

# **NCHRP**

## **REPORT 544**

**NATIONAL  
COOPERATIVE  
HIGHWAY  
RESEARCH  
PROGRAM**

### **Environmentally Sensitive Channel- and Bank-Protection Measures**

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**NCHRP REPORT 544**

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**Environmentally Sensitive  
Channel- and Bank-Protection  
Measures**

**JOHN McCULLAH**

AND

**DONALD GRAY**

Salix Applied Earthcare  
Redding, CA

**SUBJECT AREAS**

Energy and Environment • Bridges, Other Structures, Hydraulics and Hydrology • Soils, Geology, and Foundations

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**TRANSPORTATION RESEARCH BOARD**

WASHINGTON, D.C.

2005

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## FOREWORD

*By Timothy G. Hess  
Staff Officer  
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This report presents a description of useful environmentally sensitive channel- and bank-protection measures, design guidelines for their application, and a selection system for determining the most appropriate channel- and bank-protection measure. This report will be particularly useful to professionals responsible for design and construction of channel- and bank-protection measures in environmentally sensitive areas.

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Environmentally sensitive channel- and bank-protection measures—such as bio-engineering, root wads, large woody debris, riparian vegetation, bendway weirs, and energy dissipaters—are being called for more frequently to protect transportation facilities from erosion, scour, and lateral migration. However, relatively little guidance has been developed to help practitioners apply environmentally sensitive channel- and bank-protection measures with confidence that their designs are adequate. Traditional channel- and bank-protection techniques rely on countermeasures such as riprap, gabions, cable-tied blocks, or grout-filled bags, which may not offer sufficient in-stream functions, such as habitat diversity, fish passage, water quality, and energy dissipation. The use of more environmentally sensitive measures for the protection of channels and stream banks has been hampered by the lack of selection criteria and design guidelines.

Under NCHRP Project 24-19, Salix Applied Earthcare developed selection criteria, design guidelines, and a compilation of techniques used for environmentally sensitive channel- and bank-protection measures. After conducting an extensive literature review and evaluation of commonly used environmentally sensitive techniques, the research team identified 44 environmentally sensitive channel- and bank-protection techniques for study. The channel- and bank-protection techniques were grouped into four major categories, namely (1) River Training Techniques, (2) Bank Armor and Protection, (3) Riparian Buffer and River Corridor Treatments, and (4) Slope Stabilization. Technique descriptions and guidelines for their applications were developed. Finally, a rule-based technique selection system was also developed. The selection system is presented as an interactive software program entitled “Greenbank,” which can be found on the accompanying CD-ROM (CRP-CD-58).

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## CHAPTER 1

# INTRODUCTION

Each year, more discoveries are made regarding the impact that human activity and infrastructure have on the surrounding environment. For many years, project designers have included structures that perform well for stabilizing streambanks and decreasing pollution of our nation's waters by reducing erosion. However, many of these structures are missing key components critical to complete environmental restoration.

### CHANGING REQUIREMENTS

In response to increased knowledge and public concern, regulations and other requirements have been placed on agencies and organizations to implement environmentally friendly and beneficial practices. This requires projects to incorporate components into erosion and sediment control programs that provide improved habitat for the flora and fauna of our waters, produce aesthetic value for roadsides and waterways, and advance the sustainability of stable streambanks and riverine systems. Under many conditions, these "soft" practices are more successful for erosion control than structural "hard" systems and provide the additional benefit of restoring ecological value to streams and rivers. These environmentally sensitive "soft" practices combine with traditional structures to provide engineers with the ability to restore ecological health and stability within the infrastructures so critical to human society.

To answer the need for specifications and guidance regarding environmentally sensitive channel- and bank-protection measures, NCHRP funded the development of Environmentally Sensitive Channel- and Bank-Protection Measures to aid highway engineers, restoration ecologists, watershed hydrologists, biologists, and soil conservationists in designing projects that restore stream and river systems, while protecting property and structures. This report and the accompanying CD are the result of that project. The CD includes typical design drawings, construction and installation specifications, a comprehensive bibliography with numerous links to the documents listed, and an extensive photo gallery of project examples, all based on extensive research and experience. Also included is a software program, entitled Greenbank, that provides users with a reliable, straightforward approach to selecting these innovative techniques for streambank protection. The program allows users to enter site characteristics and restraints and, using that

information, selects the techniques most suited to the project. Appendix A provides descriptions and illustrations of environmentally sensitive channel- and bank-protection techniques. Appendix B is a user's manual for Greenbank.

### What It Means to Be Environmentally Sensitive

There is an ever-growing number of streambank stabilization practices, and many were considered for inclusion in this report and CD. Most were not included because they offered little in the way of environmental benefit beyond simply reducing bank erosion or channel incision. To be included in these guidelines, techniques had to enhance or protect aquatic or terrestrial habitats, provide aesthetic value, or both. Although aesthetic values vary from person to person, measures were avoided that appeared visually incompatible with naturally occurring riparian features. We generally included measures that facilitated natural revegetation of eroding banks either directly (by planting) or indirectly (for example, by slope stabilization) but were visually unobtrusive. The appearance of banks treated with such measures should eventually be compatible with naturally occurring riparian features and demonstrate a properly functioning stream system. Often these measures lead to green, verdant, inviting banks that are accessible for recreational use. The techniques included in this report and CD have varying environmental benefits, and those benefits are identified in this report.

### Interdisciplinary Effort

Due to the dynamic nature of any projects within or adjacent to a stream and the current awareness on the part of designers, the public, and the regulatory community, it is critical that interdisciplinary teams be developed. Members of different disciplines provide insight and guidance into specific concerns surrounding a project and can provide the necessary input for project success. Examples of specialists include riparian ecologists, aquatic biologists, geomorphologists, hydraulic engineers, structural engineers, geologists, botanists, biologists, and erosion control specialists. Specialists should be involved early in project development to identify the environmental benefits desired, to promote communication, and to facilitate the adjustment of project plans and designs.

## Applicability

A variety of concerns regarding the applicability of these techniques have been expressed by highway engineers. It is imperative that project designers consult with specialists knowledgeable of local conditions to enhance the success of their project. As an example, the correct selection of a species of willow or cottonwood adapted to the local region is critical to the success of many of these techniques. Climate zone will also dictate the growing and dormant periods of those species. It is also extremely important for designers to understand the specific ecological issues surrounding a particular water body and to design structures with those concerns in mind. For example, a threatened or endangered species of fish in a particular area may have specific requirements, which would be identified by local agency representatives.

It should be noted that the knowledge gleaned from the case studies included in the CD is applicable to projects all across the nation, since the projects were installed in a variety of situations across a broad range of stream and river types.

These guidelines are not meant to replace or disregard the abundance of available engineering data, equations, or design protocol. It is critical that factors such as scour depth, tractive force, and design high water be determined for each particular project and be incorporated into project design.

## Sustainability of Environmentally Sensitive Techniques

Concerns are widespread throughout the industry regarding the longevity and strength provided by environmentally sensitive techniques. Extensive research was performed to obtain reliable information regarding hydraulic loading limits for each technique discussed. It was found that many of the techniques will be just as strong as, if not stronger than, “hard engineering” counterparts. One source (Escaramia, 1998) classifies bioengineering alone as light, meaning soft practices are known to withstand mean cross-sectional velocities no greater than 1 m/s (3.3 ft/s). However, many bioengineering techniques and most biotechnical practices have been documented to withstand much higher local velocities. Structures such as riprap are usually enhanced rather than weakened by combining a “hard” technique with “soft” components. The CD provides tables regarding velocities sustained by each specific technique and the sources of the information. It was found that many of the techniques can withstand velocities up to 3.5 m/s (12 ft/s).

## Data Availability and Research Opportunities

Data availability was found to vary considerably amongst the techniques. Each technique was assigned to one of three levels based on the amount and quality of available data and the number of successful case studies and examples found

throughout the nation. These level designations provide guidance to the user for selecting each technique. For example, Level I techniques may be selected for use in situations where a higher level of confidence is desired, whereas Level III techniques may be used in trials or situations where experimentation is more acceptable.

This report found that major opportunities exist for studying particular components of installation and the impacts individual techniques have on project success. The need exists for more performance data, such as allowable velocities for some techniques and the amount of vegetative cover required to reach project objectives. As a result of the extensive literature review performed and expert input and testimonials, research opportunities are identified in the detailed descriptions of each technique on the accompanying CD.

The CD provides the information and guidelines needed to design and install structures and practices that will stabilize streams and rivers while providing the improved habitat and ecological health needed for a better environment. This report documents the procedures used for gathering the information needed to establish these guidelines.

