline soil; good soil-binding characteristics; forms dense stands
Sumac	Rhus glabra	NOL	3-20	l-	•	•				sn		forms loose thicket; east of Cascades only
Golden currant	Ribes aureum	FAC+	6	l-	•	•	•			sn-pt sh	spreading	east of Cascades only
Squaw currant	Ribes cereum	FAC	2-4	l-	•	•	•			sn-pt sh		east of Cascades only

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					A	B	C	D	E			
Black gooseberry/ Swamp gooseberry	Ribes lacustre	FAC+ †	2-7	l-h		•	•	•		pt sh-sh		drought tolerant; grows in a variety of soils but prefers loamy soils; often grows on rotting wood and spring seepage sites that become dry in late summer; NOTE: is alternate host for White Pine Blister Rust may not be an issue if it s naturally abundant in area
Red-flowering currant	Ribes sanguineum	NOL	5-10	l-	•	•				sn-pt sh	fibrous, shallow	prefers loamy soils; found on rocky slopes, disturbed sites and dry open woods
Wood rose/ Baldhip rose	Rosa gymnocarpa	FACU	2-6	l-m	•	•	•			pt sh		tough, hardy; extremely drought tolerant; prefers rocky soils; excellent soil-binding characteristics
*Nootka Rose	Rosa nutkana	FAC- †	2-10	l-		•	•	•		sn-pt sh	fibrous, shallow	rapid volunteer on damp soil; thicket forming; tolerates salt spray, saturated soils, or inundation for much of the growing season; excellent soil-binding characteristics; prefers nitrogen-rich, loamy soils
Clustered Rose/ Swamp Rose	Rosa piscocarpa	FACU †	6	l-	•	•	•			sn-pt sh		tolerates infertile soils; prefers loamy soils; excellent soil binding characteristics; west of Cascades only
Wood s Rose/ Prairie Rose	Rosa woodsii	FACU †	6	l-m	•	•	•			sn-pt sh		prefers moist, well-drained clay loam, sandy loam, or sandy soil; thicket forming; east of Cascades only
Thimbleberry	Rubus parviflorus	FACU+ †	2-10	l-h	•	•	•			sn-pt sh	fibrous, shallow	found along road edges, clearings, avalanche tracks and shorelines, or under light forest canopy; drought tolerant; intolerant of saturated soils; good soil-binding qualities; thicket forming; prefers sandy loam rich in humus

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					A	B	C	D	E			
*Salmonberry	Rubus spectabilis	FAC †	6-15	l-m		•	•	•		sn-sh	fibrous, shallow	well-adapted to eroded or disturbed sites; takes full sun if lots of moisture; spreads rapidly; dense thickets can inhibit native tree establishment; mostly west of Cascades
*Under-green willow	Salix commutata	OBL †	8	m-h				•	•	sn		edges of rivers, lakes, wetlands, gravelly benches, fresh alluvial and morainal materials, open forests
*Drummond willow	Salix drummondiana	FACW †	12	l-h			•	•	•	sn	shallow to deep	east of Cascades only
*Coyote willow	Salix exigua	OBL †	10	l-m				•	•	sn	shallow, widespread	colonizes coarse gravel and bar islands; usually grows partly submerged; thicket forming; east of Cascades only
*Columbia R. willow	Salix fluviatilis	OBL †	13	l				•	•	sn		prefers sand, gravel, or silt; banks of Columbia River only
*Geyer willow	Salix geyeriana	FACW+ †	15	l-h			•	•	•	sn	shallow to deep	likes inundation, sluggish water, wet meadows; deposition tolerant
*Hooker s willow	Salix hookeriana	FACW -†	20-30	l-			•	•	•	sn	fibrous, moderately deep	naturally found <5mi from coast; salt-spray tolerant; sandy, gravelly or loamy soils
*Arroyo willow	Salix lasiolepis	FACW †	35	l			•	•	•	sn	shallow to deep	flood and deposition tolerant; prefers coarse textured soils; east of Cascades only
*Heart-leaf willow	Salix rigida	OBL †	12	l-m				•	•	sn		generally uncommon, except on gravel and sandbars along major rivers
*Sitka willow	Salix sitchensis	FACW	3-26	l-m			•	•	•	sn	fibrous, moderately deep and widespread	tolerates seasonal flooding; prefers sandy or loamy soils; found in clearings, avalanche tracks, on edges of streams, lakes, wetlands, moist forests

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					**A**	**B**	**C**	**D**	**E**			
*Blue elderberry	Sambucus caerulea	FAC-	20	l	•	•	•			sn-pt sh		good soil-binding qualities; grows well in a variety of soils; moderate salinity tolerance; favors moist soils of valley bottoms and sunny open slopes; in arid areas, restricted to streambanks and river bottoms
*Red elderberry	Sambucus racemosa	FACU †	6-20	l-m	•	•	•			sn-pt sh	fibrous; strong, adventitious roots; spreading; moderate	rapid grower; grows well on disturbed sites in a variety of soils; found on streambanks, swampy thickets, moist clearings, open woods; moderate salinity tolerance
Cascade mountain ash	Sorbus scopulina	NI	20	m-h	•	•				sn		
Sitka mountain ash	Sorbus sitchensis	NOL	12-20	m-h	•	•	•			sn		found on streambanks, forest openings, edges of meadows or rock slides; prefers rich well-drained soils
*Douglas spirea	Spiraea douglasii	FACW †	3-6	l-h			•	•	•	sn	extensive, fibrous, shallow	forms dense thickets; spreads quickly and aggressively; tolerates seasonal inundation; prefers loamy soils
Creeping snowberry	Symphoricarpos mollis	NOL †	1.5	l-m	•	•				pt sh	extensive, branching, fibrous	forms dense thickets
Snowberry	Symphoricarpos albus	FACU †	2-6	l-m	•	•	•			sn-pt sh	extensive, branching, fibrous, shallow	forms dense thickets; tolerates high winds, some flooding while dormant; excellent soil-binding characteristics; prefers loamy soils
Oval-leaf huckleberry	Vaccinium ovalifolium	UPL	2-6	l-m	•	•				pt sh-sh		prefers loamy acid soils; found in bogs, moist coniferous forests
Evergreen huckleberry	Vaccinium ovatum	NOL	2-15	l-m	•	•				pt sh-sh	fibrous, shallow	slow growing; tolerates salt spray; prefers mature shade, slightly acidic rocky or gravelly soils; evergreen; coastal
Wild cranberry	Vaccinium oxycoccos	OBL	1	l-m				•	•	pt sh		boggy sites; vine-like; evergreen

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

Species		Indicator Status (1)	Maximum Height (2) (ft)	Elevation Range (3)	Plant Associations (4)					Light Req (5)	Rooting Character (6)	Comments
Common Name	Scientific Name											
Shrubs/ Groundcover					A	B	C	D	E			
Red huckleberry	Vaccinium parvifolium	NOL	3-13	l	•	•				pt sh-sh	moderate	prefers loamy, acid soils or rotting wood; requires lots of organic matter; west of Cascades only
Highbush cranberry	Viburnum edule	FACW	2-12	l-m			•	•	•	sn-pt sh		found in moist woods, wetland margins, streambanks, river terraces
Oregon viburnum	Viburnum ellipticum	NOL	10		•	•	•			sn-pt sh		found in thickets and open woods; west of Cascades only
Wild guelder rose	Viburnum opulus	NOL	10			•	•	•		sn-sh	strong adventitious roots	found in moist woods

Table H-6 CONTINUED: Woody species recommended for revegetation of riparian corridors.[11]

FOOTNOTES for Table H-6

* Indicates plant propagates well from hardwood cuttings planted directly in the field.[2,3]

(1) Indicator Status = plant indicator status (UPL, FAC, etc., see below) From U.S. Department of the Interior, Fish and Wildlife Service.[12] A positive (+) sign, when used with indicators, means "slightly more frequently found in wetlands" and a negative (-) sign, when used with indicators, means "slightly less frequently found in wetlands." Species marked (†) indicate trees and shrubs tolerant of severe pruning (or grazing); these either stump sprout readily or form suckers from roots.

- UPL — Obligate Upland: occurring almost exclusively in nonwetland environments.
- FACU — Facultative Upland: occurring primarily in nonwetland environments, but occasionally found in wetlands.
- FAC — Facultative: occurring with approximately equal frequencies in wetlands and nonwetlands.
- FACW — Facultative Wetland: occurring primarily in wetland environments, but occasionally found in non-wetlands.
- OBL — Obligate Wetland: occurring almost exclusively in wetland environments.
- NI — No Indicator: there was insufficient data available to determine an indicator status.
- NOL — Not on List: species does not occur in wetlands anywhere in the United States. Therefore, it is not included in the National List of Plant Species that Occur in Wetlands.[12]

(2) Maximum Height: the approximate height (feet) to which plants will grow under natural conditions with sufficient time. Mature height or the size at which plants begin to flower and produce seeds is substantially less in many species.

(3) Elevation Range: the elevations where the species commonly occurs. l=low, sea level to 2500 feet; m=med, 2500 to 4500 feet; h=high, above 4500 feet. All elevations are variable depending on microclimates. Where information is incomplete, refer directly to the source.

(4) Plant Associations: planting suggestions for different soil. Information from the King County soil survey[13] and indicator status.[12] Nomenclature follows Flora of the Pacific Northwest[14] and National List of Plant Species that Occur in Wetlands.[12] Plant associations recommended for various soil moisture levels:

A. Very Droughty Soils: use UPL and FACU species. These conditions may be expected in porous or well-drained (sandy) soils or high on the bank, especially on south or west facing banks with little shade.

B. Droughty Soils: use mostly UPL and FACU species; FAC species may be used occasionally if site conditions are somewhat moist. These soils occur in areas similar to very droughty soil, but where moisture retention is better (e.g., less sandy soils, shade and north- or east-facing banks).

C. Moderate Soils: use FACU, FAC and FACW species. Much of western Washington has these soils. They are loamy soils with some clay, on level areas to steep slopes. They may be shallow soils over hardpan or areas where seeps are common. Plant selection should consider microcli matic conditions including seeps, slope, aspect, etc. Steeper slopes, for example, will be drier than moderate soils because of water run off.

D. Wet Soils: use mostly FAC and FACW species; OBL species can be used in particularly wet areas as long as the soil is not compacted. They retain water rather than allowing it to run off after rain and are moist to wet for most of all of the year. Because these areas have minimal slope and typically slow-moving streams, erosion is seldom a problem.

E. Very Wet Soils: use FACW and OBL species. These soils can be found along meandering rivers and streams with low banks. There is typically a high water table that allows the development of organic soils (peats and mucks). They are not well suited to large woody vegetation, as trees tend to blow over. Dense thickets of shrubs and small trees are common. Because these areas have minimal slope and typically slow-moving streams, erosion is seldom a problem.

(5) Light Requirement: sn = full sun, pt sh = part shade, sh = full shade.

(6) Rooting Character: "Fibrous" indicates that plant lacks a central root; root mass is composed of fibrous lateral roots. "Tap" indicates that plant has a stout, central main root. "Shallow," "moderate" and "deep" refer to relative rooting depth. Note that depth and character of roots are determined by soil conditions as well as species characteristics.

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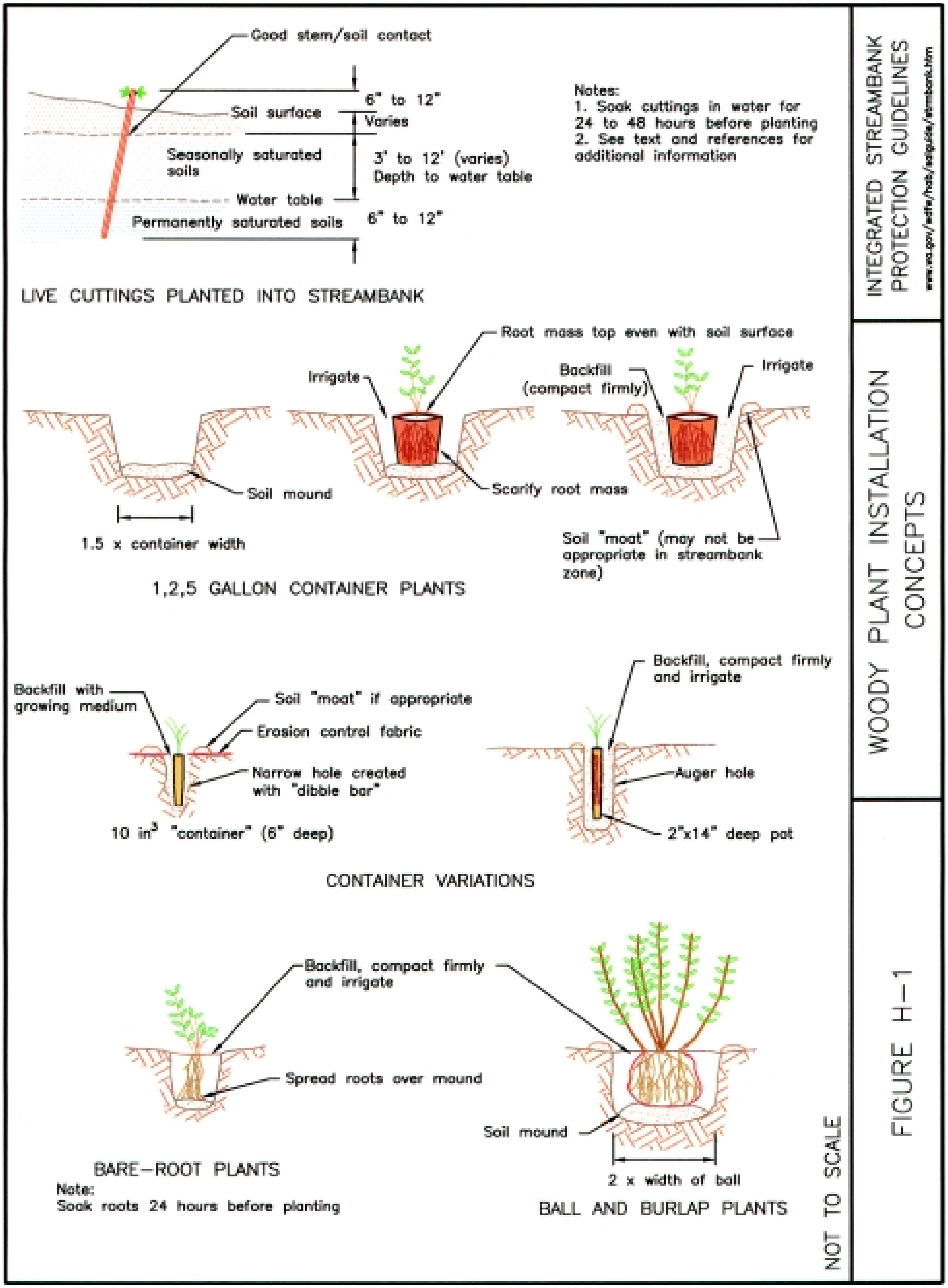
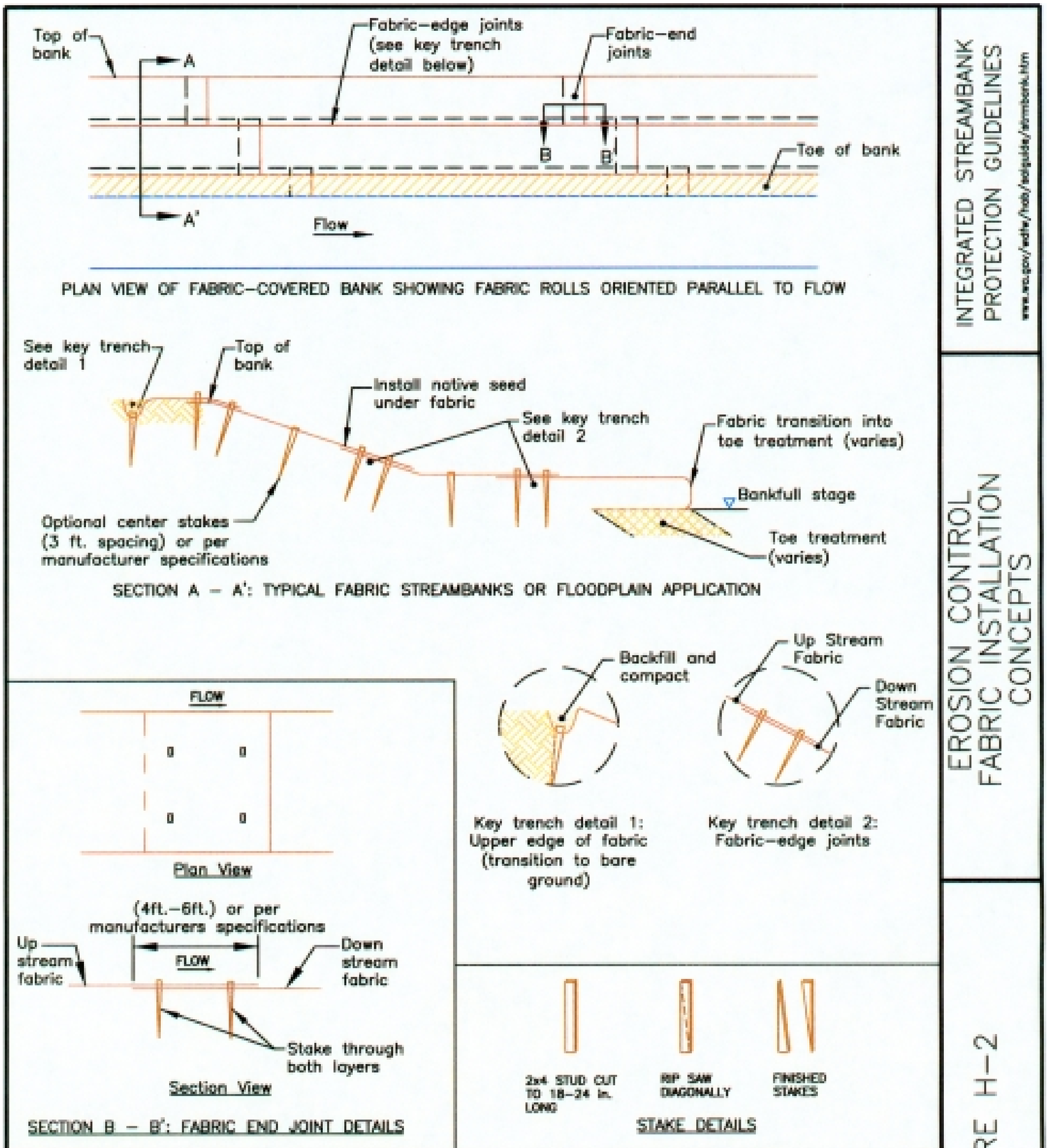


Good stem/soil contact
Soil surface
6" to 12"
Varies
Seasonally saturated soils
3' to 12' (varies)
Depth to water table
Water table
Permanently saturated soils
6" to 12"
Notes:
1. Soak cuttings in water for 24 to 48 hours before planting
2. See text and references for additional information
LIVE CUTTINGS PLANTED INTO STREAMBANK
Root mass top even with soil surface
Irrigate
Backfill (compact firmly)
Irrigate
Soil mound
Scarify root mass
1.5 x container width
Soil "moat" (may not be appropriate in streambank zone)
1,2,5 GALLON CONTAINER PLANTS
Backfill, compact firmly and irrigate
Backfill with growing medium
Soil "moat" if appropriate
Erosion control fabric
Narrow hole created with "dibble bar"
Auger hole
10 in³ "container" (6" deep)
2"x14" deep pot
CONTAINER VARIATIONS
Backfill, compact firmly and irrigate
Spread roots over mound
Soil mound
BARE-ROOT PLANTS
Note:
Soak roots 24 hours before planting
2 x width of ball
BALL AND BURLAP PLANTS
NOT TO SCALE
INTEGRATED STREAMBANK PROTECTION GUIDELINES
WOODY PLANT INSTALLATION CONCEPTS
FIGURE H-1



Notes:

1. Do not place fabric below elevation that supports growth of perennial vegetation, except if used in a deformable toe design.
2. As shown in key trench details, secure the fabric-edge joints with wooden stakes on 3 foot centers. Staked fabric must be taut and firmly covering soil. When staking fabric allow the stake to break the minimum number of strands. Drive stakes so that a maximum of 2 inches is left exposed.
3. Join fabric ends by lapping the upstream piece of fabric over the downstream piece as shown in section B–B'. Overlaps should be staggered from lift to lift a minimum of 15 feet.
4. Consult manufacturer for specific installation guidelines.

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Appendix I

Anchoring and Placement of Large Woody Debris

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Appendix I

Anchoring and Placement of Large Woody Debris

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

The use of large woody debris can play a crucial role when used by itself, but also when used in concert with or incorporated into other techniques. Large woody debris can enhance the effectiveness of bank-protection treatments while mitigating the treatments' negative effects on fish habitat. The use of rock and other bank-hardening materials in streambank-protection projects often results in the loss of fish habitat. Rock revetments create smooth banks, resulting in high near-bank velocities, loss of cover and a reduction in structural and hydraulic complexity. Structural complexity and hydraulic complexity created by large woody debris are important components of good fish habitat. It has been found that fish use increases when large woody debris is included in rock revetment projects.[1] Placement of large woody debris is, therefore, considered an ideal form of mitigation. As an added benefit, some sites have shown that wood added for habitat restoration performs a bank-protection function as well. Downstream velocities are decreased and energy is dissipated in the form of turbulence around the large woody debris, encouraging deposition and reducing near-bank scour, while enhancing complex rearing and holding habitat for salmonids at low and high flows.

Properly placed and anchored large woody debris, when used as part of a bank-protection treatment, can assist in providing reliable bank protection as well as enhance the structural and hydraulic complexity of the channel. In contrast, poorly placed or improperly anchored large woody debris has a high probability of becoming dislodged under high flows, resulting in a failure of the project objectives and potential impacts to downstream infrastructure. Large wood should be placed in locations and configurations where it could be expected to occur naturally to increase its reliability in providing fish and wildlife habitat.

APPLICATION

Large woody debris is used in streambank-protection treatments for three primary reasons:

1. to assist in providing bank protection,
2. to enhance fish habitat, and
3. to accelerate floodplain and riparian structure in recovering alluvial channels.

Large woody debris can be keyed into the streambank, partially embedded into the channel, pieced together to form channel-spanning, midchannel or lateral jams in large rivers, and placed in floodplains to provide roughness in channels that are laterally migrating following incision. Depending upon the size of the large woody debris relative to the channel, its placement may constrict the channel by creating roughness, blocking a portion of the channel and potentially aggrade upstream channel segments. The energy dissipation associated with large woody debris creates a scour pool in erodible bed material, which in turn creates cover habitat. Scour-pool characteristics are somewhat predictable and are influenced by the shape, size and orientation of large woody debris. Large wood on floodplains provides high-flow refuge habitat for salmonids. Floodplain wood also enhances fine-sediment deposition required to establish riparian vegetation on new bar forms in alluvial streams.

There are many ways to configure large wood to accomplish a variety of objectives. When applying wood to any situation, a good understanding of the site's hydrology, hydraulics and geomorphology is important. The ability to obtain and match the wood size with the objectives and stream power are key to a successful project using large wood. In larger streams, it can be difficult to collect the size of wood needed to naturally function and accomplish habitat goals and objectives. It is possible to overcome this using smaller, undersized wood that is creatively pieced together and secured to emulate the geomorphic and hydraulic influence that a larger, old-growth piece could have in a given location. In these situations, effective placement must consider stability, function, longevity, risk and safety.

The natural effectiveness of large woody debris is largely dependent on channel type. Some streams are too steep, too confined or have too high a bedload volume to respond to the placement of large woody debris. Some streams and stream reaches have a naturally smaller large-wood influence than others. The ability of the adjacent riparian areas to grow trees that can influence channel morphology when delivered to the stream plays a key role in where large wood will most likely create habitat in a given watershed. This not only changes between watersheds but is also a continuum as one moves from the top to the bottom of individual watersheds. Geology and watershed scale processes sort and establish different roles for wood, depending upon wood size and location in the watershed. For example, a large tree branch that collects gravel in a headwater tributary would be part of the debris floating down and captured by a log jam further downstream. Understanding the basic processes and geography of wood location within individual watersheds are concepts that should be considered when installing or reintroducing large wood to streams and riparian areas.

The selection of correctly sized large woody debris is fundamental to the success of a project. Wood placed in a channel that the stream cannot move can have a dramatic effect on channel shape, grade and orientation. In these cases, the wood behaves more like rock. There are many positive but also potentially negative consequences of using wood so large that a small or medium stream cannot move it. This is especially true in alluvial channels and in areas where infrastructure is present. It is important to understand sediment transport, streambank stability and the upstream flood impacts when aggressively using large wood in these situations.

Conversely, undersized large woody debris placed in a channel can have little or no effect in terms of bank protection or fish habitat. It is also important to accurately assess the wood volume needed to realistically accomplish the desired objectives. Wood volumes required to restore natural function and habitat in larger streams are often underestimated. This is especially true in degraded alluvial environments where substantial amounts of wood placements are required in flood-prone areas outside of the low-flow channel.

In some small valley or meadow streams, and in a few areas in eastern Washington, wood is not a natural component of channel systems. While the addition of wood may still provide habitat and mitigation value, it should be acknowledged that in such systems wood may be less appropriate.

PLACEMENT CONSIDERATIONS

The design of large-woody-debris projects must be carefully considered to ensure their success as both bank protection and habitat. Unfortunately, the failures of some bank-protection projects involving large woody debris for habitat mitigation have been wrongly attributed to the wood rather than to the designer for not creating an integrated project. As designers become more adept at incorporating large woody debris into streambank-protection projects, its effectiveness and frequency of use will increase. *Figure I-1* (at the end of this appendix) shows several bank-protection projects incorporating large woody debris into them.

Large woody debris should not be placed during emergency conditions or for the purpose of alleviating emergency problems. Large woody debris can only be anchored or placed effectively in relatively calm and/or dewatered environments.

Large Woody Debris for Catching Debris

It is generally accepted that the more wood found in a given reach, the better the habitat. Large woody debris, used as mitigation, should be installed as dense clusters or have the capability of recruiting other debris from the stream. Single logs provide little habitat by themselves; and, as time passes, even isolated rootwads become featureless stumps providing little cover.

Wood recruitment is the stream's habitat-revitalizing force, adding complexity and renewing cover over time. Streambank-protection techniques made of rock are not effective at recruiting wood on their own, so large woody debris should be incorporated into them; large woody debris tends to collect other debris, encouraging the recruitment of even more wood. For wood recruitment to occur properly, logs with rootwads should be positioned so that a portion of the rootwads is above the flood-flow water surface. Floods make large woody debris available as they erode banks, drawing large and small trees into the active channel. Small trees and wood material added to the channel float downstream and are often captured by existing downstream log jams. If logs with rootwads are installed alone and low on rock revetments, they will not collect this liberated debris as it floats by. The ideal solution is to have wood at various elevations on the bank to ensure recruitment at all flows.

In systems with high banks and infrequent out-of-bank flows, the wood stays along the thalweg in the deeper, faster moving water and does not tend to accumulate along the banks. In order to recruit debris, large wood in rock-treated banks must stick out into the flow and be high enough to capture floating debris. Wood tends to accumulate at the downstream end of a bend as momentum resists making the final turn. This is a good place to expect logs to rack up on placed large woody debris.

Large Woody Debris in Rock Toes or Revetments

Engineered log jams provide immediate, stable habitat and bank protection. Log jams that have been installed in front of rock toes or revetments as mitigation have provided some habitat value. With the effective use of wood in streambank protection on the rise, it is wise to consider using wood instead of rock if at all possible. Trees with rootwads are the best material to use.

Rock for bank-protection projects is frequently sized according to a minimum stable dimension or gradation. These stability equations and tables are for smooth banks with flow running on an alignment parallel to the bank. When wood is added to the revetment design, failure may result from turbulence or redirected flow unanticipated in the original rock-sizing criteria. The designer must account for these hydraulic forces in stone sizing and the determination of stone layer thickness. Experience suggests that it is best to use the largest rock available for rock revetments, toes, groins and barbs that incorporate large woody debris. Refer to the discussion about *Riprap* in Chapter 6, *Techniques* for rock sizing information. While it may save money to opt for the minimum stable rock size for a particular project, the increase in risk may be unacceptable when also using wood. During floods, wood buoyancy and upstream wood collection cause shifts in hydraulic forces; and, together with impacts from large, floating logs, can quickly make even the largest rock inadequate to hold smaller-sized wood in place. A good understanding of the worst-case flood forces that could occur at the project site enables a design that will be long-lived and emulate the size of material that would naturally occur at each site.

The use of such large rocks and logs necessitates layered bedding, especially in fine-sediment banks and streambeds. Successful projects use progressively finer granular layers between the rock and the native bank material. Fine-grained soils may require small-diameter crushed rock or screened sand and gravel, followed by quarry spalls and light, loose riprap. Refer to the discussion about subsurface drainage in Chapter 6 for more information regarding selection of filter materials between riprap and native materials. Another approach is to use a well-graded pit run to provide the filter layer behind the riprap.

Based on a review of recent riprap revetment projects with large woody debris, two techniques show the most promise for stability and habitat:

- On an outside bend, large logs are embedded in a boulder toe, with rootwads extending in the channel. The logs are 30 feet long, embedded 15 feet into the bank and ballasted. The upstream angle can be from 30 to 50 degrees. Other logs can be attached to them. The log is placed at bed level. In confined streams with deep flood flow, additional logs are placed higher to collect debris.
- Log jams are constructed off the rock face to avoid jeopardizing rock placements and bank protection.

Large Woody Debris in Groins and Barbs

Large woody debris is used in groins in about the same way it is used in rock toes and revetments. However, there are a few added complications. Large logs with intact, finely branched rootwads are preferred for use in groins. They should be placed at bed level for cover purposes and also at higher stages to encourage recruitment. Logs need to be well embedded in the structure, placing one-half to two-thirds of the lower part of the tree trunk in the rock. The rock size should be increased to act as ballast; unless, as has been recommended, the largest rock available is already specified.

The positioning of large woody debris in the structure is the subject of some debate. It depends, in part, upon whether the structure is a barb or a groin. Barbs are positioned low and produce less scour and turbulence. As a result, sediment tends to accumulate around them and a new bankline develops. If large woody debris is placed near the bank upstream or downstream of a barb, it is likely to be in a deposition zone, and its value as cover is reduced or eliminated. To enhance fish habitat, it is useful to place large woody debris near the tip of barbs; however, designers have expressed concerns that this is the area of highest stress, and large woody debris may destabilize the structure and reduce its effectiveness as bank protection. This concern applies primarily to high-energy environments. Using wood on the end of a barb could cause problems if it collects additional wood and allows hydraulic scour to be focused on the bank the barb is designed to protect. Large woody debris, if placed near the tip, should be positioned low in the water column to provide cover, while reducing its ability to collect debris. A good understanding of the watershed wood transport/supply, hydrology, hydraulics and geomorphology are important. If the structure is properly designed, large woody debris will stay in it and improve habitat. Risk analysis and design requirements will help determine the applicability of wood in barbs at a given site.

In contrast to barbs, groins are high structures that trigger more pronounced turbulence and scour. As a result, the area near the bank may stay scoured, and large woody debris located here can provide good cover and complexity. Wood can also be placed near the tip on the upstream face of groins. There is usually more rock in groins than in barbs, so wood can be positioned more securely in groins than in barbs.

ANCHORING CONSIDERATIONS

Successful projects have used many types and methods of anchoring. Personal preferences and site conditions govern which types and methods are used. Wood placed in groups with multiple, fixed anchoring points will tend to be more stable than single pieces with one anchoring point. Structures made of single or multiple pieces of large woody debris, boulders and other materials are commonly used in streams and rivers as habitat features, fish-passage structures and bed- and channel-stabilization features.

The design of anchoring systems should consider the balance of forces between structure buoyancy and weight, and between drag forces and frictional resisting forces. The drag and friction calculations are prone to error, largely due to the unpredictable potential for a structure to collect additional debris. Partially buried logs extending into the current are often subjected to substantial oscillation and vibration. These movements can weaken a structure. The difficulty in predicting forces on structures in a river leads to the need for a substantial factor of safety in anchoring design. A minimum safety factor of 2.0 is recommended.

Types of Anchors

There are three common ways of anchoring materials in a river:

1. holding the feature rigidly in place using ballast;
2. tethering the structure so there is some degree of movement flexibility with varying flows; and
3. using passive anchoring, where the weight and shape of the structure is the anchor, and movement at some flow level is acceptable.

Rigid Anchors

Rigid anchoring is usually desired where long-term grade control or direct bank protection is the objective. Some structures that are embedded in the bank can lead to continued bank failure if they shift or move downstream.. Due to the anticipated permanence of this approach, it is important that the structure being anchored is properly designed and positioned. The anchoring methods most commonly used include ballast (cabling or pinning), a deadman, bedrock, and piled or standing trees. Rigid anchoring can also be accomplished by direct burial of part of the structure. Woody debris embedded in a barb, groin, rock toe and revetment are examples of rigid-anchor structures.

Flexible Anchors

Flexible (tether) anchors use materials that are similar to those used in rigid anchors; however, in this case, tethers allow the large woody debris structure to shift with changing flow stage or direction. Tethers are appropriate where the structure is providing roughness or cover and where exact positioning of the feature is not critical. Such an approach is intended to provide a base for other debris to collect and stabilize in one location. The tether must be designed to prevent the structure from moving near the bank. One desirable outcome of using such structures is the creation of local scour. Tethered structures move with the current, scouring or "mining" everywhere they move. Secure tethering requires that anchors be attached at several points on the structure.

Tethered structures float and allow flood flows to pass under them, presumably reducing stress on the structure.[2] However, flexible anchoring introduces dynamic forces that add stress to the anchoring system. Structures are often tethered to points both on the bank and in the channel. Tethered anchors should not be used in high-energy stream channels.