## PROJECT TASKS

The project commenced on May 1, 2001. This Final Report describes the work carried out from the inception of the project through November 30, 2004. The various tasks outlined in the Work Plan included the following:

- Task 1—Literature Review and Agency Survey
- Task 2—Formulation of Work Plan
- Task 3—Interim Report
- Task 4—Execution of Approved Work Plan
- Task 5—Preparation of Supporting Tools
- Task 6—Final Report

These tasks are enumerated and described in greater detail in Chapter 2. The results of the literature review and evaluation are described in Chapter 3. The literature review includes an evaluation of multiple information sources: books, conference proceedings, agency technical reports, agency guidance manuals and handbooks, and websites.

The research team discussed the appropriate term for the entire suite of channel- and streambank-protection measures at some length and decided that *technique* was more appropriate than *measure* or *countermeasure*. It was recognized that some treatments may be applied outside the highway right-of-way to mitigate and enhance stream morphology or corridor and habitat values. It was observed that some bank-protection procedures do not entail construction of something, but instead may actually require deconstruction, for example, slope flattening and regrading—a fundamental approach for stabilizing slopes, including streambanks. In light of these considerations, the word *technique* is used below to refer to all types of environmentally sensitive channel- and bank-protection measures.

The project research team developed a survey form (questionnaire) that was sent to state DOTs and some representative regulatory agencies asking about experiences relevant to this project. Responses to the survey are summarized in Chapter 4. The survey revealed information about the most common problems or concerns with environmental techniques for channel-erosion control, the most common techniques employed, and qualitative and quantitative data for a variety of techniques.

Selected environmentally sensitive channel- and bank-protection measures (techniques) are described in Chapter 5. The project research team identified and narrowed down the list of candidate techniques to 44. These techniques are grouped into four major categories, namely, (1) River Training Techniques, (2) Bank Armor and Protection, (3) Riparian Buffer and River Corridor Treatments, and (4) Slope Stabilization. The work plan called for preparation of guidelines for each technique. The research team initially focused efforts on the preparation of brief summaries (fact sheets) for each technique, which would provide short descriptions of each method in addition to preliminary data. It was decided, however, that these fact sheets were redundant to longer guidelines, and work was terminated on them. A brief description and schematic drawing of each technique can be found in Appendix A. Chapter 5 lists all the subjects discussed in relation to each of the techniques on the enclosed CD. These subjects include the technique's category and propose, detailed design guidelines and specifications, and so forth.

In addition to the techniques discussed, the research uncovered many subjects of direct relevance and applicability to the entire spectrum of environmentally sensitive channel- and bank-protection work. These special topics—ranging from management of conveyance and combining techniques to protecting and improving aquatic habitat and the role of geotextiles and natural fabrics—are also listed in Chapter 5. The accompanying CD includes the discussion of each of these special topics.

The accompanying CD also includes other important information, such as case studies and a photo gallery. The case studies give detailed descriptions of past projects that included environmentally sensitive techniques, the results of the projects, and observations regarding project performance. The photo gallery includes photos from case studies, examples, and more in an easy-to-access format for the user.

A rule-based technique selection system for use by DOTs or consulting engineers is described in Chapter 6. The system contains a set of rules relating the strengths and weaknesses (hydraulic, geotechnical, and environmental) of each technique to relevant site characteristics. This system, entitled Greenbank, is not intended for designing bank protection but rather to assist the user in selecting a reasonable technique or countermeasure. Greenbank provides the user with a short list of appropriate techniques for closer consideration and provides references and justifications for these outputs. Appendix B, Greenbank Decision Support Tool User's Guide, discusses the information provided by the software in more detail.

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## CHAPTER 2

### TASKS

The approved work plan identified six tasks that serve as the main agenda for the project research; these are briefly summarized below.

#### **TASK 1—LITERATURE REVIEW AND AGENCY SURVEY**

##### **A. Review of Technical Literature**

The team reviewed and evaluated the published technical literature on environmentally sensitive slope protection and erosion control. Included in the review were such sources as books, agency guidance manuals, handbooks, technical reports, journal articles, and conference or workshop proceedings that have been published on the techniques.

##### **B. Survey of State Transportation and Regulatory Agencies**

The team surveyed the design staff of state DOTs and regulatory agencies to identify unpublished information, such as performance data, drawings, specifications, and guidance pertaining to the application of the techniques.

#### **TASK 2—FORMULATION OF WORK PLAN**

##### **A. Identification and Description of Environmentally Sensitive Techniques**

The team developed a hierarchical list and classification system for the techniques, including descriptions, design guidelines, and selection criteria for the various techniques. The team incorporated the list of techniques into a selection matrix that describes the functional applications, suitability for various river conditions, environmental attributes, and maintenance requirements of each technique.

##### **B. Special Topic Modules**

The team developed summaries on important topics that are related generally to the selection, design, and implementation of environmentally sensitive streambank- and

channel-protection measures. These discussions and guidelines are referred to herein as special topics.

##### **C. Selection System**

The team developed selection criteria and incorporated them into an expert selection system that may be used to identify techniques that are suitable for specified river conditions, erosion problems, and economic constraints and that address specified environmental goals or objectives.

#### **TASK 3—INTERIM REPORT**

Information developed in Tasks 1 and 2 formed the main basis for an interim report. At a minimum the interim report included the following:

1. A literature review and evaluation of environmentally sensitive channel- and streambank-protection measures,
2. Results of a survey of state transportation and regulatory agencies,
3. A complete list of environmentally sensitive channel- and bank-protection techniques for which the research team will develop guidance,
4. Complete design guidance (fact sheet, specifications, information in text and tabular format, and well-refined drafting examples) for one of the environmentally sensitive channel- and bank-protection techniques in each major group,
5. A status report on the development of the expert selection system using the Exsys CORVID software, and
6. A revised proposed work plan attached as an appendix.

The interim report was submitted as outlined; responses to panel comments on the report were also prepared and submitted back to the panel.

#### **TASK 4—EXECUTION OF APPROVED WORK PLAN**

The team executed the approved work plan and developed selection criteria and design guidelines for the approved list of environmentally sensitive channel- and bank-protection

techniques. In addition to the techniques, special topics were developed and prepared.

#### **A. Technique Descriptions**

Design guidelines for each technique were finalized. Most of the guidelines include rules for selection criteria, materials needed, construction specifications, detail drawings in .dwg (AutoCAD) and .dgn (MicroStation) formats, photos and other images, .pdf (Adobe Acrobat) project case studies (if available), and source references.

#### **B. Critical Evaluation of Stream Classification Systems**

The research included a review and evaluation of stream classification systems as a possible tool for stream restoration and technique selection/design. In this regard several different types of classification systems, such as Buffington and Montgomery (1997) or the various Channel Evolution Models (Simon, 1989; Schumm, et al. 1984), were considered. Finally, the simple system developed by Brice and Blodgett (1978) for application to transportation infrastructure issues in the river environment was adopted.

#### **C. Case Study Descriptions**

Important case studies from the literature, from field site visits, from reports and discussions with state highway agencies, and from the personal experience of team members were selected for inclusion in the final report.

#### **D. Selection and Specification of Plant Materials**

The final report includes selection criteria and available resources for locating plant materials. Extensive and detailed information on plant materials suitable for different climatic, soil, and local site conditions can be found in appendices to some of the publications noted in Chapter 3, Literature Review and Evaluation.

#### **TASK 5—PREPARATION OF SUPPORTING TOOLS**

Task 5 primarily involved designing and drafting the supporting technical drawings in both .dwg and .dgn formats. Construction specifications for the techniques were finalized at this time. This task also included development, collection, and formatting of photographs, charts, tables, figures, and other visual material. This material was used throughout the final report, the final CD product, and the expert system software program.

#### **TASK 6—FINAL REPORT**

The final report is supplemented with a CD-ROM that is attached into a sleeve on this report cover. This report is a synthesis of the information provided on the accompanying CD-ROM. It includes technical information, the list of techniques, and instructions on how to use the technique selection system. The full specifications, technical drawings in .dgn and .dwg formats, design considerations, the rule-based technique selection system, and supporting documentation, such as case studies and photos, are on the accompanying CD.

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## CHAPTER 3

# LITERATURE REVIEW AND EVALUATION

### GENERAL EVALUATION

A surprisingly large number of books, guidance manuals, technical reports, journal articles, and conference or workshop proceedings have been published on environmentally sensitive slope-protection and erosion-control measures. Many of these references are devoted in full or in part to techniques that are applicable to streambank and channel protection. The main limitation of the existing technical literature is not so much its paucity as its abundance. In some cases, regional specificity and lack of ready availability constrain usefulness. Many articles appear in obscure publications of limited distribution and accessibility. Perhaps most important, the quality of design guidance varies widely. Some techniques are documented by anecdotal case studies with very little data and only a few photographs, while other techniques have been subjected to controlled testing in hydraulic laboratories. Similarly, detailed analytical design approaches have been developed for some techniques, but others continue to be designed by rules of thumb or individual judgment. As noted below in the section describing DOT survey results, qualitative information is often more abundant than quantitative data.