Passive Anchors

Passive anchors use the weight and shape of a structure itself to provide resistance to movement. Log jams can be anchored by large debris pieces (whose own weight will stabilize them), rootwads, and frictional resistance of the buried bole.[3] Bracing one or both ends of a log against trees or bedrock is also a form of passive anchoring. Individual boulders can be placed within a woody-debris matrix without cabling because they provide additional weight for structural stability. A debris structure can be considered passively anchored as long as they are cabled or pinned in a rigid matrix but remain unattached to any exterior anchors. The structure may become mobile at high flows, but the size and shape of the structure keeps it from moving a great distance. This may be a preferred approach for some habitat-mitigation structures. If cable is used, it should be galvanized and have a steel core. Half-inch cable has been used successfully in upper, fifth-order streams within high-energy, rain-on-snow flood environments. Just as boulders should be properly sized, so should cables. Cable smaller than one-half inch in diameter is not appropriate.

METHODS OF ANCHORING

Cabling or Chaining

This method includes attachment with various materials including cable, wire rope, chain, rope and straps. Where a permanent, rigid anchor is desired, cable (wire rope) and chain are appropriate choices. If temporary anchoring is the goal, the use of hemp or other biodegradable, natural-fiber rope or strap may be the solution. Rope or straps of synthetic material may have a life expectancy somewhere between cable and biodegradable ropes.

Cable is available in galvanized and nongalvanized forms. Galvanized cable has the advantage of being resistant to corrosion but should still be cleaned prior to being used with adhesives such as epoxy. Cable can be cut in the field using guillotine-type cutters (which tend to leave a frayed end that can be difficult to insert into holes) or by using a skill saw with a metal cutting blade (which makes a cleaner cut). The best way to cut cable in the field is with a hydraulic shear, which can be carried in a backpack and weighs approximately 15 pounds.

Cables are typically connected to each other and to anchors and woody debris using cable clamps. *Cable clamps* (clips) are a weak point in cable anchors. Using safety factors of two to three times the estimated loading is prudent in the dynamic environment of streams. Improperly placed clips can reduce the efficiency of the connection up to 40 percent of the cable strength. Thus, it is important to pay careful attention to this aspect of anchor design and construction. Clip efficiency is affected by orientation, tightening, spacing and the number of clips used.[4] The minimum number of clips ranges from two clips for 3/8-inch-diameter cable to five clips for one-inch diameter cable. Standard wire rope clips on a thimble eye obtain up to 80 percent of the strength of the rope when properly made. Specialty hardware can form eye loops with up to 100 percent of the rope strength. Flemish loops (a hand-formed loop) only develop up to 70 percent of the strength of the wire rope.

When attaching cable to logs, always remove the bark from the area enclosed by the cable. Otherwise, the cable will loosen as the bark rots. To prevent the cable from slipping along the log, insert the cable through a drilled hole in the log or create a notch around the log using a chainsaw or axe. If rigid anchoring is required, a winch or other equipment is necessary to tension the cable properly before tightening the attachment hardware. Key wood placements should be oriented perpendicular to each other. Following cabling, any wood movement should not be able to create slack in the cable. Staples can be used in addition to cable clamps (in some cases, instead of cable clamps) to secure cables to large woody debris. When installing staples, avoid excessive crimping of the cable.

Pinning

Steel pins have been used successfully to connect individual pieces of large woody debris, to attach large woody debris to other anchors and to serve as direct anchors (by being driven into the substrate). Wooden dowels have also been suggested for pinning, but no known applications are in place.

The main concerns associated with pinning include adequate strength, durability of materials and security of attachment. Determining forces on large woody debris in rivers is challenging, so using conservative factors of safety in design is recommended. Durability of steel pins depends upon the corrosive or electrolytic nature of the soils and water, which may greatly reduce longevity at some locations.

Pin-attachment effectiveness depends upon the materials used. Threaded rods or rebar are the most common materials used. Rebar pinning relies on shaft friction to maintain attachment. Using a cable clamp at one or both ends or bending the protruding rebar end reduces the chance of pullout. When using threaded rods or bolts as connectors, large washers should always be used. Pilot holes are necessary for driving pins through large logs, and special, extended-shaft auger bits must be made for drilling through stacked logs.

Angle iron plates with four holes on each end for spikes have been used successfully in high-energy environments. These should be used to supplement cable in debris jams within higher-energy environments. Half-inch lag bolts or spikes at least six to eight inches long should be used.

Pieces of debris have also been anchored using various lengths of rebar driven into the streambed or bank. The rebar is driven through a pilot hole in the debris and into the streambed using a fence-post driver, sledgehammer or vibrator hammer with a special adapter for the rebar. These applications have had variable success due to difficulty in driving the rebar to adequate depth and the varying ability of subsoil to secure the driven rebar. For this reason, this method is not recommended as the sole method of anchoring treatments requiring long-term, rigid anchors.

Deadman Anchors

A deadman is a common form of anchor using a wide array of potential materials. The concept of a deadman is to bury an anchor in the bed or bank. The anchor pushes against a wedge of undisturbed soil when tensioned. One advantage of a deadman anchor is that it can be placed in the bank away from the potential erosion zone, keeping heavy equipment out of the stream. A structure usually requires at least two deadman anchors or a combination of a deadman and other anchors. A single deadman might be used as a tether anchor.

Commercial anchors are available that can be driven or screwed into the soil. The driven style is set by providing tension on the anchor. The tension causes the deployment of legs or plates, which actually provide the anchorage. These anchors depend entirely on the shear strength of the soil and, therefore, are not acceptable in unconsolidated gravel beds.

Buried boulders, logs, concrete blocks or steel shapes are also used as deadman anchors. They have the advantage of their weight adding ballast, and they have more bearing area than commercial anchors. In the application of ecology blocks as deadman anchors, the anchor tie should be cable- or chain-wrapped around the block, not through the lifting eye on the block.

Designing deadman anchors requires information on soil characteristics. The strength and tightness of soil will determine the style and number of anchors required. In design, a simple pull-out analysis should be completed to determine the appropriate depth and style of anchor for a particular application. In addition, the manufacturer's specifications should always be followed for commercial anchor systems.

The movement of anchored debris can cause the anchoring cable or chain to slice through and loosen the soil lying between the anchor and the debris. When this occurs, the soil becomes more susceptible to erosion. For this reason, deadman anchoring systems should be designed such that they minimize the range of movement of a piece of anchored debris. Multiple, strategically located anchors will typically restrict woody debris movement more effectively than a single anchor. If movement of the woody debris is desired, an alternative anchoring system, such as ballast or pilings, should be considered.

Anchoring to Bedrock and Boulders

When structures are to be placed on or near bedrock or anchored to boulders, the rock can be drilled and anchors set into it. The bedrock or boulders must be suitable and durable. The rock should be free from segregation, seams, cracks and other defects tending to destroy its resistance to weathering. Attachment to the bedrock or boulders can be accomplished by inserting cable, rebar, threaded rod or rock bolt anchors into a hole filled with the appropriate grout or adhesive as required by the manufacturer. Oiled cable must be carefully cleaned with acetone or muratic acid to allow bonding with the adhesive. The drilled hole must reach into unfractured rock to develop full anchor strength, and it must be of a depth and diameter as specified by the manufacturer. There are many types of anchor adhesives on the market. The type selected should take into account wet conditions, possible oversized holes, etc.

The following are steps recommended by typical product literature for attaching threaded rod or rebar to bedrock or boulders using an epoxy adhesive (similar techniques can be used for rock bolt anchors:

1. drill anchor hole typically 1/16 inch larger in diameter than the rod or 1/8 inch larger in diameter than the rebar. Cable has also been used as an insert, but some failures have been observed, probably due to the nonuniform surface relative to the drilled-hole alignment. If using cable, a better method would be to attach the cable to a rod or rebar;
2. clean the hole with a wire brush. Use air to blow out the hole to remove all dust and debris;
3. if the cable or steel rod is lubricated, clean the cable using acetone or muratic acid;
4. inject the adhesive into the hole per the manufacturer's specifications;
5. insert the rod or rebar, and turn it slowly until the end contacts the bottom of the hole (air pockets at the bottom of the hole reduce bonding strength);
6. make adjustments to the fastener before specified gel times; and
7. allow curing to occur (curing time is a function of temperature and varies from one to three hours).

Some adhesives may require dry surfaces for proper adhesion. Prior to using an adhesive, it's important to verify the conditions under which the adhesive functions most effectively and to make sure the product has not reached or exceeded its expiration date. Using adhesives that require dry surfaces should not be used on structures to be cabled instream.

If applied properly, some adhesives can hold to the point of cable failure.[5] While some systems provide adhesion under water, in practice they are difficult to apply in a flowing stream with consistent success. It is important to consider how wood will be cabled during the construction and placement. Failure to consider cabling during construction will reduce cabling effectiveness and structural integrity.

Another common anchoring method is to use threaded expansion anchors or rock bolts. There are a variety of commercial expansion anchors available. Advantages of rock bolts over glued-in cable or steel rod include faster installation time and achievement of full strength upon installation (no drying time necessary). A disadvantage of mechanical anchors is that they are more susceptible to vibration effects than glued anchors are. Another type of rock bolt anchor is the groutable, rebar type. This anchor is set and then pressure grouted to seal and fill all voids or cracks in the rocks. This type can be used in weaker rock.

Pilings

Where equipment access allows and soils are appropriate, structures can be anchored with piles. Piling materials include logs, wood timbers, steel beams or pipes. In streams with fine-grained bed material, logs can be sharpened on one end and driven into the bed with an excavator equipped with a thumb attachment. They can also be pushed horizontally into banks as long as soil composition is able to provide structure. Many streams have bed and bank material that is too large or compacted for this approach, and pile-driving equipment must be used. Pointed steel caps will aid in driving logs into a gravel/cobble bed. Steel beams or pipes can be used in the channel where the structure or bed material will cover the pilings. Pins or cables are used to attach materials to pilings. Logs can be wedged between pilings and held in place by water pressure. This approach has also been used successfully for building log jams. A web of cable between a series of pilings can also trap and hold woody debris, although boater-safety concerns preclude the use of this technique in most cases.

Typical piling anchor designs require one-half to two-thirds of the piling length be buried below the streambed surface. This is critical for structures where the pilings are located near or in the scour zone of the structure. Piling depth must be determined with consideration for the potential scour depths expected resulting from the design flood and forces acting on the piles. Additional pilings away from the scour zone may be required as they are in some designs of engineered log jams designs (see example drawings in the discussion about *Engineered Log Jams* in Chapter 6). A professional engineer should determine the structural requirements for anchorage using pilings.

Ballast

Any object that adds to the weight and frictional resistance of a structure is considered ballast. The most commonly used ballast material is rock. The rock (usually large boulders) is typically attached to the large woody debris using cables or chains, or by pinning. Concrete blocks can also be used; but, because they are unattractive, they are preferred in locations where they will remain out of sight. Another approach is to stack additional logs on top of a structure as ballast, with the logs that remain above the design flood elevation providing weight to the structure. The logs may either be attached or unattached to the structure. Since this type of structure may be higher than adjacent banks and can block a significant flow area of the channel, it may not be appropriate to use next to an unvegetated bank or high-risk area without additional bank protection.

Combinations of Anchoring Methods

Anchoring methods are often used in combinations suited to the particular task at hand. For instance, a constructed log jam may consist of logs pinned to each other and then cabled to boulder ballast. It is up to the designer to mix and match the anchoring techniques presented here (and any other feasible techniques) to produce an anchoring system for a specific project and situation. Creatively using large, standing trees, bedrock, boulders and sharp bends to passively anchor or establish large-wood accumulations are techniques used to create stable wood habitat that emulates natural habitat. The ability to visualize flood stage and response during construction at low flow is very helpful. Understanding the geomorphology, hydrology and hydraulics of the site during design enables one to better visualize flood stage and use what already exists on site to help construct a solid wood habitat project.

HABITAT CONSIDERATIONS

Once in the stream channel, large woody debris influences coarse-sediment storage, increases habitat diversity and complexity, retains gravel for spawning habitat, improves flow heterogeneity, provides long-term nutrient storage and substrate for aquatic invertebrates, moderates flow disturbances, increases retention of allochthonous (leaf litter) inputs, and provides refuge for aquatic organisms during a range of flow events.[6]

Wood, particularly smaller twigs, and leaves (which decay rapidly) provide a food source to some aquatic insects that fish consume. Large woody debris can capture smaller logs and fine, woody debris and retain it better than riprap can. Using only large wood to stabilize banks is a relatively new technology emulating the process of self-stabilization observed when large trees fall into rivers after being undercut. There have been several successful projects using only wood to stabilize banks. As with all tools, using wood to stabilize streambanks does not work in every location. Refer to the discussion about *Roughness Trees* in Chapter 6 for more detail about using wood in bank-protection projects.

Enhancement of fish-habitat features is also a benefit; it improves structural and hydraulic diversity, thereby providing habitat for a multitude of life stages and species of fish. Woody debris is an important component of juvenile salmonid habitat in larger rivers during spring, summer and winter. Habitat and fish-population surveys have demonstrated increased densities in areas with large woody debris. Coho salmon densities were positively related to increasing large woody debris surface areas in the main stem of Washington State's Clearwater River[7] and Skagit River.[8] It has also been demonstrated that chinook salmon tend to cluster near brush or large woody debris cover.[9] Fish densities are positively correlated with the increased surface area provided by large woody debris.[1]

A bibliography of literature addressing the role of wood in aquatic systems and riparian areas has been assembled by researchers in the United States, United Kingdom and Russia. It is available on-line at http://riverwood.orst.edu/html/intro.html.

RISK

Risks inherent in the use of woody debris include:

- boater safety;
- structural damage to the stone revetment, barb, etc. (if embedded in these structures), due to turbulence and concentrated flow caused by the large woody debris' placement in the structure and its orientation to the approach flow;
- structural damage to the stone revetment, barb, etc., due to the levering out of embedded large woody debris by flood flows, or the pull-out of deadman anchors;
- opportunity for cables and anchors to come loose within the channel, creating hazards for recreational users;
- blockage of culverts or bridge openings by large woody debris that has come loose and migrated from its point of installation; and
- a major change in channel direction and depth and can create a bifurcated or braided channels.

All of these risks can be minimized by exercising care in designing the placement of large woody debris.

ACQUISITION OF LARGE WOODY DEBRIS

Larger wood pieces are used for bank protection and the creation of log jams to create stable structures that emulate historic channel processes. Wherever possible, large woody debris should be used with intact rootwads. Obtaining, transporting and placing this wood is becoming increasingly difficult. Moderate-sized pieces can be obtained from timber companies or developers and transported in a trash hauler. Key pieces, appropriate for larger rivers, can be transported whole or in pieces on large flatbed trailers. Large wood cut for transport can be glued, cabled and/or bolted at the site to recreate original dimensions. Largeness is important; so, if only smaller pieces are available, then largeness and complexity should be emulated by binding them together.

Large woody debris should be of a size (length and width) and species to remain intact and stable for many years. Avoid using hardwood species such as alder or cottonwood, which decay rapidly; coniferous species such as cedar, fir and pine are better choices. Large-diameter and/or long logs, imported from off-site, may need to be cut into pieces for transport and then reassembled on site by splicing, gluing and tacking the pieces back together. Use of on-site wood resources can greatly simplify construction and reduce costs.

When standard equipment has not been able to move wood of the required size and length to the work site, helicopters have been used successfully to fly in whole trees weighing as much as 25,000 pounds from adjacent, upland blow-down locations and staging areas.

Wood is intended to remain submerged or partially submerged, so wood buoyancy can pose a problem during installation. To address this problem, the site may need to be dewatered to allow for placement and anchoring of large pieces. The use of wood that has already been saturated with water can simplify construction by reducing buoyancy problems during installation. Logs may need to have ballast attached before placement if the site cannot be adequately dewatered.

Turbidity will be a significant problem during installation due to the amount of digging in the channel bed that is required for installation. This can be addressed by dewatering the installation site, or by creating a coffer system that isolates the immediate site from flowing water.

Protection of the existing riparian zone should be a high priority, particularly in drier climates where replacement of the canopy can take decades. The use of walking excavators, winches and hand labor may be required at some sites.

As with any in-channel enhancement project, construction should be conducted during a period where the potential impacts to aquatic resources are minimal. Low-flow conditions are preferable for the placement of large woody debris jams. Instream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Further discussion of construction and dewatering can also be found in Appendix M, *Construction Considerations.*

MONITORING AND MAINTENANCE

Monitoring should be conducted during or following high-water events (i.e., floods). At a minimum, large woody debris placements should be monitored during and/or after two-year flow events for a minimum of five years following project completion to ensure the integrity of the anchors. If individual pieces have moved or become loose, they should be re-anchored. If large woody debris has been lost, the structure should be evaluated to decide if replacement is warranted. Replacement may depend upon potential damage to the recovering vegetation, as well as potential future damage to the bank if no repairs occur.

Objectives of monitoring include:

- evaluating the structural integrity of installed structures;
- evaluating structures relative to objectives of bank protection and fish habitat;
- measuring and surveying (topographically and photographically) any changes to banks and bed of stream; and
- measuring hydraulic and hydrologic impacts of the project.

For a comprehensive review of habitat-monitoring protocols, refer to Johnson, et al.[10] Habitat-monitoring protocols will likely require a monitoring schedule that is more comprehensive than that required for the integrity of the structure.