Some important examples of the technical literature on environmentally sensitive channel- and bank-protection measures are listed and discussed briefly below. This resource base has been augmented more recently by technical notes and related publications that are now available on the World Wide Web. The review that follows is not intended to be exhaustive, but it is illustrative of key information sources that are for the most part readily available. The review is limited to books, guidance manuals or handbooks, agency technical reports, and websites.

Readers should be aware that “gray literature” (reports, websites, technical notes, proceedings papers, brochures and other documents not subjected to independent peer review) is usually of lower quality than peer reviewed journal papers.

A complete list of all documents, including technical journal papers, used in preparing the technique guidelines and special topics is included in the comprehensive bibliography. The accompanying CD also includes this list of documents, under References, and has the added feature of providing links to .pdf files containing the full text of many of the documents.

### SPECIFIC REVIEW

#### Books

*The Use of Vegetation in Civil Engineering Practice.* 1990. Written by N. J. Coppin and I. Richards. Describes the use and engineering function of vegetation in a number of engineering applications, including erosion control and bank protection. The first book to set out in a comprehensive manner the ways in which vegetation modifies physical soil properties and the functional role that vegetation plays in slope stabilization, water erosion control, watercourse and shoreline protection, wind erosion control, and control of runoff in small catchments. Published by Butterworths: Sevenoaks, Kent (UK).

*Water Bioengineering Techniques for Watercourse Bank and Shoreline Protection.* 1994. Written by H. M. Schiechl and R. Stern. A comprehensive compendium of countermeasures and design guidelines. Includes chapters on water bioengineering systems (including longitudinal and transverse structures) and on selection, care, and maintenance of vegetation along waterways. Published by Blackwell Science, London.

*Biotechnical and Soil Bioengineering Slope Stabilization.* 1996. Written by D. H. Gray and R. B. Sotir. Descriptions and guidelines of biostabilization measures. Includes a chapter on selection and design of biotechnical channel lining systems. Published by John Wiley and Sons, New York.

*Waterway Bank Protection: A Guide to Erosion Assessment and Management.* 1999. Written by R. P. C. Morgan, A. J. Collins, and M. J. Hann. This is an encyclopedic look at bank-protection measures and contains a logical selection algorithm. A bibliography (in MS Access or Excel) is included on diskette. Its main short-coming is that the entire work is targeted at conditions found in Great Britain. A copy can usually be obtained via interlibrary loan at a university library. Published by R& D Publication 11, The Stationary Office, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD, U. K. (pp105)

#### Agency Guidance Manuals and Handbooks

*Streambank Protection Guidelines for Landowners and Local Governments.* 1983. Written by M. P. Keown. Environmental Laboratory, U.S. Army Engineer Waterways

Experiment Station. Succinct review of the nature and causes of streambank erosion and failure; essential elements of a plan of action; stream-rerouting, channel modification, and bank-protection measures. Available from NTIS, U.S. Department of Commerce, Springfield, VA. #ADA193023.

*Stream Habitat Improvement Handbook*. 1992. Issued by the USDA Forest Service, Tech Publ. R8-TP 16. Primarily a compendium of in-stream structure designs to correct or improve habitat deficiencies.

"Streambank and Shoreline Protection." 1996. Chapter 16 of the *Engineering Field Handbook*, U.S. Department of Agriculture. The companion chapter to Chapter 18: Soil Bioengineering for Upland Slope Protection. This chapter describes the use of vegetative plantings, soil bioengineering, and structural systems used either alone or in combination with one another for protecting streambanks and shorelines. Guidelines and design considerations are presented for the following treatments: (1) *soil bioengineering measures*: live staking, live fascines, fiber rolls, branchpacking, vegetated geogrids, and brushmattress, (2) *vegetative/structural measures*: tree revetments, willow post plantings, log/rootwad revetments, live crib walls, vegetated riprap (joint planting), and vegetated gabion mattresses.

*Bridge Scour and Stream Instability Countermeasures*. 1997. Written by P. F. Lagasse et al. Issued by the U.S.DOT. HEC-23. Primarily a compendium of hydraulic techniques (namely, river training structures and armoring countermeasures). Includes a useful matrix of countermeasures that can be adopted to evaluate their functional applications and suitability for different river conditions.

*Guidelines for Stream and Wetland Protection in Kentucky*. 1997. Issued by the Kentucky Division of Water. Description of a variety of environmentally sensitive measures for repairing streambank erosion and restoring aquatic habitat. A printed copy of this document can be ordered free, courtesy of the U.S. Environmental Protection Agency and the Kentucky Division of Water. Contact: Kentucky Division of Water, 14 Reilly Road, Frankfort, KY, 40601.

*Stream Corridor Restoration: Principles, Processes, and Practices*. 1998. Federal Interagency Stream Restoration Working Group. A comprehensive, cooperative effort by 15 federal agencies of the U.S. government to address stream degradation problems and outline possible solutions. The August 2001 revision of the 1998 document is available online at [http://www.nrcs.usda.gov/technical/stream\\_restoration/](http://www.nrcs.usda.gov/technical/stream_restoration/) (last accessed May 2, 2005).

*Streambank Investigation and Stabilization Handbook*. 1998. U.S. Army Engineer Research and Development Center, Vicksburg, MS. Comprehensive compilation of research and techniques for streambank/erosion control applications related to planning, engineering, contracting, construction, and maintenance. Includes extensive collection of figures, tables, and color photos. Provides technical design guidelines for a variety of streambank-protection measures. Also available in CD-ROM with browser-like navigation features from Veri-Tech, Inc. at [www.veritechinc.com](http://www.veritechinc.com).

*Integrated Streambank Protection Guidelines*. 2003. Issued by the Washington Department of Fish and Wildlife. Provides advice for selecting and designing protection techniques that protect or restore aquatic and riparian habitats. Advocates integration of natural river processes in the selection and design process. Maintains that bank-protection measures should be selected to address site- and reach-based conditions to avoid habitat impacts. Suggests consideration of methods other than riprap armoring, such as roughening a bank line, directing flow away from an eroding bank, revegetation, floodplain management, maintaining riparian corridors, restoring oxbows/wetlands, relocating at-risk infrastructures, and managing meander belts.

### Agency Technical Reports

*Streambank Erosion Control and Demonstration, Interim Report*. 1981. Report issued by the U.S. Army Corps of Engineers. A massive, 8-volume report detailing the results of numerous streambank-erosion control trials around the country. Contains the results of both conventional and alternative treatments. Dated but rich source of information that represents the state of the art of streambank protection at the time of publication.

*Bioengineering for Streambank Erosion Control: Report 1, Guidelines*. 1997. Written by H. Allen and J. R. Leech. Technical Report EL-97-8. Issued by U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

*Design of Roadside Channels with Flexible Linings*. 1998. Written by Y. H. Chen and G. K. Cotton. HEC-15/FHWA-IP-87-7. Prepared for the Federal Highway Administration. Contains information on Manning coefficient and allowable tractive stress for a variety of lining systems, including riprap, vegetation, and various rolled erosion control products.

*Determination of Resistance Due to Shrubs and Woody Vegetation*. 2000. Written by G. E. Freeman, W. H. Rahmeyer, and R. R. Copeland. Technical report ERDC/CHL TR-00-25 prepared for the Engineer Research and Development Center, U.S. Army Corps of Engineers. Results of flume studies conducted to determine hydraulic resistance of flexible plants that deform with turbulent flow. Study considered the effects on channel resistance for the variables of plant type, plant geometry, plant density, plant flexibility, and submerged and partially submerged conditions. Regression equations were developed for determining the Manning roughness coefficient.

### Websites

There are a number of websites that contain useful guidelines and information about streambank-protection techniques, including techniques that can be classified as environmentally sensitive channel- and streambank-protection measures. Most of the sites have been posted by federal or state agencies. A number of sites that describe case studies or applications of

such measures have been posted by private consultants. Some of the sites that have useful and relevant information are listed and briefly reviewed below.