Maintenance needs are greatly reduced if large woody debris is engineered and installed properly. Maintenance may include securing damaged or degraded anchoring systems for the life of the project and removing nonwood components (cable) when structures fail or exceed their project life.

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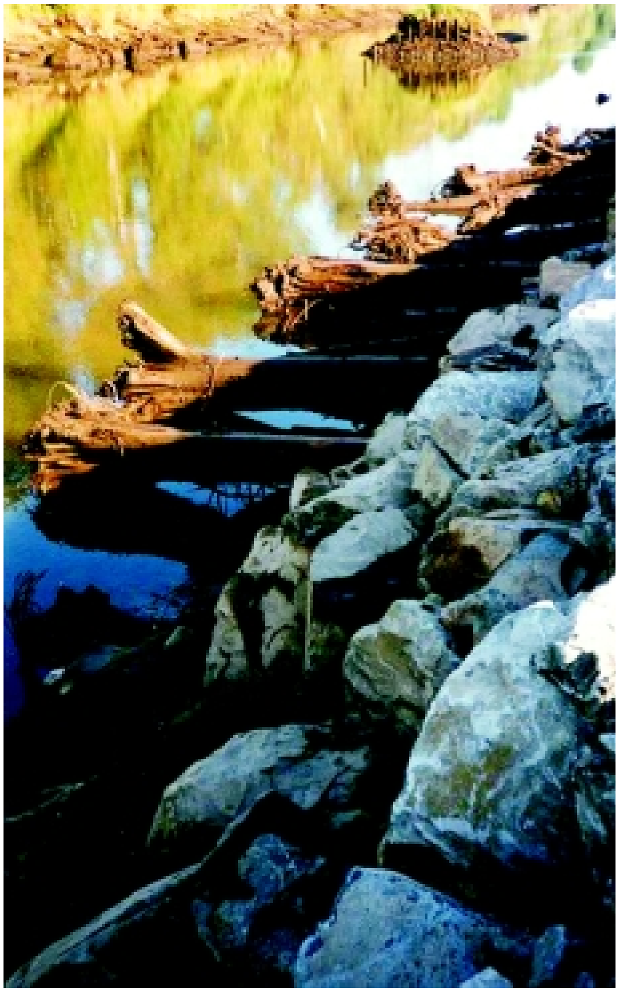

a. Large Woody Debris embedded in Rock Toe. Green River.
Source: King County Department of Natural Resources.

b. Large Woody Debris embedded and collected on Groin. Hoh River. 1998.

c. Large Woody Debris embedded in Rock Toe. Salmon Creek, Tributary to Columbia River.
Source: Inter-Fluve, Inc.

d. Large Woody Debris embedded in Groins. Big Quilcene River. 1997.

e. Large Woody Debris embedded in Groin. South Fork, Nooksack River. 2002.

Figure I-1. Large woody debris used in conjunction with various treatments.

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Monitoring

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Appendix J
Monitoring

This appendix is intended to provide general guidelines for developing streambank-protection monitoring plans. Monitoring is defined as the collection and assessment of repeated observations or measurements over time to evaluate the performance and impacts of bank-protection treatments. This appendix provides a framework for monitoring activities that integrates riparian and fluvial processes with assessments of the physical integrity and performance of streambank-protection treatments.

MONITORING PROJECT SUCCESS

Monitoring activities enable property owners, scientists and regulators to observe bank-protection performance under a range of changing environmental factors, including flooding or drought, channel shifts and erosion, and biologic factors such as beaver activity or the effects of animal grazing. In addition, a comprehensive monitoring plan creates a foundation for maintenance activities that ensure project goals are met and that the project continues to perform as intended over time. And, finally, monitoring allows those engaged in protecting or regulating the protection of streambanks to identify ways to improve and refine bank-protection techniques.

MONITORING MITIGATION ACTIVITIES

Monitoring activities may also be necessary to demonstrate successful habitat maintenance. Consequently, monitoring mitigation activities and impacts associated with bank-protection projects will be a requirement of most projects. The objective of monitoring habitat is to document impacts to habitat, and success of avoidance, minimization and compensatory mitigation activities. However, the discussion of specific mitigation and habitat-monitoring activities is beyond the scope of this document. For further discussion and direction in mitigation monitoring for habitat, refer to *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest -Directory and Synthesis of Protocols and Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia*.[1]

This appendix will introduce and discuss the key components of monitoring streambank-protection projects. Additional and specific information on monitoring streambank-protection projects can be found in Chapter 6, *Techniques,* where each technique description contains a discussion on monitoring considerations.

MONITORING-PLAN DEVELOPMENT

Developing a monitoring plan includes determining objectives, identifying parameters to be measured, establishing a monitoring protocol, collecting data and reporting results. These steps are first outlined and subsequently detailed below.

1. Statement of objectives:
   - project objectives
   - mitigation objectives (targets), and
   - monitoring objectives.
2. Identification of monitoring parameters:
   - determination of success criteria,
   - measurable attributes, and
   - determination of monitoring intensity.
3. Establishment of monitoring protocol:
   - geographic extent of monitoring, and
   - determination of monitoring duration and frequency.
4. Collection and reporting of monitoring data:
   - baseline data, and
   - reporting of monitoring data.

Statement of Objectives

Project and mitigation objectives drive the monitoring process and ultimately define project success. Project objectives should be clearly stated in the project design and understood by all entities involved. Mitigation objectives, or targets, must be provided for all projects requiring compensatory mitigation. Criteria developed for bank-protection design and mitigation design will reflect the project objectives and may be useful in some circumstances as a basis for developing monitoring parameters and attributes (see Chapter 4, *Considerations for a Solution*).

Project Objectives

The fundamental purpose of monitoring is to evaluate the success of a streambank-protection project with respect to the objectives of that project. Project objectives are generally oriented toward protecting a streambank or features landward of the streambank from erosion. Project objectives are generally framed within the context of acceptable risk and may include varying spatial and temporal scales, which may differ significantly among projects. Acceptable risk may include protection up to a given discharge event, after which bank failure does not necessarily represent failure with respect to objectives. Streambank-protection objectives are discussed in more detail in Chapter 4.

Mitigation Objectives (Targets)

Common compensatory-mitigation targets are:

- to improve factors within the watershed that limit fish production,
- to restore properly functioning habitat,
- to replicate natural conditions, and
- to restore or replace preproject conditions.

As discussed in Chapter 4, mitigation targets vary in scope from an entire watershed down to specific project site conditions. Targets vary in substance according to the objectives and authorities of agencies that permit work in stream channels. The habitat-mitigation monitoring plan must be in keeping with the initial, mitigation needs assessment and must reflect the original mitigation target. It is likely that the habitat-mitigation objective will drive the entire habitat-monitoring plan.

Monitoring Objectives

Monitoring objectives are used to evaluate project performance in relation to bank-protection objectives, mitigation objectives and any corollary objectives, including those for habitat. Additionally, where an experimental technique is applied, monitoring objectives will include evaluation of how closely aligned the project design is to the original design criteria.

Monitoring Parameters

Monitoring parameters are components of a bank-protection project that need to be assessed to evaluate whether project objectives have been met. A project consisting of just riprap protection may have a small set of monitoring parameters, such as the integrity of installed riprap, channel cross-section stability, and upstream/downstream bank conditions. Any mitigation for such a project will also require monitoring parameters. Monitoring parameters for an experimental project using engineered log jams may include stability/integrity of the structure, bank erosion adjacent to the structure, bed scour, thalweg realignment, sediment deposition, woody debris accumulation, documentation of high-flow hydraulics, habitat use and plant survival. Once identified, these parameters serve as a first step in developing a suite of measurable attributes, measurement techniques and success criteria that together comprise the core of the monitoring plan.

Success Criteria

Success criteria are specific, predetermined thresholds of performance for the measurable attributes of a bank-protection project. They are not the same as monitoring objectives. In many instances, success criteria will be the same as design criteria, though there may be additional criteria for measuring success included. Success criteria should be developed for the protection project as well as any associated mitigation.

Success criteria are important to monitoring because they define acceptable performance thresholds for initiating project maintenance. Typically, if a success criterion is not achieved, a maintenance activity such as replanting or repositioning of rock may be required. Success criteria are not necessary or possible for all monitoring attributes. For example, photography from fixed photo points can be used as a monitoring technique for qualitative attributes that are not linked to definitive criteria for success. In this application, monitoring can be performed for qualitative evaluation as opposed to distinct success evaluation.

Measurable Attributes

It is important to identify the measurable attributes and evaluation techniques for each monitoring parameter. The suggested process consists of selecting the measurable attributes that most effectively characterize each parameter, followed by the most effective method to measure, or evaluate, that attribute. For example, bank slope and shape is a measurable attribute of the success of a bank protection treatment. A cross-section survey is an effective measurement tool for measuring this attribute and provides more detailed, quantitative data than a written description with photos. Similarly, plant survival is a measurable attribute for vegetation establishment and can be measured by a physical count of live stems and/or aerial foliage cover.

To understand project success, monitoring must be done relative to preproject conditions. Attributes and measurement techniques applied to pre- and postproject implementation must be consistent so results can be compared and are therefore meaningful.

Table J-1 includes some examples of measurable attributes and evaluation techniques for selected monitoring parameters. For further detail on monitoring parameters and measurable attributes, refer to each individual technique described in Chapter 6.

Monitoring Parameter	Measurable Attribute	Evaluation Technique
Bank protection	Cross section shape Channel planform	Cross section survey Aerial photographs Channel alignment site survey
Upstream and downstream geomorphic impacts	Cross section shape and channel planform	Cross section survey Aerial photographs Channel alignment site survey
High-flow hydraulics	Local flow patterns Flow angle of approach to bank Zones of active erosion Flow history, including peak-flow return intervals Occurrence of debris jams	Video Video Photo documentation, survey Hydrologic analysis Photo documentation, survey
Fish habitat	Rearing habitat (quantity/quality) Spawning habitat (quantity/quality) Cover (quantity/quality)	Stream temperature Bed-material composition Water depth and velocity Percent cover, shading Habitat mapping Population assessments for fish and invertebrates
Vegetation establishment	Plant-survival rate Plant diversity Natural-recruitment patterns Uniformity of aerial cover Bird and wildlife presence	Percent vegetative cover Species composition, density Size distribution Age/class distribution

Table J-1. Sample monitoring parameters, listed with measurable attributes and potential evaluation techniques applicable to streambank- protection projects.[2]

Monitoring Intensity

Monitoring intensity refers to the level of detail required in the monitoring process, regardless of whether the process is qualitative or quantitative.

Qualitative monitoring tends to be descriptive and often consists of visual observations, the use of broad descriptive categories (good/fair/poor, present/absent, or unstable/stable) or the use of permanent recording methods such as photo points.[4] On the other hand, quantitative monitoring is objective and consists of a series of discreet, replicable measurements that are usually analyzed statistically and can be more easily related to design criteria and/or success criteria.

Qualitative monitoring is relatively inexpensive and allows for rapid assessment of relatively large areas, making it effective for general assessments of bank-protection integrity and vegetation. However, qualitative monitoring does not produce results that can be easily compared. Despite this limitation, qualitative monitoring is effective for inspection of the integrity of most structural bank protection techniques, including toe treatments, fabric-covered upper banks, woody-debris structures and instream channel modifications. Additionally, qualitative monitoring allows for recognition of nonquantifiable attributes, such as cracks and soil loss, which may be early signs of imminent bank failure.

Quantitative monitoring provides numerical data that can be statistically evaluated, but it tends to be relatively tedious and expensive. With good attention to detail, a considerable amount of information can be collected using a quantitative approach. Appropriate applications of quantitative monitoring include projects in which temporal changes in vegetation cover or channel cross-section form or grade are expected and need to be accurately assessed. In addition, mitigation components of streambank projects often require quantitative monitoring approaches to meet agency-mandated success criteria.

Monitoring Protocol

Perhaps the most complex part of developing a monitoring plan is specifying the protocols for each parameter and for each specific attribute. For some attributes, protocols can be relatively simple, but for others the level of detail and related considerations can be substantial. Some common protocols include:

- specification of methods and geographic extent of measurements,
- identification of monitoring period and frequency,
- design of monitoring forms, and
- a description of data-analysis techniques.

For a comprehensive review of monitoring protocols, refer to *Johnson, et al*.[1]

Geographic Extent of Monitoring

It is important to identify the geographic extent of monitoring if a project includes risks of upstream and/or downstream impacts to both the channel and habitat processes. The longitudinal (upstream or downstream) extent of impacts is related to the scope of the project, the geomorphic setting and the specific technique and mitigation applied. As a general rule, a study reach that is 20 to 50 channel widths in length should be sufficient for monitoring impacts to channel form.[2] It is important to remember, however, that the longitudinal extent of monitoring is site-specific and should be based on specific project objectives.

Monitoring Duration and Frequency

Both the duration and frequency of monitoring are important components of a monitoring plan. A monitoring duration of three years should be considered a minimum for most bank-protection projects. A three-year monitoring period allows a project to be exposed to a range of flows and gives vegetation time to pass from the critical establishment phase to a more mature phase. However, changes in channel form may require a high flow or a series of high flows that have a low probability of occurrence during a three-year period. In other words, the geomorphic success of a project may not be properly evaluated until such flows occur. In addition, riparian vegetation may take many years of growth before its success in bank stabilization can be evaluated with any confidence. Any upstream and downstream project effects will likely require a series of high flows to before they become apparent. Therefore, the duration of monitoring may need to extend until some design flow event occurs, or until some vegetation density or percent cover is reached.

It may be appropriate to extend monitoring activities following certain flow events, for example within one month of any 10-year or greater flow. The primary determinants of a monitoring period should be project scope and project risk. Streambank-protection projects with numerous structural components that are subjected to considerable scrutiny or exposed to substantive risk should probably be monitored for five years. Monitoring these projects for a shorter period of time may fail to detect important indicators of project performance.

Monitoring frequency refers to how often monitoring activities will occur during any monitoring year and what time of year they should occur. In many cases, a single, annual monitoring effort is sufficient. The monitoring frequency may need to be based on the occurrence of specific flood events, especially when project risk is a factor, such as when a bank treatment is protecting a valuable resource. Alternatively, the monitoring frequency may be systematic during certain times of year. For example, it may be appropriate to conduct all habitat monitoring on one frequency interval that is tied to spawning schedules, while bank-protection elements and instream structures are monitored on another frequency interval that is tied to hydrologic sequences.

An economical solution to limited monitoring budgets is to adjust the schedule of the monitoring plan so that more intensive, quantitative data is collected during the critical first three years. After this initial period, the scope of monitoring can be reduced. For example, vegetative success of a biotechnical treatment may be sampled intensively for statistical analysis during the first three years. But after that time, a qualitative description of revegetation patterns may be sufficient to evaluate project success. After a few years, the objectives, scope and monitoring duration may change to reflect maintenance needs, rather than to achieve success criteria.

Collecting and Reporting of Monitoring Data

Collecting and reporting data is critical to a successful monitoring plan.

Baseline Data

Development of a monitoring plan should include specifying and assembling baseline data that will be referenced in subsequent monitoring. Project success can only be evaluated in reference to a baseline condition, which may be measured immediately before project construction and/or immediately upon completion. It may need to include historical information.[3] Baseline data should correspond in format and detail to all subsequent data collected in order to measure success or impacts on both qualitative and quantitative levels. It is important to consider the timing of baseline conditions relative to annual hydrologic cycles and fish life cycles. Baseline-data collection and subsequent monitoring should be conducted at the same time of the year relative to fish life cycles and hydrologic conditions.

Baseline-data collection should include, but not be limited to,

- the establishment of permanent benchmarks (located away from areas of potential bank erosion);
- an as-built survey to document the project's configuration relative to permanent benchmarks;
- a summary of site hydrology (including location of the nearest gauging station) and values for critical flows that will be used to initiate monitoring events;
- documentation of aerial photography, summary of erosion history and any other geomorphic data pertinent to project location and design;
- documentation of preproject site and reach data pertaining to fish use, the riparian corridor, floodplain function and overall habitat condition; and
- documentation of any other conditions related to project or mitigation objectives.

Additionally, baseline data should be collected using the methods established in the monitoring protocol. It is crucial that qualitative and quantitative baseline-data collection be thorough and appropriate to provide a sound foundation for subsequent data collection and monitoring.[3]

Reporting Monitoring Data

Monitoring protocols should include a format for recording and presenting all monitoring data, including baseline data. All subsequent data from each monitoring period should follow the same format as that collected as baseline date and can then be evaluated with respect to baseline conditions.

Qualitative data is best represented as drawings or photo series with associated text. Drawings should all be digitized in consistent scale such that they can be reproduced as overlays or within a single drawing. Similarly, photo series should be taken from benchmarked photo points, with consistent use of lenses and orientation, so that photos can be viewed as overlays of chronological monitoring events. In some instances, qualitative data may be presented in tabular format, when the protocol requires judgment of quality, appearance or other nonvisual attributes.

Quantitative data should be presented in tabular format such that subsequent monitoring events can be readily compared from year to year and over the project life. Quantitative data input in a tabular format can be represented graphically. That way, each measured parameter can have a graphic representation that reveals change over time and indicates when critical thresholds for success or maintenance have been reached or achieved.

MONITORING-PLAN COMPONENTS

The following list can serve as a checklist of topics and details that should be included in any monitoring plan.