**EMRRP Technical Notes.** U.S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory,

<http://el.erdc.usace.army.mil/emrrp/tnotes.html> (last accessed May 2, 2005)

A series of short illustrated notes on stream restoration that allows users to access, save, and print documents in Adobe Acrobat (PDF) format. A thumbnail summary at the beginning of each note provides information on relative cost, complexity, and benefit of each measure. The following technical notes are particularly relevant and useful:

EMRRP-SR-01	Glossary of Stream Restoration Terms	Feb 2000
EMRRP-SR-04	Coir Geotextile Roll and Wetland Plants for Streambank Erosion Control	Feb 2000
EMRRP-SR-06	Habitat Requirements for Freshwater Fishes	Feb 2000
EMRRP-SR-07	Resistance Due to Vegetation	May 2000
EMRRP-SR-08	Determining Drag Coefficients and Area for Vegetation	Feb 2000
EMRRP-SR-09	Reconnection of Floodplains with Incised Channels	May 2000
EMRRP-SR-11	Boulder Clusters	Feb 2000
EMRRP-SR-12	Irrigation Systems for Establishing Vegetation	Feb 2000
EMRRP-SR-13	Streambank Enhancements with Large Woody Debris	May 2000
EMRRP-SR-21	Rootwad Composites for Streambank Control and Fish Habitat Improvement	May 2000
EMRRP-SR-23	Brush Mattresses for Streambank Erosion Control	May 2000
EMRRP-SR-24	Design Recommendations for Riparian Corridors and Vegetated Buffer Strips	Apr 2000
EMRRP-SR-28	Units and Conversions for Stream Restoration Projects	May 2001
EMRRP-SR-29	Stability Thresholds for Stream Restoration Materials	May 2001
EMRRP-SR-31	Live and Inert Fascine Streambank Erosion Control	May 2001
EMRRP-SR-32	Impacts of Stabilization Measures	May 2001
EMRRP-SR-33	Plant Material Selection and Acquisition	May 2001

**Guidelines for Stream and Wetland Protection.** Department of Environmental Protection. Kentucky Division of Water.

<http://www.water.ky.gov/> (general website accessed November 17, 2004; however, due to technical issues, this manual was lost and they are working on putting it back on the web)

Provides an index to a 52-page manual that discusses stream behavior, stream types, restoration of streams, streambank erosion, riparian zones, and wetlands. Individual pages from the guide can be downloaded as PDF Acrobat files. The guide includes 59 photographs to help illustrate the main points of discussion. Seven appendices include overviews of hydro-geomorphic wetland functions, sources for obtaining native plants, a list of consultants, and a comprehensive stream restoration bibliography. The information provided is applicable across state lines.

**Stream Restoration Library.** Greene County New York Soil and Water Conservation District, Stream Restoration Program.

<http://www.gcsxcd.com/stream/library/> (last accessed November 17, 2004)

Site contains downloadable documents such as spreadsheets, typical drawings, construction specifications and other tools for stream restoration managers. The stream restoration construction specifications have been used on district projects ranging in cost from \$10K to \$700K. The following documents with stream restoration and vegetative specifications can be downloaded from the site:

Stream Restoration Specifications (typical drawings have not yet been added):

- SR-01: Rock vanes
- SR-02: W-weirs
- SR-03: Cross vanes
- SR-04: Root-wads
- SR-05: (Reserved)
- SR-06: (Reserved)
- SR-07: Stream channel excavation
- SR-08: Rock riprap

Vegetation Specifications (addresses implementation of vegetative components of stream restoration):

- VS-01: Live fascines
- VS-02: Sod mats
- VS-03: Live stakes/posts
- VS-04: Live materials/transplants
- VS-05: Seeding and mulching

**Environmental Management Program.** Texas Transportation Institute. Texas A&M University System. College Station, TX.

[http://tti.tamu.edu/enviro\\_mgmt/projects](http://tti.tamu.edu/enviro_mgmt/projects) (last accessed November 17, 2004)

Describes several environmentally oriented research projects, including one entitled, "Regional Applications for Biotechnical Methods of Streambank Protection in Texas," which involved identifying bioengineering and biotechnical streambank stabilization technologies appropriate to the climatic and resource regions of Texas.

**Soil Bioengineering Home.** Washington State DOT. Engineering and Environmental Programs. Roadside and Site Development. Olympia, WA.

<http://www.wsdot.wa.gov/eesc/design/roadside/sb.htm> (last accessed November 17, 2004)

Not oriented to streambank protection per se, but website has many useful features, including case histories of soil bioengineering projects with photos, several hundred references for soil bioengineering and vegetative stabilization, links to on-line publications and restoration websites, and design information including typical drawings, specification examples, and cost examples.

**NebGuide.** Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, NE.

<http://www.ianr.unl.edu/pubs/soil/g1307.htm> (last accessed November 17, 2004)

The NebGuide describes bioengineering techniques for hillslope-, streambank-, and lakeshore erosion control. Tips for a successful bioengineering installation and demonstration project are described.

**The Cross Vane, W-Weir and J-Hook Structures.** D.L. Rosgen. Wildland Hydrology Inc., Pagosa Springs, CO.

<http://www.wildlandhydrology.com/assets/cross-vane.pdf> (last accessed November 17, 2004)

The descriptions, design specifications, placement locations, spacing and various applications of Cross-Vane, W-Weir and J-Hook Vane structures are presented. Empirical relations for minimum rock size based on bankfull shear stress are presented. Drawings for each structure are provided that display appropriate use of footers (foundation rocks), cross-section shape, profile shape, appropriate channel locations, angles, slopes, spacings, and elevations.

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## CHAPTER 4

# STATE DOT AND AGENCY SURVEY

### SURVEY DESIGN

The project research team developed and formatted a survey form (questionnaire) that was sent to state DOTs and some other representative agencies that regulate highway projects. The project team anticipated that the agency surveys would uncover some new technology and monitoring data related to engineering performance, cost effectiveness, and environmental results. Copies of this initial survey were mailed out in July of 2001. Based on the findings and limitations of the first survey, a second survey was developed and mailed out in April 2002.

### SURVEY RESPONSE AND FINDINGS

#### Initial Survey

Twenty-six state DOTs responded to the initial survey. The most common problems or concerns with environmental techniques were: (1) limited experience designing, installing, and monitoring a new or modified technique; (2) lack of long-term, postconstruction data; (3) lack of hydraulic guidelines; and (4) general concerns about vegetation failure if not well established before high-flow events. The most common techniques employed were geotextile fabrics and variations on revegetation techniques.

Following the return of the initial survey, agencies and subcontractors with the most experience were contacted for additional information. Useful data were received for rock vanes, vanes with j-hooks, boulder clusters, vegetated riprap, and vortex weirs.

#### Follow-Up Survey

The project team sent out a second survey to collect more comprehensive and informative responses. These revised surveys asked agency personnel to provide better site and reach descriptions and more quantitative information about reach hydrology and characteristics. Responses to the second survey were informative; however, there were still problems with the quantity and quality of the answers.

Responses were received from a total of 29 states; there were 26 responses to the first survey, 22 responses to the sec-

ond survey, and 3 general responses. Many states responded to both surveys. Several respondents noted that they were not able to provide comprehensive responses to the questionnaires because they lacked completion reports, monitoring data, and time to complete the survey.

The largest impediment to survey responses was lack of time for DOT employees to fill out the surveys or provide information. In one case, the responder made a new box next to each question, labeled it "Unknown," and then proceeded to check it. Another employee stated on the survey form that he had a large amount of information about the different techniques that his agency employed; however, when the employee was asked to send the information, he stated that he could not do this, as he did not have any spare time. This problem was completely understandable; however, it severely limited the amount of obtainable information and consequently the ability to compare techniques over a variety of conditions.

The second largest impediment was the lack of monitoring data. Resources to support monitoring are scarce, and monitoring is often not included in project budgets. Without monitoring, it is hard to make conclusions about hydraulic or geotechnical performance, the survival of vegetation, and so forth. Another difficulty was compiling comprehensive data since individuals seemed hesitant to report failures, even though failures may yield valuable information.

Another obstacle experienced in obtaining information was that environmentally sensitive streambank stabilization techniques are usually passed over in favor of more traditional methods. Survey responses and follow-up correspondence suggested that the environmentally sensitive techniques are not used often due to lack of data. This creates a "chicken and the egg" problem. There is very little information on these techniques because use is infrequent, and use is infrequent because there is very little information on the techniques.

On the plus side, however, several states were able to provide quality information.

A lack of knowledge on the part of the designers, construction contractors, and crew was identified as a factor in project failure. The impression was that managers and planners get training and read manuals about techniques, but the people who are actually designing, specifying, and installing the measures have received no training. One respondent who did not attribute failures to lack of knowledge on the part of the designers mentioned that "landscape architects came in

after the project was complete to vegetate it,” perhaps indicating a lack of integration among project components. These types of human problems evidently reduce success rates for environmentally sensitive/biotechnical projects. The survey results show a major emphasis on application of these measures to creeks as opposed to rivers. In the 21 states that have used the techniques, well over 250 projects were done on channels referred to as streams or creeks, while only 50 projects were reported on channels with names that include the word *river*. Although the use of these terms varies regionally, streams and creeks usually refer to smaller chan-

nels than rivers. Significantly, although one-third of the respondents reported recurring problems with the techniques, not one state reported completely unsatisfactory performance of the measures.

These trends were considered in preparing the technique guidelines. For example, the importance of incorporating plant materials during construction, as opposed to planting after traditional protection measures are placed, is stressed. In addition, because there is such a bias toward projects in streams and creeks, this report focuses on issues associated with smaller channels.

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## CHAPTER 5

# TECHNIQUE DESCRIPTIONS AND GUIDELINES

### HIERARCHICAL LIST OF TECHNIQUES

The research team examined and revised the list of techniques over the duration of the project. Although some techniques were combined, guidelines were developed for 44 discrete techniques.

A hierarchical system was adopted to classify the universe of techniques. Hydraulic countermeasures are separated into two major groups, namely, (1) River Training and (2) Bank Armor and Protection. Two more categories were added, namely, (3) Riparian and Stream Opportunities and (4) Slope Stabilization. A hierarchical list and classification of environmentally sensitive channel- and bank-protection techniques is shown in Table 1. The list places each technique in one of the preceding major groups and further classifies or identifies each technique by categories and subcategories. This classification system was developed largely to assist in the selection of appropriate treatments.

The three-level rating system was developed to account for the amount, quality, and reliability of available information:

Level I—Well-established, well-documented (good performance and monitoring data available), reliable design criteria based on lab/field studies.

Level II—Intermediate, greater uncertainty (used frequently but do not have the level of detail, quality of information, and reliability that characterize Level I); little or inadequate monitoring.

Level III—Emerging, promising technique. Does not have the track record and level of information characterizing Level I or II.

### TECHNIQUE GUIDELINES

Technique design guidelines and specifications are presented in a web browser-based interactive format on the accompanying CD. The software is liberally illustrated with color photographs of real projects. Clicking on a photograph will expand it so that details can be seen. The CD is user friendly, with expandable and collapsible menus, hotlinks between technique pages and special topics where relevant, and links to many references in .pdf format.

All technique guidelines can be found on the attached CD. Each technique guideline includes the following items:

1. Category
2. Design Status
3. Also Known As
4. Description
5. Purpose
6. Planning
  - a. Useful for Erosion Processes:
  - b. Spatial Application:
  - c. Hydrologic/Geomorphic Setting:
  - d. Conditions Where Practice Applies:
  - e. Complexity:
  - f. Design Guidelines/Typical Drawings:
7. Environmental Considerations/Benefits
8. Hydraulic Loading
9. Combination Opportunities
10. Advantages
11. Limitations
12. Materials and Equipment
13. Construction/Installation
14. Cost
15. Maintenance/Monitoring
16. Common Reasons/Circumstances for Failure
17. Case Studies and Examples
18. Research Opportunities
19. References

### SPECIAL TOPICS

The following subjects of relevance to environmentally sensitive streambank and channel protection are briefly discussed in special topic documents composed by the research team and included on the accompanying CD:

1. Bankfull Discharge
2. Bio-Adaptive Plant Response
3. Checklist/Guidelines for Effective Design
4. Combining Techniques
5. Designing Stone Structures
6. Ecological Aspects of Bridge Design
7. Geotextiles and Root Penetration
8. Harvesting/Handling of Woody Cuttings
9. Management of Conveyance
10. Optimal Compaction and Other Strategies
11. Physical Aquatic Habitat
12. Proper Functioning Condition

TABLE 1 Final list of technique guidelines

Category	Technique	Level
<b>River Training</b>		
<b>Transverse Structures</b>	Spur dikes	I
	Vanes	I
	Bendway weirs	I
	Large woody debris structures	II
<b>Longitudinal Structures</b>	Stone weirs	II
	Longitudinal stone toe	I
	Longitudinal stone toe with spurs	I
	Coconut fiber rolls	II
	Vegetated gabion basket	I
	Live cribwalls	II
	Vegetated mechanically stabilized earth	I
	Live siltation	II
	Live brushlayering	I
<b>Channel Planform Measures</b>	Vegetated floodways	II
	Meander restoration	II
<b>Bank Armor and Protection</b>		
<b>Groundcovers</b>	Vegetation alone	II
	Live staking	I
	Willow posts and poles	II
	Live fascines	I
	Turf reinforcement mats	II
	Erosion control blankets	II
	Geocellular containment systems	II
<b>Revetments</b>	Rootwad revetments	II
	Live brush mattress	I
	Vegetated articulated concrete blocks	I
	Vegetated riprap	I
	Soil and grass covered riprap	II
	Vegetated gabion mattress	II
	Cobble or gravel armors	II
Trench fill revetment	II	
<b>Riparian and Stream Opportunities</b>		
<b>Top-of-Bank Treatments</b>	Live gully repair	III
	Vanes with J-hooks	I
<b>In-Stream Habitat Improvements</b>	Cross vanes	I
	Boulder clusters	II
	Newbury rock riffles	II
<b>Slope Stabilization</b>		
<b>Drainage Measures</b>	Diversion dike	II
	Slope drain	II
	Live pole drain	III
	Chimney drain	II
	Trench drain	II
	Drop inlet	II
	Fascines with subsurface drain	II
<b>Bank Regrading</b>	Slope Flattening	II
<b>In-Situ Reinforcement</b>	Stone-fill trenches	II

13. Resistive (Continuous) vs. Redirective (Discontinuous)
14. Revetments to Resist Wave Wash
15. Self-Launching Stone/Well Graded Stone

16. Sources, Species, and Durability of Large Wood
17. The Key to Stability is the Key
18. The Role of Geotextiles and Natural Fabrics

## CHAPTER 6

# TECHNIQUE SELECTION SYSTEM

### SELECTION STRATEGY AND APPROACH

Greenbank is a rule-based selection software program developed for use by DOT or consulting engineers. The governing rules relate the strengths and weaknesses (hydraulic, geotechnical and environmental) of each technique to the relevant site conditions and project constraints. The knowledge base is contained in a matrix that allows the user to examine the rules and the basic rationale or reasoning behind each technique. Such an approach avoids the controversy associated with selecting techniques based on a particular stream classification system. This approach also allows the user to conduct sensitivity analyses when reach descriptors are based on estimates.

This software is roughly patterned on an earlier expert system known by the acronym ENDOW (Environmental Design of Waterways) developed in the mid-1980s at the U.S. Army Engineer Waterways Experiment Station (Shields and Aziz, 1992). The new selection system, Greenbank, was developed using a Windows-based tool known as Exsys CORVID. The CORVID system allowed the development of a tailor-made, interactive decision-making tool.

As noted previously, some 44 discrete techniques were identified and adopted. Design criteria for some (Level I Techniques) are highly developed, with abundant studies in flumes, field experiments, and mathematical analyses. Others (Level II and Level III Techniques) are less well documented and are supported only by anecdotal or qualitative observation. The rule-based system allowed the application of the current knowledge for each technique. In the case of hydraulic criteria, for example, there is a tabulation from the literature prepared by Fischenich (2001b), as well as others. Geotechnical criteria are well known in some cases, unknown in others, and sometimes not applicable. Due to regional differences in ecosystems, much of the environmental criteria must be general and generic. In any case, the Greenbank system is intended not to provide detailed design criteria, but rather to offer a list of techniques that match (1) dominant erosion processes and (2) environmental resources of special concern at the site in question.

### GREENBANK DECISION SUPPORT TOOL

The Greenbank decision support tool can be run using a web browser (i.e., recent versions of Internet Explorer or

Netscape). The program, which contains rules to screen all 44 techniques and all attendant files, may be read from the accompanying CD. (Once the CD is started, an icon at the lower right corner of every screen opens the support tool.) A typical Greenbank consultation begins with the software asking the user to provide information about the proposed project. Specific aquatic habitat requirements can be taken into account in a systematic manner. The user is asked to specify environmental resources or aquatic attributes of interest from a list of 11 possibilities: (1) benthic habitat, (2) decreased sedimentation, (3) enhanced bed stabilization, (4) fish rearing habitat, (5) holding areas for adult fish, (6) in-stream and overhead cover, (7) pool and riffle enhancement, (8) public acceptance potential, (9) riparian habitat, (10) velocity refugia for fish, and (11) water quality improvement. Based on this initial response, the system asks for more specific information about environmental issues.

The user is then asked to characterize the erosion problem as (1) gullyng, (2) erosion or scour by stream flow or wave wash, or (3) mass wasting (i.e., slope failure). If the user is uncertain about the nature of the erosion at his or her site, links are provided with text and photos to help the user identify the dominant erosion process(es). In the case of erosion or scour by stream flow, the user can also input hydraulic criteria (i.e., design velocity and boundary shear stress), which allows Greenbank to compare these criteria with available published allowable values. A worksheet is provided to assist the user in computing estimates of velocity or shear stress.

The user is also asked to classify the spatial extent of the problem as local or general. If the erosion is general, the user must identify the parts of the stream channel cross section that appear to be eroding: top bank, middle bank, toe, or channel bed. Through this dialog, the user is led to identify the dominant erosion mechanisms operative at the site in question. Up to 4 erosion mechanisms may be selected from a master list of 12 processes. The user is then asked to specify the maximum acceptable unit cost (relative to a riprap blanket).