1. Statement of objectives:
   - *project objectives,*
   - *mitigation targets,* and
   - *monitoring objectives.*
2. Baseline conditions:
   - *geographic extent of monitoring*: Include a map illustrating the geographic extent of monitoring for baseline data and all surveying to be conducted during monitoring. Various monitoring components may have differing geographic boundaries.
   - *baseline data*: A set of all data to be collected for all parameters to be measured as part of the monitoring program should be collected prior to conducting the project if possible and, at a minimum, immediately upon completion. Baseline data may include only as-built information if it is impractical or unnecessary to measure success relative to pre-existing conditions.
   - *permanent reference points*: The monitoring plan should list any requirements regarding permanent or temporary benchmarks linked to monitoring activities, such as photo documentation, channel cross sections, vegetation transects, groundwater wells and photo points.
3. Monitoring protocol:
   - *personnel qualifications*: The monitoring plan should specify the required experience level for personnel involved in monitoring data collection and analysis and the preparation of the monitoring report. This is essential for any monitoring activities sent out to bid.
   - *maps/plan sheets/drawings*: The monitoring plan should specify the need for drawings and associated information such as the position of bank-protection measures, planting zones, cross sections, photo points and benchmarks.
   - *description of measurement techniques*: A description should be included of specific techniques and methods for each parameter to be measured. Techniques and methods may include specific equipment and personnel necessary to acquire accurate and consistent data.
4. Monitoring schedule:
   - *frequency*: Frequency may vary over time and may be sequenced according to calendar dates or scheduled relative to specific flow events.
   - *duration*: The duration of the monitoring may be established according to calendar dates, or may be dependent upon achieving specific success criteria.
   - *submittal dates*: Include submittal dates for all progress reports and final monitoring reports.

5. Reporting of monitoring data: The plan should specify:
    - to whom copies of the monitoring report (s) should be submitted;
    - what the monitoring report format should be; and
    - what, if any, related data-presentation requirements may be involved.
6. Maintenance: The plan should specify what criteria or thresholds will initiate maintenance activities for all project components where it is appropriate.

MONITORING EXPERIMENTAL TECHNIQUES

New approaches to streambank protection continually evolve. Established protection methods, such as riprap, have well-documented design guidelines that result in high levels of protecting streambanks. However, standard design guidelines are lacking for many new types of bank-protection techniques. Comprehensive monitoring is important in order to assess new and experimental approaches and should focus on evaluating projects relative to their design criteria and the designs themselves so that future projects will be even more effective. It is essential that project objectives, designs, construction, mitigation and monitoring be integrated so that monitoring results educate practitioners about all known aspects of bank protection.

Monitoring activities should be designed to evaluate the performance of the treatment relative to specific criteria in addition to the overall objectives of the treatment. Because these criteria consist of measurable attributes, the monitoring plan can include methods for measuring these specific attributes to evaluate the success of the design and implementation, as separate from project objectives.

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Appendix K

Literature Review of Revetments

ANNOTATED BIBLIOGRAPHY OF IMPACTS OF RIPRAP HABITATS ON FISH POPULATIONS

Written by: U.S. Army Corps of Engineers, Seattle District.
March 13, 1997; Updated June 1, 2001

PACIFIC NORTHWEST

	TITLE	AUTHORS	SUMMARY
1	**Effects of Riprap Bank Reinforcement on Juvenile Salmonids in Four Western Washington Streams.**	Li and Shrek. 1984 NOTES: • Lower Deschutes River data is similar to Skagit River conditions. The riprap conditions evaluated apply to larger streams. Decker Creek is the second most similar. • No coho were found at the Lower Deschutes test section.	• Examined summer and fall salmonid populations. • Abundance of coho and trout young-of-year (YOY) declined in newly riprapped sections of larger streams while steelhead and cutthroat populations increased. • Negative short-term effects of construction increased with severity of habitat alteration, and decreased with an increase in stream size, and increasing fish size. • Previous research shows: lost production under certain conditions in streams having discharges of less than 10 ft^3/s. Large decreases in salmonid production after channelization (but not through the use of riprap) on Big Beef Ck. • Other studies show a potential to increase production through additions of habitat complexity, but little research has been done to show effects of removing habitat complexity. • Results show population increases for all salmonids (except trout) over time in all larger-stream construction sites. However, the increases were smaller than those observed at control sites, indicating greater preference for habitat conditions found in control sections.

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	TITLE	AUTHORS	SUMMARY
2	**Channelization and Livestock Impacts on Salmonid Habitat and Biomass in Western Washington**	Chapman and Knudsen. 1980 NOTES: • Channelization impacts winter habitat most. • Some test sites had more biomass in the summer than observed at control sites. The cause was determined to be less vegetation and more light at test sites.	• Studied conditions in streams of less than 0.3 m/sec velocity. • Characterized impact by exposure of raw soil, in-water placement of riprap, time since disturbance, and general appearance. • During summer sampling, coho were least affected by riprap, and cutthroat (largest) were the most affected. • Found no potential predator/prey correlation for cutthroat and coho. • 25 percent more fish in test in summer; 95 percent fewer fish in winter. • Neither the test or control reaches held many coho salmon during the winter months because the biomass was at only two percent of that recorded in the summer. • Light availability may be an important limiting factor for salmonid biomass in the summer in many streams. • Removal of the canopy and streamside vegetation over substantial reaches can cause low salmonid biomasses.
3	**Comparison of Habitats Near Spur Dikes, Continuous Revetments, and Natural Banks for Larval, Juvenile and Adult Fishes of the Willamette River.**	Li and Shreck. 1984 NOTES: • This study focused on all species of fish including cyprinids, catastomids, centrarchids, salmonids, and cottids. Cooler water was found to be detrimental when considering all species inclusively. • The study determined that groins provide better habitat than continuous revetments. There is not enough information on salmonids to determine their preferences, although other references suggest they prefer roughened habitats.	• The diversity and density of larval and juvenile fishes at spur dikes (groins) were intermediate between natural banks and continuous revetments. Spur dikes were found to accumulate woody debris better. • Two factors were consistent among the species observed: juvenile fishes avoided velocities greater than 11 cm/sec, and they were found at depths no greater than 30 cm. • Fish composition between natural and riprap banks differed. High densities of a smaller number of species were found in revetted habitats. Mostly those that fed on bottom-dwelling invertebrates and green algae/diatoms and small fishes able to use the interstices as cover.

	TITLE	AUTHORS	SUMMARY
			• Larval fishes were observed in the interstices of the riprap banks near shore but not sampled. • Large-scale sucker juveniles were supported best by natural banks, spur dikes and lastly, continuous revetments. • Juvenile sculpins tended to avoid riprap with only a few obsereved in its proximity. • Bass, bluegill, catfish, and crappie were not caught in riprapped sections.
4	**Effects of Stream Channelization on the Salmonid Habitat and Populations of Lower Big Beef Creek**	Cederholm and Koski. 1977 NOTE: • This report describes wide-spread damage to a river system due to bulldozing a new channel. It includes little discussion on streambank problems.	• Historically, Big Beef Creek was channelized to reduce flooding. • Channelization resulted in an increase in sediment contribution, streambed scour and a decrease in habitat characteristics. • Coho populations recovered faster than steelhead in the four years following channelization. • Chum salmon redds declined and shifted upstream to compensate for channelized sections. • Four years following channelization, bank cover returned to levels 50 percent prior to channelization (Alders grew to 2 meters). • There is evidence that coho may avoid dense cover in summer, and prefer open glides while steelhead prefer dense shade. • The report recommends using riprap as an alternative to channelization. • Large decreases in salmonid production were observed after channelization (not using riprap) on Big Beef Creek.
5	**The Short Term Physical and Biological Effects of Stream Channelization at Big Beef Creek Kitsap County, Washington.**	Cedarholm. 1972 NOTES: • The stated reason for channelizing was to improve salmon and trout rearing and spawning habitat, and for flood control.	• A literature review of studies that looked at alterations of the physical habitat by channelization revealed that: • the effects of man-made stream-channel alterations on game-fish (trout) production in 13 Montana streams produced only one-fifth the number of game fish as did unaltered section os the stream.

TITLE	AUTHORS	SUMMARY
	• Channel was bulldozed and cleared. • Pools and cover changes were measured. • Traditional chum spawning areas within the project area were found to move upstream and outside the channelization.	• Survey of 45 different Idaho streams that had undergone stream alterations found that undisturbed stream channels produced from 1.5 to 112 times more pounds of game fish than disturbed channels. On average, undisturbed sections contained eight times greater poundage of game fish. • Channelization of Big Spring Creek in Montana resulted in the complete destruction of trout stream habitat. After channelization, the pools, riffles, bank vegetation, invertebrates and other essentials were lost. • Various construction activities affecting rivers and streams, particularly direct modification of natural meanders through straightening and deepening, causes substantial losses of productivity compared to the original natural stream configurations. • The chum salmon may recognize the lack of hiding cover in channelized sections, resulting in their movement to more suitable areas upstream. • Accelerated streambank erosion and streambed degradation was observed within the channelized area. • Both coho and steelhead prefer habitat associated with pools. Pools with permanent hiding cover result in the greatest overwintering salmonid populations. Their abundance in pools presumably represents an integration of all the factors (besides space) that regulate their health and numbers, such as food production in the riffle areas. • Pool densities were low compared to conditions before channelization. • Two years following stream channelization, the number of juvenile coho per square meter increased to about 150 percent the density found before channelization (densities were measured in pools only).

	TITLE	AUTHORS	SUMMARY
			• Steelhead recovery was slow, partially because of reduced streambank cover. • Removing streambank cover reduces the number and weight of trout. Rainbow trout were more active in Shagehen Creek in relation to overhead cover. Alterations that increased hiding places increased the survival-rate percentage of brook trout fingerlings. • Increases in overwintering survival of brook trout is believed due to physical improvement in space-refuge factors (cover, depth, pool area). • Emigration of rainbow and chinook was reduced when there was substantial amounts of cover provided by large rubble.
6	**Pilot Study of the Physical Conditions of Fisheries Environments in River Basins on the Olympic Peninsula**	Orsborn. 1990 NOTE: • Interstitial spaces were used by rainbow, cutthroat and chinook.	• Newly emerged fry were found to move to shallow margins. • Migration to deeper and faster water occured as fishes grew. • All species seek cover habitat when water temperatures decrease in the fall and winter. • Overwintering habitat is the limiting factor in many drainages. Interstitial spaces are used by juvenile rainbow, cutthroat and chinook. Side channels are used by coho.
7	**Distribution of Fish and Stream Habitats and Influences of Watershed Conditions, Beckler River, Washington**	Wissmar and Beer. 1994 NOTE: • LWD contributes to habitat complexity and potential carrying capacity.	• During the 1980s, concern about declining coho and chinook stocks led to cooperative efforts to initiate stream-channel, bank-stabilization and habitat-improvement projects in the Beckler River basin. Monitoring of populations has been too infrequent to determine the success of these projects. • Recruitment of large woody debris occurs as channels shift and streambanks erode during periods of high discharge. • The presence of large woody debris increases the surface area and roughness of the streambank and channel, contributing to habitat complexity and potential carrying capacity.

	TITLE	AUTHORS	SUMMARY
			• Degradation of stream habitats by channel erosion and removal of large woody debris is evident in the greatly reduced habitat diversity and potential capacities to support fish. • The stream network needs to connect habitats required for: 1) various fish life cycles, 2) refuge from disturbances, 3) source areas that provide population for colonizing disturbed and restored habitats.
8	**Rock Size Affects Juvenile Salmonid Use of Streambank Riprap.**	Lister et al. 1995	• Assessment of habitat alteration in two southern British Columbia streams. The Thompson River wetted channel width is 100 m to 200 m wide with a mean annual discharge of 775 m^3/s. • Along the Thompson River, large riprap supported higher chinook and steelhead densities than small riprap and cobble-boulder banks during summer and winter. • Densities were greater along large riprap banks than small riprap banks, but wild coho exhibited no preference. • Suitable banks for juvenile salmonids were relatively steep, contained large rock and were constructed in a way that maximized roughness. • Study sites were situated for observing rearing and overwintering juvenile chinook salmon and rainbow steelhead trout. • It was assumed that salmonid juveniles at the study sites were rearing, not actively migrating. • It is assumed that visual checks provided valid estimates of relative bank-material size. Noted in previous winter studies juvenile salmonids were hiding within the substrate during the day. • Juvenile chinook, coho and steelhead parr were observed at higher densities at boulder-placement sites than reference sites without boulders.

	TITLE	AUTHORS	SUMMARY
			• Drifting insects are the primary food source for salmonids. Drift at a given location was positively related to water velocity. Scientists have observed that juvenile chinook salmon and steelhead trout occupied stations that allowed them to hold position in low- or near-zero velocity, usually near the stream bottom but adjacent to high-velocity flow. • Large riprap usually supported higher juvenile salmonid densities than banks composed of either natural cobble-boulder material or small riprap. • Fish distribution was clumped – 72 percent of the population was found within only 17 percent of the study site. • Additions of large boulders increased stream-habitat desirability for juvenile coho salmon and steelhead trout. • Interstices within the riprap blanket provided refuge for fish. The preference of Thompson River chinook and steelhead for large riprap in winter reflects their tendency to seek cover within a boulder or rubble substrate for overwintering. • It was recommended that riprap embankments intended to provide habitat for juvenile salmonids be constructed of coarser material than typically specified through common design criteria. Also, the practice of providing a hydraulically efficient surface is contrary to habitat requirements.
9	**FY 1995 Skagit River Chinook Restoration Research**	Hayman et al. 1996 NOTES: • Backwater and natural banks are more productive as fish habitat than riprap. Setback levees in lower rivers could be very productive. • This report does not include lower Skagit habitats.	• Investigation compared backwaters, natural banks, hydromodified banks (riprap), and bar habitat. • 0+ year chinook production (fish/m^2) was 1.78 (backwater), 0.97 (natural), 0.348 (riprap), and 0.44 (bar habitat). • Yearling chinook did not rear in any of the sampled areas.

	TITLE	AUTHORS	SUMMARY
			• Three types of fish life cycles were observed: 1) emergent fry migrating to ocean, 2) emergent fry rearing in estuary before ocean, 3) fingerling migrants (90-day) that emerge and reside in freshwater before migrating to the ocean. • Chinook use of hydromodified banks (riprap) averaged four times less than natural banks.
10	**Seasonal Fish Densities Near River Banks Stabilization Methods, First Year Report for the Flood Technical Assistance Project.**	Peters et al. 1998 U.S. Fish and Wildlife Service, North Pacific Coast Ecoregion Western Washington Office Aquatic Resources Division, Lacey, Washington.	• Study evaluated seasonal salmonid densities at five different types of bank-stabilization projects (riprap, riprap with large woody debris (LWD), rock deflectors, rock deflectors with LWD, and LWD exclusively) relative to natural control areas near the stabilized site. • Sites stabilized using large woody debris had consistently greater salmonid densities than their associated control areas. • Juvenile chinook and total juvenile salmonids densities during the spring were significantly lower at riprap-stabilized sites than natural control areas. • Coho fry densities during the spring were significantly lower at combination stabilized sites than at natural control areas. • Salmonid fry, total juvenile salmonids and total fish densities during the winter were significantly greater at sites stabilized using LWD than at natural control areas. • 1+ age trout densites during the spring were greater at sites using a combination of bank-stabilization techniques than at natural control areas but were lower at rock-deflector-stabilized sites. • 1+ age trout densities during the summer were significantly less at riprap-stabilized sites than at natural control areas. • 2+ age trout densities during the spring were significantly lower at deflectors than at natural control areas.

	TITLE	AUTHORS	SUMMARY
			• 0-age trout densities during the spring were greater at rock-deflector sites than at natural control areas. • LWD incorporated into riprap and rock deflectors did not improve rearing conditions for juvenile salmonids. The authors believe that this was the result of poorly placed LWD. The woody material formed only sparse cover for salmonids, since single logs or trimmed rootwads were used. The performance of large woody debris as mitigation in riprap and rock deflector projects may have been improved if the debris formed complex cover, which could have provided juvenile salmonids refuge from predators.
11	**Habitat Complexity, Salmonid Use, and Predation of Salmonids at the Bioengineered Revetment at the Maplewood Golf Course on the Cedar River Washington.**	Missildine et al. 2001	• The study examined the influence of modifying a riprap bank-stabilization project into a rock-deflector, large woody debris (LWD), and bioengineered (combination) bank-stabilization project on habitat complexity and fish densities from January to mid-June. • Habitat complexity, in the form of secondary habitats and cover, increased at the new combination project compared to the old riprap project. • Mean water velocities at the new combination project were more favorable for juvenile salmonid rearing. • Relative densities of salmonid parr and cottids were consistently greater at the new combination revetment than at a naturally stable bank that served as a control site. • Juvenile chinook salmon and total salmonid relative densities were less at the new revetment compared to the control area during January through March, though greater from April through June.

	TITLE	AUTHORS	SUMMARY
			• Relative densities of chinook salmon, salmonid parr, total salmonids, and cottids were greater at the new combination project than the old riprap project. • Predation on salmonids was relatively low at the combination project and the control area.
12	**Juvenile Salmonid Use of Natural and Hydromodified Stream Bank Habitat in the Mainstem Skagit River, Northwest Washington.**	Beamer and Henderson. 1998 Skagit System Cooperative Report prepared for U.S. Army Corps of Engineers, Seattle District, Environmental Resources Section. La Conner, Washington.	• Study compared juvenile salmonid use at natural and hydromodified (rip rap) bank types in the mainstem Skagit River. • Natural banks had a greater accumulation of wood versus hydromodified banks. • Wood cover was found to increase over time after hydromodification. • Juvenile chinook and coho were more abundant in areas with greater wood cover. • Juvenile rainbow showed preference for riprap (large-size rock). • Fish abundance was greater in rootwad cover versus single logs for all species except sub-yearling chum. • Sub-yearling chum prefer aquatic plants and cobble. • The findings suggest that the use of natural cover types along with bank protection may mitigate some site-level (but not reach-level) impacts of hydromodification.

CALIFORNIA

	TITLE	AUTHORS	SUMMARY
1	**Woody Vegetation and Riprap Stability Along the Sacramento River Mile 84.5 -119.**	Shields. 1991 NOTE: • This document examined the effects of vegetation on hydromodified streambanks, including the reduction of channel conveyance, impairment of revetment visibility for inspection, hindrance of flood-fighting activities, adverse effects on revetment durability from local scour by growth and uprooting of trees, and piping through levees caused by roots (Gray et al, 1991)	• Since revetment vegetation occurs along riparian corridors, its habitat value per unit area is greater than similar vegetation away from waterways. • Aerial photography showed that about 11 percent of the revetted segments supported woody vegetation types 2 (woody vegetation 4-12 ft high) or 3 (woody vegetation greater than 12 ft high) prior to the flood, but only nine percent after the flood. • Relative to aerial photos, state inspection records under-reported revetment vegetation by about 80 percent, indicating only two or three percent of the revetted bank line was vegetated before and after the 1986 flood, respectively. • Review of files revealed five instances of revetment damage attributed to the 1986 flood in the study reach. None of the five sites supported woody vegetation before or after the flood. • Damage rate for vegetated segments was roughly twice as high as for unvegetated segments, this was due to the fact that vegetated revetments were generally older. In fact, when revetments of similar age, material, and location were compared, vegetated revetments were less damaged.
2	**Juvenile Salmon Study Butte Basin Reach: Sacramento River Bank Protection Project.**	U.S. Fish and Wildlife Service. 1992	• The objective of this study was to determine the relative abundance of juvenile chinook salmon relative to various rock revetment arangements. • Monitoring occurred over three years. • The study looked at natural banks, rock fish groins and standard revetments. • Rock revetments alone had the lowest average habitat value and lowest value two out of the three years.

	TITLE	AUTHORS	SUMMARY
			• Rock groins had the greatest incremental benefits when comparing habitat improvement against cost. • Present bank-stabilization practices and riprapping destroys most, if not all, unique values of shaded riverine aquatic cover. • Example of the impacts of riprap is the transformation of irregularly shaped riverbanks to ones that are straightened and covered with a uniform, smooth layer of quarry rock. • Results of the study indicate that the experimental mitigation measures were able to recover some habitat values lost from revetments. Though none appeared to provide full replacement of habitat value based on the salmon utilization measurements. • Avoidance mitigation such as set-back levees and other approaches are recommended.
3	**Study of the Effects of Riprap on Chinook Salmon in The Sacremento River, California**	U.S. Fish and Wildlife Service 1988 NOTE: • This study was an effort to statistically determine density-dependent effects of riprap revetments on Chinook salmon.	• Study found that greater numbers of juvenile chinook salmon can be captured along cut banks than along riprap in the Sacramento River. The significance of these observations depends upon whether or not density-dependent mortality is important for young salmon that depend on the limited amounts of food and space available in the river. • Study recommended that efforts to evaluate alternatives to standard riprap, such as different slope configurations and the use of larger rocks should be continued. • A long-term effect, perhaps lasting for centuries, could result from cessation of bank erosion because it eliminates most spawning-gravel recruitment. • If loss of habitat is the only direct result of riprap installation (quantity change but not quality change) where there is surplus rearing habitat, then the riprap will likely have no effect on the production of salmon.

	TITLE	AUTHORS	SUMMARY
			• Where rearing habitat is limited, survival of juvenile salmon may decline where riprap has been installed. Fish grow faster and avoid predators more effectively in natural, unaltered habitat. • Satisfactory approaches are not available to assess separately the effect of a loss in quality of habitat and of a loss in quantity of habitat. Approaches are not available because knowledge of the movements and distribution of young salmon is poorly defined and capture of a large proportion of the fish in a reach of stream is not practical. • Juvenile salmon are more accepting of riprap when large rock is used; however, this material may also attract predator fishes.
4	**Sacramento River and Tributaries Bank Protection and Erosion Control Investigation. Evaluation of Impacts to Fisheries.**	State of California Department of Fish and Game. 1983 NOTE: • Major diet components were not significantly different between test and control area	• The study noted the presence of three insect families that comprised the majority of the chinook diet including: chironomid, mayflies, and aphids. No statistical differences in the abundance of these insects were found between cut bank and riprap areas. • Average of only one-third the number of chinook in riprap vs. control areas. It was believed that differences relate to the increase in the zone of turbulent flow when large rock is present. • The study found a higher diversity of species present in riprapped areas than in the control areas, which is attributed to the large size of rock used. • Though steelhead trout were not a focus of this study, they were observed in the study area. There appears to be no significant difference in steelhead presence between riprap and natural habitat areas. • The majority of salmon fry migrate during darkness. Most downstream migration and emergence from gravel occurred at night with less than five percent of movement occuring during daylight hours.

	TITLE	AUTHORS	SUMMARY
			• It was suggested that the age of the riprap treatment has an effect on fish habitat preference (no evidence was mentioned to support this hypothesis). General observations indicate that low-velocity areas with considerable cover tend to have higher daytime salmon densities than the type of habitat typical of cut banks. Riprap effects probably do not extend all the way to mid-river. • Project impacts were believed to have caused a six-percent reduction in the abundance of adult spawners (this was, however, a near-worst-case estimate). • Sloping banks to provide shallow-water habitat at greater flow ranges may reduce the losses of fish .
5	**Biological Data Report Regarding Sacramento River Bank Protection Project Impacts on Winter-Run Chinook Salmon. Second and third Phases.**	ECOS, Inc. 1991 NOTES: • This report examined riprap size/type and its potential effects on salmonid use. • From historic levels only two to three percent of of the natural, woody, riparian vegetation remains along the Sacramento River. It is currently confined to an approximately 30 foot width. • Potentially adverse impacts resulting from the second-phase of the bank-protection project on habitat components were identified, although the extent of those impacts are difficult to quantify. Individual, incremental impacts are possibly minor.	• Since 1972, there has been a 22 to 26 percent reduction of river-edge riparian habitat. Most of this reduction is attributed to bank-stabilization projects. • Chinook salmon production is affected by riparian loss.The loss of a riparian buffer has caused changes in water temperature, reduced instream-cover and reduced habitat diversity. • The most significant, intermediate impacts to fishery resources occurs at bank-protection projects that involve removal of near-shore riparian vegetation, grading of the bank slope and placement of rock revetment over the graded slope. • The principal causes for low use of revetted areas by chinook juveniles are believed to be elevated velocity levels along riprap substrate and a reduction of large, instream cover habitat. Drift densities of invertebrate prey species was not found to be significantly different. • Data from other regions indicate that the impacts of riprap are greatest on fish health during the fry stage of development when their tolerance of depth and velocity extremes is narrower. • Chinook fry are less likely to be displaced by stream flows into downstream riprapped areas than are other salmonid types that emerge during winter or spring.

TITLE	AUTHORS	SUMMARY
		• Riprap affects smolts most during periods when fish are stationary and feeding (typically during daylight hours). • Juvenile chinook are commonly found associated with instream cover, which shelters juveniles from predators and severe environmental conditions and provides efficient feeding stations. An explanation for their presence at sites without instream cover was not provided by this work. • Low-hanging riparian vegetation, undercut banks and submerged woody debris are important habitat components for rearing juvenile salmonids as protection from avian and terrestrial predators and as sources of shade. • Little is known concerning the importance of shade to juvenile chinook salmon, although it is significant during periods of elevated water temperatures. • Construction-related increases in water turbidity were local and temporary. Juvenile salmon avoid turbid water as will adult salmon. Decreased production of fish-food organisms caused by turbidity was not found to be significant by this study. • Water velocities in proximity to large, angular rock may negate its positive characteristics and partly explain the low use of riprap habitat by juvenile chinook salmon. • Replacement of woody debris or natural substrate cover with quarry rock results in a reduction of habitat quality. • It was found that higher numbers of juvenile chinook salmon congregate around cut bank rock revetment sites where both gravel and fish groins have been added, than found at nearby natural areas. • Juvenile chinook abundance was observed to be higher at rock revetted areas with fish groins than at standard rock areas, although the extent of the mitigative value of groins has not been quantified.

TROUT HABITAT

	TITLE	AUTHORS	SUMMARY
1	**Better Trout Habitat- A Guide to Stream Restoration and Management.**	Hunter. 1995 NOTE: • Studies cited were conducted on small streams.	• A common mistake in bank-stabilization projects is to stabilize eroding banks on the outside of meander bends where the eroding process is natural and creates prime habitat. • If the riparian vegetation is in poor condition, erosion can be greatly accelerated, leading to the loss of land and to collapsed banks that do not provide cover. Often, the response to this situation is to provide structural bank protection in the form of riprap. However this locks the stream into a single, rigid course and limits its ability to create trout habitat. • Boulders have been placed along the margin of the stream where overhanging grasses provide cover. These boulders breakup a long riffle and provide rearing habitat for juvenile trout. • Habitat created by boulders placed along banks in riffles contains juvenile chinook and steelhead while adults have been found to use boulder berms for resting.
2	**Some Effects of Channelization on the Fishes and Invertebrates of Rush Creek, Modoc County, California**	Moyle. 1976 NOTES: • Channelization includes both riprap and channel straightening. • As observed in other studies smaller fish used the channelized section.	• Channelized sections contained fewer and smaller trout as well as a lower biomass than the unchannelized sections. Overall, total fish biomass in the channelized sections was less than one third of that found in the unchannelized sections. • Negative effects on fish and invertebrate populations were noted, but poorly documented. • Average sizes of rainbow trout, brown trout and Modoc sucker were smaller in channelized sections than in unchannelized sections. Pit sculpins and brown trout were more abundant in the channelized sections.

	TITLE	AUTHORS	SUMMARY
			• 80 percent of the biomass in channelized section was rainbow and brown trout. • Studies in Montana show that channelization reduces the average size and number of trout. • Lost carrying capacity was caused by loss of: pools, overhanging bushes, large boulders and other cover habitat components. Only riffle-dwelling fish were able to use the scant cover and turbulent water of the channelized sections.
3	**The Physical and Biological Effects of Physical Alteration on Montana Trout Streams and Their Political Implications. Symposium on Stream Channel Modification.**	Bianchi and Marcoux. 1975	• There were approximately three times as many brown trout in a natural section as compared to a bulldozed section and two times as many as compared to a riprapped section.
4	**Manual of Stream Channelization Impacts on Fish and Wildlife.**	Simpson. 1982 NOTE: • Valuable sections on biological impacts.	Channelization effects are more pronounced for aquatic organisms, and upstream effects are probably greater than downstream effects.
5	**The Place of Channel Improvement in Watershed Development. In-Stream Channelization: A Symposium.**	Martin. 1971	Documented evidence of irreparable damages to fish and wildlife is needed so that mitigation measures and enhancement practices for fish and wildlife can be recognized.

MISSISSIPPI

	TITLE	AUTHORS	SUMMARY
1	**Using Riprap to Create or Improve Riverine Habitat.**	Dardeau. 1995	• Case studies along the Mississippi River illustrate the habitat value of riprap, which is particularly pronounced in alluvial river systems dominated by soft substrates. • Riprap provides hard substrate for invertebrates, which is especially important in alluvial river systems where this material is scarce or absent. • Non-keyed placement of rock can provide direct habitat benefits to fish because such placement of riprap approximates natural situations in which velocity and substrate size are positively associated.
2	**Effects of Channel Restabilization on Habitat Diversity, Twenty Mile Creek, Mississippi**	Shields and Hoover. 1991 NOTES: • Stabilization projects can provide habitat and refuge for some fish species. • (Since this study was done in Mississippi, it has limited application to the Pacific Northwest where conditions are significantly different.) • This study describes the importance of providing diversity in habitat characteristics at bank stabilization projects.	• Grade-control structures (weirs with stone-protected stilling basins) and various types of streambank protection were constructed along the channel in the early 1980s to restore stability. • Grade-control structures also promote biological recovery in unstable, channelized streams by providing coarse, stable substrate. • Three grade-control structures and assorted streambank-protection measures (concrete jacks, stone revetments and combinations of structure, grasses and woody species, primarily Salix spp.) were installed. Grade-control structures consisted of sheet pile or stone weirs with crests above the streambed and approach channels and stilling basins lined with stone riprap and graded stone riprap. • The frequency of eroding banks was greatly reduced due to the presence of riprap revetments. • Diversity was variable among all stations but was higher in Twenty Mile Creek, especially at grade-control structures,

	TITLE	AUTHORS	SUMMARY
			presumably due to higher levels of physical diversity there. • Stream channelization and destabilization reduce aquatic habitat diversity. Although the relationship is complex, stream-fish communities respond positively to increasing levels of habitat diversity. • Grade-control structures and bank-protection structures facilitate habitat recovery in two ways: 1) by promoting overall channel stability, and 2) by serving as major habitat features. • Stabilization structures can provide refuge for fish experiencing reductions in available habitat. Channel-modification projects would be less detrimental to aquatic ecosystems if they were designed and constructed with two-stage cross sections that included low-flow channels. • Species diversity and richness of fish communities in channelized streams are positively associated with structures that increase depth, decrease velocity and increase habitat diversity at low flow.

MIDWEST

	TITLE	AUTHORS	SUMMARY
1	**Stream Channelization in the Midwest. In-Stream Channelization: A Symposium.**	Funk and Ruhr. 1971	• All states have reported that stream-fish habitat has been destroyed and degraded by channelization.
2	**Stream Channelization Effects on Fishes and Bottom Fauna in the Little Sioux River Iowa. In- Stream Channelization: a Symposium.**	Hansen. 1971	• Fish diversity was greater in unchannelized stream section. • A 90-percent reduction was reported in the number of fish per acre per inch length in 23 channelized streams. Forty years following channelization, no significant return to normal stream populations occurred. • Removal of streambank cover was an important factor contributing to higher water temperatures and higher suspended-sediment loads from channel erosion. • Results indicated that channelized sections were not favorable to stable populations of larger game fish.
3	**A Review of References to Channelization and it's Environmental Impact. In-Stream Channelization: A Symposium**	Heneger and Harmon. 1971	• Pounds of fish per acre in the channelized portion of the Blackwater River in Missouri were 131, in the slightly channelized reaches 449 (mostly carp) and in the unchannelized section 565 (primarily channel catfish). • Twenty three channelized streams and 36 natural streams examined by pounds fish per acre in the Lower Piedmont and Coastal Plain of North Carolina were found to be significantly different. Channelization reduced the number of game fish (larger than six inches) per acre by 90 percent, the weight by 85 percent and the standing crop by 80 percent. There was only limited recovery

TITLE	AUTHORS	SUMMARY
		after 40 years. • The Little Sioux River in Iowa had water temperatures with greater daily fluctuations during the summer in the channelized section. • Consistently higher turbidity levels were found in the channelized portion. • Colonization of macroinvertebrates on artificial substrates suggested lack of suitable attachment areas in the channelized portion. Numbers of fish were fewer in the channelized section. • Flint Creek (Montana), a trout stream, had a 350-foot section dredged, cleared and straightened. This section had been previously inventoried for fish populations for several years. In 1955, a year before the dredging, a total of 20 pounds of fish were taken in this section. Dredging began in 1956 and, in 1957, after the channel "improvements were completed," 1.5 pounds of fish were found in the same section. • Seven times as many fishery-sized trout and over 60 times as many whitefish were collected in natural stream sections in comparison to those that had been subjected to various types of alterations. By weight, the differential was 14 to 1.