Greenbank then assigns a score to each of the 44 techniques based on the technique's overall feasibility. This feasibility score takes into account suitability for a particular type of erosion problem, spatial location of the problem, environmental attributes specified as important, and price the

user is willing to pay. The top techniques are then output to the user, who may elect to change any or all of his or her previous responses and obtain new recommendations. Each technique recommended is linked to the corresponding tech-

nique guideline within the manual portion of the CD, so that the user can learn more about the recommended technique. The logic flow, or selection methodology, used in Greenbank is described in more detail in Appendix B.

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## BIBLIOGRAPHY

The following is a complete list of all documents, including web pages, used in preparing the technique guidelines and special topics for this report. The accompanying CD includes this list of documents under References. The full texts of items in this list that end with (pdf) are also available on the CD.

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## APPENDIX A

### DESCRIPTIVE LIST OF CHANNEL- AND BANK-PROTECTION TECHNIQUES

The following techniques are described below:

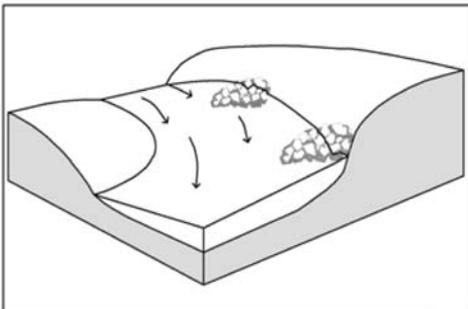
- River training
  - Spur dikes
  - Vanes
  - Bendway weirs
  - Large woody debris structures
  - Stone weirs
  - Longitudinal stone toe
  - Longitudinal stone toe with spurs
  - Coconut fiber rolls
  - Vegetated gabion basket
  - Live cribwalls
  - Vegetated mechanically stabilized earth
  - Live siltation
  - Live brushlayering
  - Vegetated floodways
  - Meander restoration
- Bank armor and protection
  - Vegetation alone
  - Live staking
  - Willow posts and poles
  - Live fascines
  - Turf reinforcement mats
  - Erosion control blankets
  - Geocellular containment systems
  - Rootwad revetments
  - Live brush mattress
  - Vegetated articulated concrete blocks
  - Vegetated riprap
  - Soil and grass covered riprap
  - Vegetated gabion mattress
  - Cobble or gravel armors
  - Trench fill revetment
- Riparian buffer and stream opportunities
  - Live gully repair
  - Vanes with J-hooks
  - Cross vanes
  - Boulder clusters
  - Newbury rock riffles
- Slope stabilization
  - Diversion dike
  - Slope drain
  - Live pole drain
  - Chimney drain
  - Trench drain
  - Drop inlet
  - Fascines with subsurface drains
  - Slope flattening
  - Stone-fill trenches

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#### RIVER TRAINING

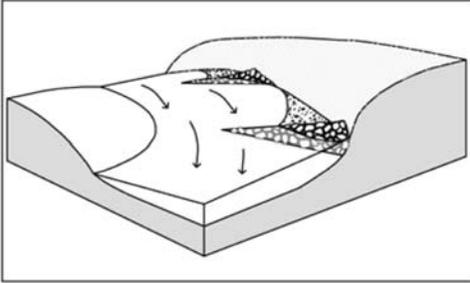
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##### SPUR DIKES



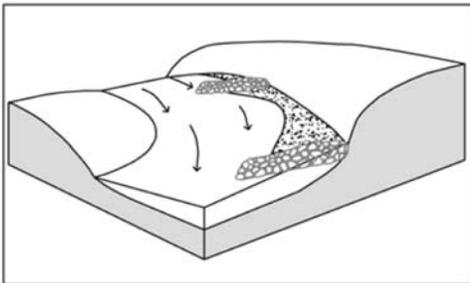
Spur dikes, deflectors, or groins are transverse structures that extend into the stream from the bank and reduce erosion by deflecting flows away from the bank. Transverse river training structures often provide pool habitat and physical diversity. Two to five structures are typically placed in series along straight or convex bank lines where flow lines are roughly parallel to the bank. Spurs, groins, and deflectors have no specific design criteria regarding crest height, crest slope, or upstream angle and therefore differ from vanes and bendway weirs. Earthen core spur dikes are groins constructed with a soil core armored by a layer of stone. Deflectors can also be constructed from natural materials, such as Large Woody Debris (LWD), or LWD embedded with rock, and designed to provide biologic benefits and habitat restoration. Stone spurs capped with a prism of earth reinforced with live fascines are referred to as “live booms.”

## VANES



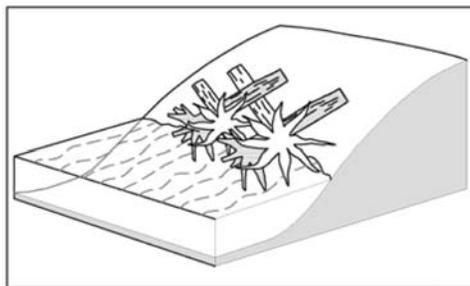
Rock vanes are discontinuous, redirective structures angled upstream 20 to 30 degrees. Generally, two or three vanes are constructed along the outer bank of a bend in order to redirect flows near the bank to the center of the channel. Typically, vanes project  $1/3$  of the stream width. The riverward tips are at channel grade, and the crests slope upward to reach bankfull stage elevation at the key. Rock vanes can preclude the need for rock armor and increase vegetative techniques as the high flows are redirected away from the bank. Vanes can increase cover, backwater area, edge or shoreline length, and the diversity of depth, velocity, and substrate. Variations include cross vanes and rock vanes with J-hooks.

## BENDWAY WEIRS



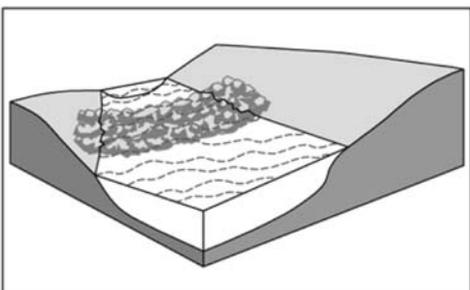
Bendway weirs are discontinuous, redirective structures usually constructed of rock, designed to capture and then safely direct the flow through a meander bend. A minimum of five structures are typically placed in series (the series are known as “weir fields”) along straight or convex bank lines. Bendway weirs differ from spurs and vanes in that they form a control system that captures and directs the streamflow through the weir field, usually all the way through the bend (hence the name bendway weirs). Bendway weirs are generally longer ( $1/3$  to  $1/2$  stream width) and lower than barbs or spurs, flat crested, and designed to be continuously submerged or at least overtopped by the design flows. Transverse river training structures often provide pool habitat and physical diversity.

## LARGE WOODY DEBRIS STRUCTURES



Large woody debris (LWD) structures (also known as engineered log jams) made from felled trees may be used to deflect erosive flows and promote sediment deposition at the base of eroding banks. Root wads, consisting of a short section of trunk and attached root bole, can also be used or incorporated into the structures. Using the classical spur design criteria and methods, the placement of LWD structures can be designed to achieve optimum benefit for both aquatic habitat and bank protection.

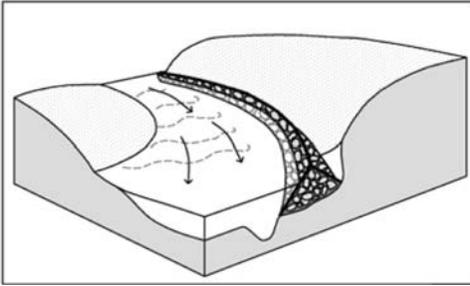
## STONE WEIRS



Stone weirs are structures that span the stream and produce a drop in the water surface elevation. These structures are frequently made of angular quarried stone, but logs, sheet piling, concrete, boulders and masonry are also quite common. Well-constructed stone weirs can prevent or retard channel bed erosion and upstream progression of knickpoints and headcuts, as well as provide pool habitats for aquatic biota. Stone weirs or similar grade control structures are often intended to raise or elevate the bottom of incised channels, with the ultimate goal of elevating a dropping water table. Variations on stone weirs that have additional habitat benefits are newbury rock riffles and cross vanes.

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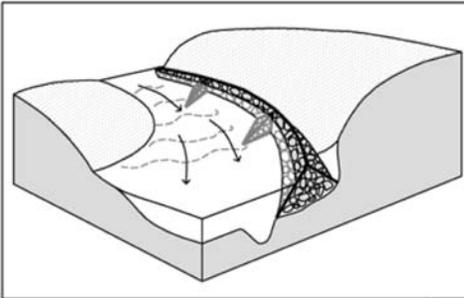
### LONGITUDINAL STONE TOE



A longitudinal stone toe (also known as longitudinal peaked stone toe protection [LPSTP]) is continuous bank protection consisting of a stone dike placed longitudinally at, or slightly streamward of, the toe of an eroding bank. The cross section of the stone toe is usually triangular in shape. The success of this method depends upon the ability of stone to self-adjust or "launch" into scour holes formed on the stream side of the revetment. The stone toe does not need to follow the bank toe exactly, but should be designed and placed to form an improved or "smoothed" alignment through the stream bend. Longitudinal stone toes usually require much less bank disturbance and the bank landward of the toe may be revegetated by planting or natural succession. Brushlayering and willow post and poles are excellent candidates for use with this technique.