FOREIGN SOURCES

	TITLE	AUTHORS	SUMMARY
1	**Effects of River Bed Restructuring on Fish and Benthos of a Fifth Order Stream, Melk, Austria.**	Jungwirth et al. 1993 NOTE: • Recovery after three years is briefly described during the reconditioning of a channelized section of stream by adding groins and bedfalls.	• Benthic drift decreased significantly in the restructured river section, suggesting unfavorable conditions for many benthic invertebrates in the straightened section. Terrestrial invertebrates however, occasionally entering the water body, showed a tenfold increase in drift in the channelized reaches. • The number of fish species observed increased from 10 to 19 and fish density and biomass as well as annual production of 0+ age fish increases threefold. Modeled productions weren't realized, suggesting more time is needed to establish a balanced community.
2	**Effect of Channelization and Regulation of Fish Recruitment in a Floodplain River.**	Jurajda. 1994 NOTES: • This study was conducted on a tributary of the Danube. (It has limited applicability to the Pacific Northwest.) • However, characteristics of the riprap used are similar to that used in the Pacific Northwest – large angular rock, often silted.	• In the absence of areas with lentic backwaters or side arms with aquatic vegetation in the channelized river, the fish could only use the stabilized banks of stony riprap or rare, shallow-slope, gravel shorelines. Shorelines are important as a nursery for all 0+ fishes. Spawning and nursery sites are now limited to the main channel shoreline. • Fish were more influenced by changes in reproduction conditions than by changes in food sources.
3	**Fish of Channelized and Unchannelized Sections of the Bunyip River, Victoria.**	Hortle and Lake. 1983	• The short-term effects of this project (located in Australia) includes a reduction in the numbers and biomass of the resident fish populations of the stream. • The long-term effects of the project depend on whether fish populations can recover by adapting to the new conditions. • The presence of snags (woody debris) is an important determinate of fish abundance. • Channelization reduced trout populations and the lack of suitable physical habitat was the major cause. • Trout were both more abundant and reached a larger size at the unchannelized sites than at the channelized sites.

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Cost of Techniques

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Appendix L
Cost of Techniques

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Cost is often included as criteria for design and may influence selection of a treatment or dictate what protection techniques may be considered as alternatives. Bank-protection costs include design, materials, construction and dewatering, revegetation, monitoring, maintenance, mitigation and permitting. Design costs are typically 10 to 20 percent of construction costs, including revegetation. Monitoring, maintenance and permitting costs vary widely among project types and specific regulatory requirements.

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

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

- repair of damage to property and infrastructure;
- relocation of at-risk facilities;
- compliance with habitat-protection requirements under the federal Endangered Species Act or other laws;
- restoration of the channel to prevent further habitat losses caused by the protection action; and/or
- habitat mitigation for the duration of the project's impact, including monitoring and adjustments.

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

COST ESTIMATING

This appendix is intended to provide generalized information about bank-protection costs. Site-specific, project-specific criteria, as well as permitting requirements impact total bank-protection costs more than the streambank-protection technique selected. The cost examples provided here are derived from projects conducted in Washington State in recent years; however, due to the variability of site- and project-specific influences, these examples may have only limited applicability to any other site.

Cost estimates for bank protection can be derived as follows:

1. *Design streambank protection*. At a minimum, costs of a streambank-protection project cannot be effectively estimated without a conceptual design. With conceptual design, cost can be estimated based on cost of similarly constructed projects with similar implementation components and characteristics (access, tie-backs, dewatering). Generally speaking, a conceptual design usually represents about 30 percent of the final design.
2. *Estimate of materials cost*. Calculate quantities of all materials necessary for construction, and research unit prices for these materials. Unit prices may vary according to volume. Determination of unit prices should always be based on information from suppliers and should account for transportation expenses to and from the site.
3. *Determine construction sequence*. Development of the construction sequence determines many important construction-cost considerations such as what equipment is required, where access roads are needed, where staging areas can be set up and whether dewatering will be necessary. Contractors can be very helpful in determining construction sequencing and in providing cost estimates but often will need substantially more than conceptual drawings to provide estimates.
4. *Calculate cost of mitigation, monitoring and maintenance*. Maintenance costs can conservatively be estimated as five to 10 percent of construction costs; although, in riparian-restoration projects, costs may be significantly higher. Mitigation and monitoring costs will be project-specific, depending upon mitigation requirements and monitoring objectives.

Design Cost

The cost of design for streambank-protection projects is typically 10 to 15 percent of construction costs, including contingencies. Design cost depends largely upon level of analysis and format of designs. Plans may be sufficiently detailed to allow the project to be let to bid on a lump-sum basis, or largely conceptual in nature and intended only to provide guidance. For example, on a bank-reshaping project that does not require a constructed toe or dewatering, construction may proceed with little design and may be as little as five percent of total cost, depending upon permitting requirements. Conversely, on a soil-reinforced project that requires detailed drawings to contract for the project and to meet permitting requirements, design costs may approach 15 percent of total cost. Sedimentation and erosion-controls plans often require an additional level of detail. Furthermore, the nature of dewatering methods used may add considerably to design costs. The level of detail required may be a function of permitting requirements.

Materials Costs

The following categories describe materials incorporated into streambank-protection projects:

- *rock materials* - for bank-toe, upper-bank construction or filter drains;
- *soil materials* - for backfill or topsoil;
- *fabrics* - for reinforcement or erosion control;
- *artificial materials* - for fabricated structural or internal geotechnical components;
- *plant materials* - for revegetation; and
- *wood materials* - for habitat components and bank-toe or upper-bank construction.

Typical costs for specific materials in each of these categories are listed in *Table L-1*. It's important to note that these are installed costs, which include purchase of the material, hauling to the site, excavation, spoilage and installation.

Material Type	Unit of Measure	Unit Cost
Rock Materials		
Riprap	Cubic Yard	$60-$80
Pit Run	Cubic Yard	$30-$40
River Gravel	Cubic Yard	$40-$80
River Cobble	Cubic Yard	$80-$100
Boulders (2-4 ft diameter)	Cubic Yard	$40-$60
Filter Gravel	Cubic Yard	$40-$60 (placed)
Soil Materials		
Topsoil (standard grade)	Cubic Yard	$10-$15
Structural Fill	Cubic Yard	$60-$80, includes compaction
Fabric Materials		
Woven Coir Fabric	Square Yard	$2.00-$3.00
Nonwoven Coir	Square Yard	$1.00-$2.00
Nonwoven Geosynthetic Filter Fabric	Square Yard	$0.50-$0.68
Biodegradable Geotextile Fabric	Square Yard	$2.85-$3.00
Artificial Materials		
Doloes	Each	$200-$900
Plant Materials (see Table L-3)		
Wood Materials		
Large Wood With Rootwad	Each	$500-$750
Large Wood Without Rootwad	Each	$200-$300
MISCELLANEOUS		
Wooden Stakes	Each	$0.40 - $0.75
Cable	Linear Foot	$0.75 (1/2" diameter)
Cable Clamps	Each	$0.54 (cost varies based on cable diameter)

Table L-1. Typical costs of streambank-protection materials.

The cost of nonmanufactured materials, such as soil, rock and large woody debris is greatly affected by transportation and installation costs. Transportation generally requires loading the materials into street-legal vehicles, hauling, stockpiling and distributing within a project site. Materials costs can be reduced by finding on-site sources of rock and soil that can be excavated and installed with a single piece of equipment, such as a loader or dozer. However, this will depend to a great degree upon permit conditions and mitigation requirements and is generally problematic on sites where vegetation and site disturbance should be kept to a minimum.

Construction and Dewatering Costs

Construction costs include mobilization, installation (and eventual removal) of access and haul roads, dewatering, sediment control and bank-treatment construction. Construction costs are site-dependent and tend to increase dramatically with restrictions on site access and project scope. For example, a bank-protection project within a small and confined urban stream may limit equipment size and construction operations, reducing progress rates and increasing costs. Conversely, an easily accessed rural project on a larger river may accommodate large equipment and stockpile areas and may also provide an on-site source for some materials, thereby improving progress rates substantially.

For further discussion of access and haul roads, equipment selection and dewatering, refer to Appendix M, *Construction Considerations*.

Construction/Dewatering Components	Unit of Measure	Unit Cost
Access and Haul Roads		
Access with Geotextile Base	Linear Foot	$10-$20
Dewatering		
Portadam Coffer Dam (dry)	Linear Foot	$25-$40
Cement Barrier (wet)	Linear Foot	$10-$25
Gravel Barrier	Linear Foot	$5-$25
Sediment Control		
Silt Fence	Linear Foot	$1.50-$2.50
Straw/Hay Bale Barrier	Linear Foot	$1-$3

Table L-2. Range of costs for construction and dewatering components of bank-protection projects in the state of Washington.

Revegetation and Planting Costs

Revegetation is an integral part of any bank-protection project, or an associated component of repairing construction-related disturbance. Revegetation materials include seed, cuttings and plants that are rooted, balled, burlapped or potted. Mulch and irrigation are also considered revegetation materials. These are discussed in more detail in Appendix H, *Planting Considerations and Erosion-Control Fabrics*. Plant-material costs depend upon the maturity of the plants purchased. Seed and tubeling stock are sold at a fraction of the cost of more mature stock, although substantially more maintenance is required to guarantee survival. Cost of revegetation may be greatly affected by the lead time a nursery is given to acquire and/or cultivate the materials ordered. Refer to Appendix H for recommended planting densities.

Plant Material	Unit of Measure	Unit Cost
Soil Preparation	Square Yard	$2.25 (includes tilling, grading and hand raking)
Live Cuttings	Each	$2-$5 (planted)
Tubelings	Each	$1-$4 (planted)
Conservation Plugs	Each	$1-$4 (planted)
Grass Seed	Acre	$750
Evergreen Trees (3 ft height)	Each	$15
Deciduos Trees (3/4" caliper)	Each	$20
Shrubs (1-2 gallon)	Each	$8-$12
Ground Cover (1 gallon)	Each	$8-$10
Mulch	Square Yard	$2-$5
Hydroseeding	Square Foot	$0.04

Table L-3. Range of costs for plant materials applied in streambank-protection projects.

Monitoring, Maintenance and Mitigation Costs

Streambank-protection projects also require maintenance and monitoring, which are discussed in Appendix J, *Monitoring* and under each individual technique in Chapter 6, *Techniques*. Costs for maintenance and monitoring are site-specific and depend upon the degree and frequency of activity. Maintenance costs are generally variable and unpredictable, while monitoring costs are dictated largely by the amount of time spent monitoring and the techniques used. Reporting requirements associated with monitoring activities generally cost about the same as the monitoring activity itself.

Mitigation may also be a required component of streambank-protection projects. Mitigation costs may add significantly to total project costs. For this reason, it is imperative that project managers consider the full extent of mitigation required for a protection project while developing designs and costs estimates. For further discussion of mitigation, refer to the matrices presented in Chapter 5, *Identify and Select Solutions* and to individual techniques presented in Chapter 6.

RELATIVE COST OF BANK-PROTECTION TECHNIQUES

For the purposes of comparison, overall costs for a given bank-protection technique are expressed in linear-foot or bank-face-foot units. Linear-foot costs are calculated by dividing the total cost by the length of the bank protected. For bank-protection projects that have repeating components up the bank, such as reinforced soil lifts, costs may be expressed as "cost per square foot of bank face." Applying this approach, costs for new projects, particularly those with variable bank heights, can be reliably estimated using known costs for an established protection technique.

Cost Ranges for Streambank-Protection Techniques

Table L-4 shows the estimated cost ranges for various bank treatments installed primarily in Washington State between 1995 and 2000. Costs are for materials and construction only and do not include design or postconstruction components of the project. Cost ranges in many cases vary considerably. Where site- or materials-specific factors are too widely scattered in values, their units of measure and costs are expressed at "not applicable." Because any given technique can be applied to a variety of channel circumstances, cost ranges can sometimes span an order of magnitude difference. For example, a drop structure across a small stream may be installed for as little as $100, while a drop structure constructed across a large river may cost upwards of $40,000. Furthermore, site-specific construction considerations (refer to Appendix M) and materials availability can greatly affect project costs. For these reasons, the costs listed on *Table L-4* should be considered rough estimates and should be used only on a conceptual basis for the purposes of comparison.

INSTREAM FLOW-REDIRECTION TECHNIQUES		
Material	**Unit of Measure**	**Unit Cost**
Rock Materials		
Groin (rock)	Each	$2,000 - $5,000
Groin (doloes)	Each	$12,000 - $45,000
Buried Groin (rock)	Each	$2,000 - $5,000
Barb (rock)	Each	$2,000 - $5,000
Engineered Log Jam	Each	$1,800 - $80,000
Drop Structures	Each	$100-$40,000
Porous Weir	Each	$100
STRUCTURAL BANK-PROTECTION TECHNIQUES		
Anchor Points	na	na
Roughness Trees	Linear Foot	$40-$80
Riprap	Linear Foot	$30-$90
Log Toe	Linear Foot	$20-$60
Rock Tow	Linear Foot	$20-$40
Log Cribwalls	Linear Foot	$250-$350
Artificial Streambank-Protection Materials and Systems	na	na
BIOTECHNICAL BANK-PROTECTION TECHNIQUES		
Woody Plantings (at 3 ft spacing)	Acre	$25,000-$30,000
Herbaceous Cover	Acre	$7-$15
Soil Reinforcement	Linear Foot	$50-$400
Coir Logs	Linear Foot	$8-$30
Bank Reshaping	Linear Foot	$10-$45
Fascines	Linear Foot	$8-$120
Brush Layers and Mattresses	Linear Foot	$37-$50
INTERNAL BANK-DRAINAGE TECHNIQUES		
Subsurface Drainage Systems	na	na

Table L-4. Estimated cost ranges for various streambank-protection techniques.

CASE STUDIES

Three case studies of recently constructed projects in Washington State are provided to give cost exampes of various bank-protection projects.

Salmon Creek: Clark County, WA - Rock Toe, Soil Reinforced Lifts and Vegetation.

This project is an effort to implement bank protection that is sensitive to fish and wildlife habitat and addresses long-term bank stability. Bank protection was installed at approximately 20 streambank sites within the Salmon Creek drainage system to provide long-term protection of predominantly private property. Bank stability, riparian and fish and wildlife values were addressed as well as hydraulic/hydrologic condition. Width and depth of the channel varies. Average width is approximately 20 feet, and average depth is approximately five feet.

Most sites within the project area incorporated a rock toe with reinforced soil lifts and vegetation. Bank height varied from four to six feet, and protection measures included two to four soil lifts. A rock toe offers relative permanence to the bank location, while soil-reinforced lifts offer immediate protection against all flows and a long-term opportunity for healthy native riparian vegetation to thrive. *Figure L-1* shows one of the project sites after construction.

Figure L-1. Salmon Creek bank protection using rock toe, soil-reinforced lifts and vegetation.

Project access was generally provided through privately owned, single-family residences with moderately sloped back yards. Access did not present any particular limitations to materials or equipment. Site restrictions included limiting disturbance to residential property.

Project components consisted of rock toes and soil reinforced lifts planted with riparian grass-seed mix and vegetative cuttings. Materials included existing soils, imported angular rock, coir fabric (woven and nonwoven), wooden stakes, riparian grass-seed mix, willow and dogwood cuttings. Equipment used on site included dump trucks, a loader and a tracked excavator. No dewatering was used. Sediment control consisted of temporary in-channel silt barriers.

The average cost per foot of treated bank was approximately $100 (linear foot of bank), translating to an average of $10,000 per site, not including design, permitting or mobilization.

Whatcom Creek: Whatcom County, WA - Engineered Log Jams

Large wood was used to enhance cutthroat trout habitat within Whatcom Falls Park near Bellingham. Project objectives focused on creating low- and high-flow cover habitat and areas where spawning gravel could deposit within the bedrock-confined channel. This work followed clean up of a large pipeline gas spill and fire. The two-year return interval discharge is 628 cfs. The channel has a variable width within the steeply incised channel of between 90 and 30 feet. Bedrock controls the grade and width within the project reach.

Access to the channel was limited by steep, forested terrain and offered no opportunity for constructing temporary roads. The site was accessed using a spider hoe or walking/legged, all-terrain excavator.

Project components included installation of three engineered log jams. *Figure L-2* shows the project after construction. A Hilti® fastening system was used to drill and cable trees to key rocks. The increased ballast was used to simulate the drag force obtained by using trees with rootwads. All wood used was from felled trees adjacent to the creek. Galvanized-steel core cable and cable clamps were used to anchor the large wood in place. Other equipment used included: battery-operated Hilti® drill, glue, chokers and a winch mounted on the walking excavator used by workers to pull themselves out of steep areas. No dewatering was used.

Figure L-2. Engineered log jams on Whatcom Creek.

The cost for installing three log jams (using on-site large woody debris) was approximately $9,000, not including design, permitting or site access costs. The estimated cost to accomplish the same project with imported, two-to three-foot-diameter, large woody debris was $27,000.

Nooksack River: Whatcom County, WA - Groins

This project involved constructing groins along two eroding bank sites on the Nooksack River. Groins were constructed of rock; large, concrete, armor units, or "doloes"; and large wood to provide habitat value for salmonids while preventing further erosion into agricultural land. The Nooksack River at this site is a rapidly changing channel with frequent shifts in dominant channel location and orientation. Bank protection was deemed necessary to protect private agricultural land and to prevent a potential large-scale channel avulsion.

Two separate sites were protected. The first site, a 2,100-foot reach, consisted of concrete dolo groins constructed using a large-diameter, angular-stone foundation, with large doloes on the upper portion to simulate and trap large wood. The concrete dolo groins form permeable "noses" that collect woody debris more readily than the nonporous, all-rock, groin type (see *Figure L-3*). The second site, a 1,000 foot reach, consisted of 10 woody groins constructed of 16-inch-diameter (minimum), untreated timber pilings installed to a 25-foot depth, cross logs and rootwads with riprap scour protection at the base of each groin (see *Figure L-4*).

Figure L-3. Concrete dolo groins on the Nooksack River.

Figure L-4. Woody groins on the Nooksack River.

Unrestricted access to the site was available using existing county and private roads. Access roads along the bank were created.

Project components included constructed groins, installed woody debris among groins, resloping and revegetation of bank slopes between groins, and a detailed monitoring and maintenance program. Materials for the concrete-dolo groins included large-diameter (four-foot) angular rock; large, concrete armor units (25 to 40 per groin); imported woody debris; and rootwads cabled to ecology blocks with braided cable and clamps. Materials for the woody groins included straight timbers, logs with rootwads and cables. The project also included bank resloping, included hydroseeding with grass species, installing unrooted willow cuttings and planting bare-root riparian trees and shrubs. In addition, cutback trenches were incorporated at the ends of treated banks, which consisted of a launchable riprap pad within an excavated and backfilled trench. Equipment included excavators, dump trucks and loaders.

The cost for the dolo-groin treatment was approximately $440 per linear foot of bank. The cost of the woody-groin treatment was approximately $155 per linear foot of bank.

CREDITS

Figure L-1. Source: Inter-Fluve, Inc.
Figure L-2. Source: Inter-Fluve, Inc.

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Construction Considerations

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Appendix M
Construction Considerations

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Construction issues can significantly influence both the feasibility and design of a streambank-protection project. Ideally, the constructability of streambank-protection techniques should be considered during project scoping, as it may greatly influence the selection of techniques. Constructability should also be considered during the development of design criteria and the selection of construction methods; some criteria may be unaffordable to build, impractical to implement or impossible to achieve.

This appendix is intended to provide a broad overview of construction considerations. Because site-specific conditions and project-specific criteria influence construction approaches significantly, a comprehensive discussion of construction techniques is beyond the scope of this document. However, careful consideration of the topics listed here should assist streambank-protection practitioners in developing a comprehensive work plan for accomplishing project goals with respect to construction issues.

SITE LIMITATIONS

Site limitations such as location of utilities, land ownership, infrastructure, sensitive landscapes, stockpiling/disposal and access are constructability issues that may influence many design components. For this reason, site limitations should be considered during all phases of design and implementation and are best addressed by preparing a construction-sequencing plan, an outline of the major tasks and their sequential order of construction. By thinking through a conceptual construction-sequencing plan early in the design process, many issues of constructability that are dictated by site limitations can be resolved or at least brought to the forefront early on.

Utilities

Utilities are often found near or within a project site. Careful review of the site will reveal most utilities present, including power lines, railroad tracks, pipelines, buried cables, sewers and other common utilities. All utilities owners should be contacted to evaluate hidden utilities and to identify or establish protocols for working near or within utilities' rights-of-way. Urban project locations with many site limitations may require the temporary or permanent relocation of utilities to accomplish project objectives.

Stockpile and Disposal

Any significant movement of materials on-site, off-site or within the site will require a stockpile area for temporary storage of construction or waste materials. Stockpiling of construction materials (e.g., gravel, rock, soil, fabric, wood materials) and disposal of waste materials (e.g., excavated bank materials, vegetation, trash) should be considered during the construction sequencing. Careful consideration of stockpile size and location will facilitate construction, reduce cost and limit damage to sensitive areas. The location of stockpiles can significantly increase or decrease cost if it increases or decreases cycle time for construction operations.

Site Access

While some types of projects can be constructed solely with hand labor, the construction of most bank-protection projects will require heavy equipment at the project site. Site-access considerations include ingress and egress for construction staging, access to the streambank and any planned stockpile areas (e.g., construction and waste materials), and dewatering and sediment-control systems.

There are several ways to access a site for streambank construction activities:

- use an existing access point,
- construct an access point,
- construct a temporary construction platform adjacent to the streambank,
- create an in-channel access point during low-flow conditions or where the channel has been dewatered such that the work area is dry (e.g., exposed gravel bar), or
- use a spider excavator, a floating platform or heavy equipment as construction access within a wetted channel.

Access through a riparian area should be carefully marked to minimize impacts and to aid in the subsequent restoration efforts. Mitigation for construction activities will be necessary. See Chapter 4, *Considerations for a Solution* for more information about mitigation.

Access Roads

Temporary access roads may need to be constructed to transport materials and equipment to the site. Access roads must be designed and built according to the needs of the equipment, taking into account road grade, equipment size and weight distribution, and vegetation and habitat character. In particular, the need for equipment to maintain traction will drive important design decisions if ground conditions at the site are slippery, steep or soft. Street-legal dump trucks in particular are limited in their ability to travel on unpaved roads. Many types of equipment are able to travel on softer roads, causing less damage to soils because their weight is better distributed. Excavators, tracked dump trucks and other vehicles can be outfitted with extra wide tracks to reduce weight impacts and soil compaction.

In relatively nonsensitive areas (e.g., meadows, pastures, woody riparian areas), access roads can be constructed by placing road gravel on geotextile materials laid directly on the ground surface. Some of the plastic products on the market (PVC, PVE, etc.) can be used to reinforce low-load-bearing soils. This approach is appropriate when access roads will be used frequently for hauling materials or equipment or for refueling operations.

Access can also be achieved using temporary mats (e.g., linked tires, cabled ties, landing mats) to "walk" equipment across sensitive areas on a limited interval basis. This assumes little or no materials will be transported in or out of the site for the duration of the project, and whatever equipment is needed can be housed and maintained at the site.

Scheduling construction for times when the ground is either dry or frozen can also reduce impacts associated with access roads. Snow-covered, frozen soils can often be traveled with wide-track equipment with no impact to underlying vegetation or soils. Similarly, dry conditions reduce many impacts associated with soil compaction and soft soils.

In summary, the following circumstances should be considered in designing and timing construction access to the site:

- refueling location and frequency,
- sensitivity of landscape soils and vegetation,
- size and character of equipment,
- frequency of ingress/egress, and
- season and soil moisture.

Construction Platform

Construction of most bank-protection projects will require some degree of heavy-equipment mobility along and near the bank. Construction of bank protection can be conducted from the channel, from the bank or from a temporary platform. Site limitations may determine where construction is conducted.

Near-bank construction platform. Traditionally, the majority of operations are conducted in the bank and in near-bank areas. This requires either a sizeable bank-reconstruction area (which may facilitate conducting construction activities entirely within the bank-treatment footprint), or it results in considerable impact to near-bank environments. In the latter case, remediation of near-bank environments is required.

Between-bank construction platform. When site restrictions require that construction must occur within the channel banks, there are a number of options. Of particular note, the channel can be partially or completely dewatered. Dewatering a channel will require protocols for cleaning equipment, refueling equipment and handling fluid spills. Advantages of this type of operating platform include minimizing impacts to near bank areas during construction and enabling detailed manipulation of the channel bed and bank toe for habitat enhancement without the interference of flowing water during construction.

Temporary construction platform. An alternative to dewatering for between-bank construction is a temporary fill platform within the channel, constructed from large rock (with a small rock work surface). Temporary platforms can also be constructed within the channel on temporary pilings. A third alternative is to operate equipment positioned on a barge within the channel. This is particularly appropriate for dredging and excavation activities.

CONSTRUCTION PERIOD

The timing of construction will often be determined by regulatory mandates intended to reduce water-quality impacts to critical fish life cycles such as migration and spawning. The timing for construction projects that affect state waters varies throughout the state, depending upon the species present in the watercourse. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). Once the allowable construction window has been identified for your project, additional factors such as hydrologic, precipitation and revegetation considerations will assist in determining the most appropriate time to operate within the established work window.

Hydrology and Precipitation

Hydrologic analyses that can be helpful in determining an appropriate time for construction include analyses of seasonal variations in average and extreme flows. From the standpoint of feasibility and cost-effectiveness, construction should occur when average seasonal flows are low and the likelihood of high-flow events is at its lowest. This will vary geographically, depending upon the dominant hydrologic character of a watershed. Further information on methods for determining hydrologic character and approaches to hydrologic analyses are available in Appendix D, *Hydrology*.

Hydrologic analyses should also be conducted to determine the appropriate method and design for dewatering. Dewatering systems must be designed not only to handle average flows, but also to handle anticipated high flows associated with storms or other hydrologic events during the construction period. In scenarios where it is impractical or impossible to design a dewatering system that can handle storm flows, it is important to determine the extent to which the dewatering systems will be inundated during such flow events and for how long. Before proceeding with construction of a bank-protection project, the potential consequences of inundation due to high seasonal flows should be estimated and the risk of such occurrences calculated using hydrologic statistics. These analyses can be conducted for any stream using daily gauge data. They are further discussed in Appendix D.

Revegetation

Successful revegetation is largely determined by the timing of revegetation efforts. Ideally, revegetation components of a bank-protection project will be conducted to maximize the potential for survival of the plant materials installed and to enhance their ability to grow quickly. Furthermore, the success of many bioengineered techniques will require that vegetative cover be maximized in the least amount of time possible following construction. This requires minimizing the period of dormancy of installed materials between installation and the following growing season and ensuring ideal moisture conditions, which are often specific to species and plant forms installed, following construction. Detrimental moisture conditions may include either drought or inundation. For further discussion of planting considerations, refer to Appendix H, *Planting Considerations and Erosion-Control Fabrics*.

Some plant materials must be installed during construction, while others may be installed months after construction to enhance survival and success. For instance, seed must be placed under geotextile fabrics during construction. Similarly, some techniques that incorporate cuttings or other dormant materials may be integral to the structure of the protection measure. However, many plant materials, such as cuttings, tubelings and rooted stock can be planted following construction, during ideal soil-moisture conditions to improve survival rates.

EROSION AND SEDIMENT CONTROL

Erosion control includes all measures to check the migration of soil materials from a construction area into areas where moving water can carry them away. Sediment control includes all measures to reduce turbidity associated with construction activities. The success of erosion and sediment-control methods greatly depends upon weather patterns during the season of construction, dewatering methods applied and the character of the hydrograph at the project site. The period of construction will determine the method of erosion and sediment control required. Careful consideration should be given to inundation levels and flow durations derived from hydrologic statistics (see Appendix D).

Erosion control includes both the prevention of soil loss through soil cover and the trapping of soils eroded by surface flow. Erosion-control mechanisms must be effective during precipitation events and/or during inundation by stream flow. In areas that are above anticipated inundation levels, the potential for soil loss through erosion can be reduced by applying mulch (e.g., straw, wood chips and other organic materials), hydroseeding, or adding biodegradable, chemical or synthetic soil stabilizers. Any areas that may become inundated by flowing water during high-flow events should be protected by geotextile fabrics (see Appendix H). The Washington State Department of Ecology has guidance on erosion-control techniques in the *Stormwater Management Manual for Western Washington*.[1]

In addition to preventing soil loss, eroded soils must be trapped before reaching the stream. This is best accomplished using standard silt-barrier approaches, such as straw bales or a silt fence. The design and specification of silt barriers must include inspection and maintenance schedules, as well as a schedule for removal. Silt barriers require cleaning when they reach 50 percent of capacity.

Sediment control is intended to minimize the input of sediment associated with constructing bank treatments. However, it is unrealistic in most circumstances to expect complete control of sediment inputs, because the installation process for most sediment-control systems itself generates some turbidity. While there are a variety of sediment filters available that are advertised as having moving-water applications, these are impractical and ineffective for controlling sediment except on very small streams. However, sediment can be largely controlled by dewatering the site or isolating the construction area from moving water.

Dewatering

Dewatering a streambank construction area may be essential for constructability and to provide a required degree of sediment control for water-quality protection. The design and implementation of dewatering systems is often underemphasized. At a minimum, dewatering systems must be able to divert one-year flows anticipated during the period of construction. A one-year flow is the greatest flow that has a 100-percent chance of occurring every year during the construction period. This magnitude of return flow will need some qualification based on the period of construction. For instance, during the summer period, the one-year flow may be appropriate; but, during the winter, preparation for a greater-magnitude flow event will likely be required.

The possibility of inundation should be planned for in the design of dewatering systems. The probability of a dewatering system being overwhelmed by storm flows can be determined using standard hydrologic analyses. When available, the analyses should be based on data sets derived from peak flows covering the construction window for period of record. The risk of inundation, based on a probability of occurrence for a particular flow level, can then be used to gauge the relative costs associated with inundation. The cost of inundation may include lost work, lost time, damage to equipment and sediment influx in the stream.

Dewatering can be accomplished on small streams by diverting flow around a project. On larger streams, coffer dams can be used. Flows can be diverted with pumps or passive systems such as side channels, canals or tubes. Flow diversion requires careful consideration of the backwater effects on diversions, pump capacities, diversion-channel capacities and outfall protection. Diversion outfalls require temporary erosion-protection measures to prevent scour at the point of return flow from the diversion channel or pipe. Additionally, pumps require screens designed to Washington State[2] and National Marine Fisheries Service specifications to prevent loss of fish. Any diversion will similarly require a recovery plan for fish left behind when the water is gone. Fish can be recovered manually from remnant pools and transferred by bucket to downstream reaches.

Coffer-Dam Isolation

An alternative to diverting a channel is to use a coffer dam, which isolates the project site from the water in the channel. A coffer dam is an impermeable structure installed parallel to a streambank that allows water on the landward side of the structure to be pumped out, leaving the area contained by the structure free of water. *Figure M-1* shows an example of a coffer dam. Coffer dams can be created using jersey barriers, hay bales and impermeable curtains or water-filled tubes. The use of a coffer dam may confine the channel, raising water-surface elevations. Application of coffer dams will, therefore, require careful modeling of the impact on water-surface elevations during all anticipated flows.

Figure M-1. An example of a water-filled geotube coffer dam in use.

Commercially available coffer-dam systems can be applied on larger river systems. These systems can often withstand overtopping during large events. Design of coffer-dam dewatering systems should consider the infiltration rate of seepage flow from the riverbed and from banks and will require additional and constant pumping systems to address the infiltration flow. In-flow will likely be extremely turbid due to construction activities. Therefore, a sediment detention and settling basin will be required for water pumped from within the dewatered construction area.

Partial Isolation - Working in Wet

An alternative to dewatering solely for the purpose of sediment control is the use of partial isolation (see *Figure M-2*). Partial isolation is still applicable even when dewatering is not necessary for installation purposes. This method minimizes the continued release of sediments that would occur with flowing water. For this reason, work can occur in standing (versus flowing) water behind a barrier. Sediment will be released, but in smaller quantities. When the barrier is removed, sediment will be released. However, it will be distributed as a single pulse rather than a continuous stream and will result in substantially less sediment input than would otherwise occur under flowing water conditions. Water-quality impacts will need to be carefully considered before applying this approach; they may even prevent the use of this approach.

Figure M-2. Partial isolation minimizes the continued release of sediments when working in a wet-channel environment.

HEAVY EQUIPMENT

There is a wealth of heavy-equipment types available for construction projects. The equipment used can play a big role in progress rates and efficiency and, consequently, cost. A rule of thumb is to use the largest, most appropriate equipment available, given site limitations, to maximize efficiency in moving and installing materials. However, this general rule must take into account site-specific limitations (e.g., turning radii and material size) and the need to perform detail work. Most standard types of equipment, including excavators, loaders, dozers and trucks are available in a range of sizes from miniature (Bobcat or smaller) to extremely large (e.g., mine-operations equipment).

Landscape sensitivity may also be a consideration for equipment selection. While large equipment weighs more, many models essential for bank-protection work, including excavators, dozers, loaders and even dump trucks can be equipped with tracks rather than wheels. Tracks are able to distribute a vehicle's weight more evenly across a larger area than wheels can. Consequently, for the same piece of equipment, the weight per square inch of track is less in comparison to rubber tires.

Some projects will require specialized equipment that most contractors do not own or have at their ready disposal. When specialized equipment is required, progress rates are often slowed, resulting in an increase in per-hour operational costs. Consequently, construction costs may be increased by both hourly rates and slowed progress. For example, a street-legal dump truck can typically haul eight to 12 cubic yards of material. In ideal conditions, which include dry, flat ground, a tracked truck has a capacity of six cubic yards of dry fill. However, in most conditions where a tracked truck is necessary, a typical load is less than four cubic yards of relatively dry material and considerably less if the material is wet.

Specialized equipment for bank-protection applications includes:

Spider Excavator. A spider excavator is an articulated-arm excavator that operates on four independent legs rather than two tracks. It can crawl and perch on relatively steep slopes, and it can "walk" across channels with minimal impact. It can often access areas that traditional, tracked equipment cannot.

Bobcats : Bobcat is a brand of small earth-moving equipment that can run on four rubber tires or on tracks and has the ability to use a number of different tools for a variety of applications. Bobcats can be outfitted with loaders, dozer blades, hoes, drills and numerous other tools. They are ideal for moving and installing materials within small areas.

Helicopters. Helicopters can be used to import materials to remote areas. They can be practical and cost-effective for any imported earth materials, including wood, large boulders, fabric or artificial materials.

Horses. Horses can also be used for transporting materials and as a substitute for heavy equipment in many remote or access limited areas.

REFERENCES

1 Washington State department of Ecology. 2001. Stormwater Management Manual for Western Washington. Publication Nos. 99-11 through 99-15. Olympia, WA.

2 Bates, K. M. and B. Nordlum. 2001. Draft Fish Protection Screen Guidelines for Washington State. Washington Department of Fish and Wildlife, Olympia, WA.