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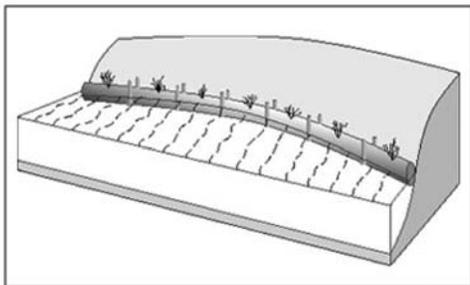
### LONGITUDINAL STONE TOE WITH SPURS



A longitudinal stone toe (also known as longitudinal peaked stone toe protection) has proven cost-effective in protecting lower banks and creating conditions leading to stabilization and revegetation of steep, caving banks. A large body of evidence indicates, however, that intermittent structures such as spurs tend to provide aquatic habitats superior to those adjacent to continuous structures like a stone toe. This technique represents an effort to achieve erosion control benefits available from a continuous stone toe and habitat benefits associated with spurs.

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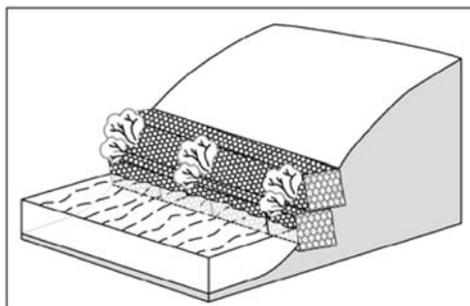
### COCONUT FIBER ROLLS



Coconut fiber rolls are manufactured, elongated cylindrical structures that are placed at the bottom of streambanks to help prevent scour and erosion. The coconut husk fibers (coir) are bound together with geotextile netting with 35 cm or 40 cm (12 in. or 18 in.) diameters and lengths of 6 m (20 ft). Coir is fairly long-lasting, typically 5 to 7 years, but must be designed with riparian revegetation to attain permanent solutions. Proper anchoring is critical and generally coir rolls are not recommended for areas with high velocities and shear. Brushlayering and live stakes are good candidates for combining with coconut fiber rolls.

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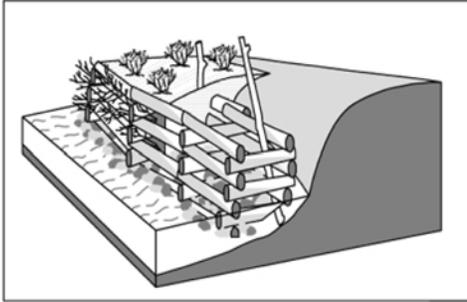
### VEGETATED GABION BASKET



Gabions are rectangular baskets made of twisted or welded-wire mesh that are filled with rock. These flexible and pervious structures can be used individually or stacked like building blocks to reinforce steep banks. Used alone, rock-filled gabions provide insufficient habitat benefit. However, woody vegetation, such as brushlayering or post and poles, can be incorporated by inserting the cuttings all the way through the basket during filling and penetrating the native subsoil. The woody vegetation can provide additional reinforcement and longevity to the structure while helping to mitigate loss of habitat.

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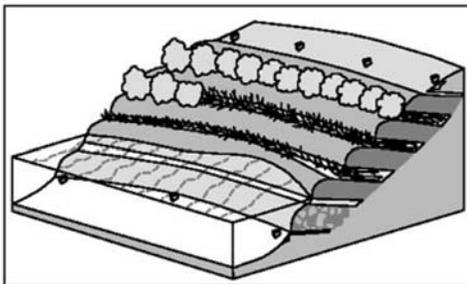
## LIVE CRIBWALLS



A cribwall is a gravity retaining structure consisting of a hollow, box-like interlocking arrangement of structural beams (for example, logs). The interior of the cribwall is filled with rock or soil. In conventional cribwalls, the structural members are fabricated from concrete, wood logs, and dimensioned timbers (usually treated wood). In live cribwalls, the structural members are usually untreated log or timber members. The structure is filled with a suitable backfill material, and live branch cuttings are inserted through openings between logs at the front of the structure and imbedded in the crib fill. These cuttings eventually root inside the fill and the growing roots gradually permeate and reinforce the fill within the structure.

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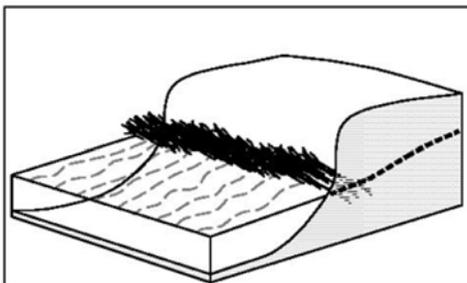
## VEGETATED MECHANICALLY STABILIZED EARTH



This technique consists of live cut branches (live brushlayering) interspersed between lifts of soil wrapped in natural fabric, for example, coir, synthetic geotextiles (turf reinforcement mats [TRMs] or erosion control blankets [ECBs]), or geogrids. The fabric, branches and optional geogrids provide the primary geotechnical reinforcement, similar to that of conventional mechanically stabilized earth, allowing relatively steep, stable slopes. The fabric wrap over the face of the soil lift prevents erosion until vegetation takes over. The live, cut branches eventually root and leaf out, providing vegetative cover and secondary reinforcement as well. This technique is recommended for use above the annual high water stage.

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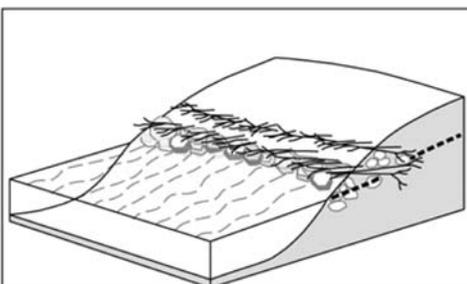
## LIVE SILTATION



Live siltation is a bioengineering technique involving the installation of a living or a nonliving brushy system at the water's edge. Willow cuttings are the most common materials used. Live siltation construction is intended to increase roughness at the stream edge thereby encouraging deposition and reducing bank erosion. The embedded branches and roots also reinforce the bank and reduce geotechnical failure, while the branches and leaves provide cover, aquatic food sources, and organic matter.

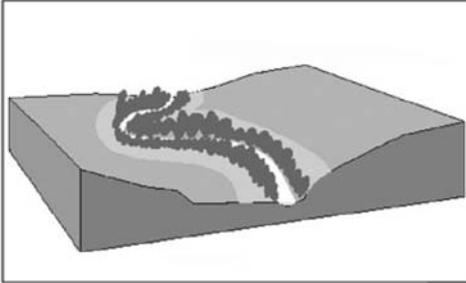
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## LIVE BRUSHLAYERING



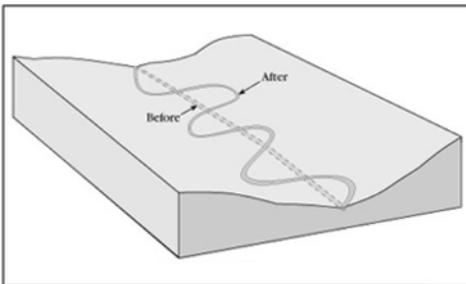
Live brushlayers are rows of live woody cuttings that are layered, alternating with successive lifts of soil fill, to construct a reinforced slope or embankment. Vertical spacing depends on slope gradient and soil conditions. Live brushlayering provides enhanced geotechnical stability, improved soil drainage, and superior erosion control. It is one of the most effective ways to establish vegetation from live cuttings. Live brushlayering is an excellent candidate for combining with other streambank stabilization measures.

## VEGETATED FLOODWAYS



Confining floodwaters to a broad floodway bordered by levees or topographic highs is attractive because the portion of the floodway not normally inundated can support vegetation and thus provide wildlife habitat or recreational opportunities. Floodways may be created by constructing levees or floodwalls or by excavation. Excavation consists of creating terraces or benches along an existing channel or a completely new flood channel (bypass). Roadway embankments sometimes serve a dual purpose by defining a floodway.

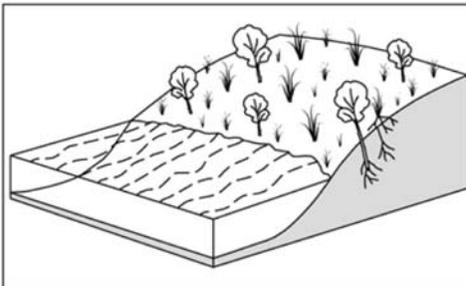
## MEANDER RESTORATION



Meanders are broad, looping (sinuous) bends in a stream channel. Meandering is a form of slope adjustment with more sinuous channel paths leading to decreased reach gradient. Fluvial and ecological functions are integrally related to the highly diverse spatial and temporal patterns of depth, velocity, bed material and cover found in meanders. Generally speaking, streams with natural meander bends do not require grade control measures. Meander restoration consists of reconstructing meandering channels that have been straightened or altered by humans.

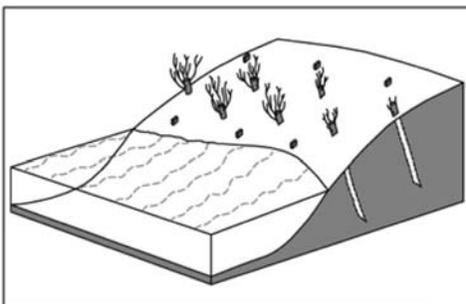
## BANK ARMOR AND PROTECTION

### VEGETATION ALONE



Vegetation can be viewed as a living, organic groundcover consisting of grasses, legumes, forbs, or woody plants. Vegetation is established on bare soils in order to help prevent surficial erosion, minimize shallow seated mass movement, provide habitat, and enhance aesthetics or visual appearance. Vegetation can be used alone under special circumstances, but it also lends itself well to conjunctive use with other erosion control techniques in a mutually beneficial manner. Living plants can be used in conjunction with nearly every type of groundcover.

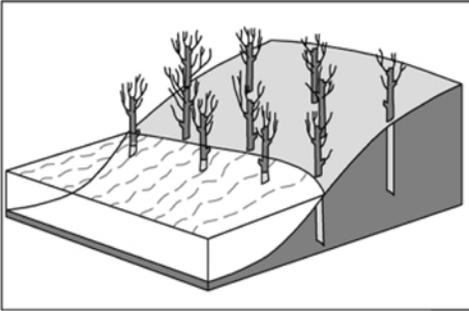
### LIVE STAKING



Live stakes are very useful as a revegetation technique, a soil reinforcement technique, and as a way to anchor erosion control materials. They are usually cut from the stem or branches of willow species, and the stakes are typically 0.5 to 1.0 m (1.5 to 3.3 ft) long. The portion of the stem in the soil will grow roots and the exposed portion will develop into a bushy riparian plant. This technique is referred to as Joint Planting when the stakes are inserted into or through riprap. Live staking is an excellent candidate for combination with other techniques.

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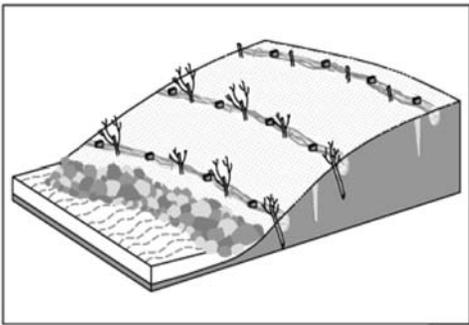
### WILLOW POSTS AND POLES



Post and pole plantings are intended to provide mechanical bank protection. Willow and cottonwood species are recommended for their ability to root and grow, particularly if they are planted deep into the streambanks. Larger and longer than live stakes, posts and poles can provide better mechanical bank protection during the period of plant establishment. Dense arrays of posts or poles can reduce velocities near the bank or bed surface, and long posts or poles reinforce banks against shallow mass failures or bank slumps. Posts and poles are also excellent candidates for combination with other structural methods, for example, LWD structures, vegetated gabion baskets, live cribwall, and cross vanes.

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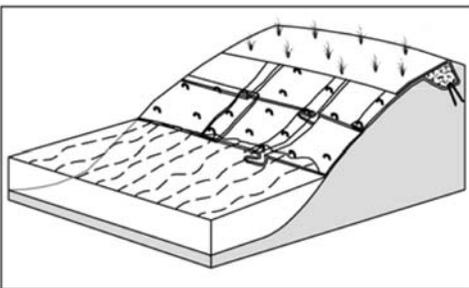
### LIVE FASCINES



Live fascines are bundles of live (and nonliving) branch cuttings placed in long rows in shallow trenches across the slope on contour or at an angle. Fascines are intended to grow vegetatively while the terraces formed will trap sediment and detritus, promoting vegetative establishment. Fascines can be utilized as a resistive measure at the stream edge and for erosion control on long bank slopes above annual high water. Fascines are also an effective way to anchor ECBs and TRMs.

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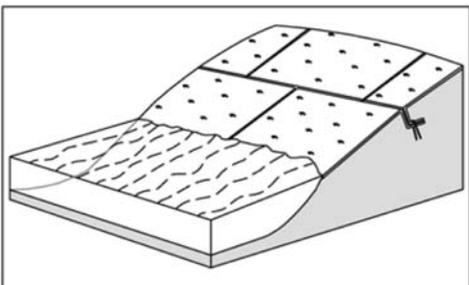
### TURF REINFORCEMENT MATS



Turf reinforcement mats (TRMs) are similar to erosion control blankets, but they are more permanent, designed to resist shear and tractive forces; they are usually specified for banks subjected to flowing water. The mats are composed of ultraviolet (UV) stabilized polymeric fibers, filaments, or nettings, integrated together to form a three-dimensional matrix 5 to 20 mm (0.2 to 0.79 in.) thick. TRMs are a biotechnical practice intended to work with vegetation (roots and shoots) in mutually reinforcing manner. As such, vegetated TRMs can resist higher tractive forces than either vegetation or TRMs can alone.

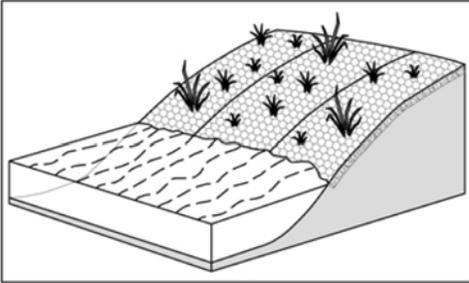
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### EROSION CONTROL BLANKETS



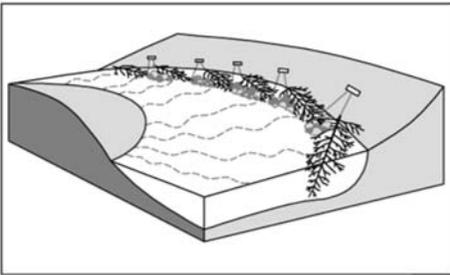
Erosion control blankets (ECBs) are a temporary rolled erosion control product consisting of flexible nets or mats that can be brought to a site, rolled out, and fastened down on a slope. ECBs are typically manufactured of fibers such as straw, wood, excelsior, coconut, or a combination of these, and then stitched to or between geosynthetic or woven natural fiber netting. Various grades of biodegradable fibers and netting can be specified depending on required durability and environmental sensitivity.

## GEOCELLULAR CONTAINMENT SYSTEMS



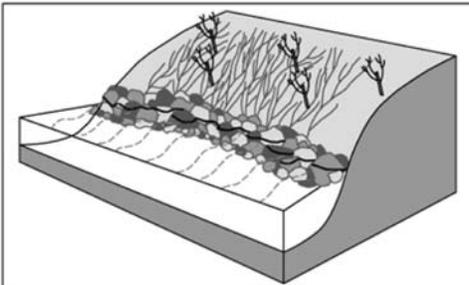
Geocellular containment systems (GCS) are flexible, three-dimensional, high density polyethylene (HDPE), honeycomb-shaped, earth-retaining structures that can be expanded and backfilled with a variety of materials to mechanically stabilize surfaces. They can be used flat, as channel or slope lining, or stacked to form a retaining wall. GCS provide very little habitat enhancements alone, therefore these systems must be combined with vegetation to be considered environmentally sensitive. Live staking and joint planting are excellent choices for combining techniques.

## ROOTWAD REVETMENTS



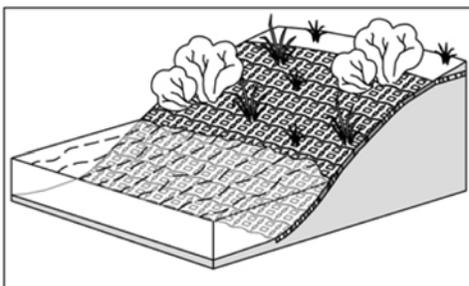
Rootwad revetments and tree revetments are structures constructed from interlocking tree materials. These structures are continuous and resistive, distinguishable from discontinuous and redirective techniques, such as LWD structures or rootwad deflectors. Rootwad revetments and tree revetments are primarily intended to resist erosive flows and are usually used on the outer bank of a meander bend when habitat diversity is desirable and tree materials are available and naturally occurring.

## LIVE BRUSH MATTRESS



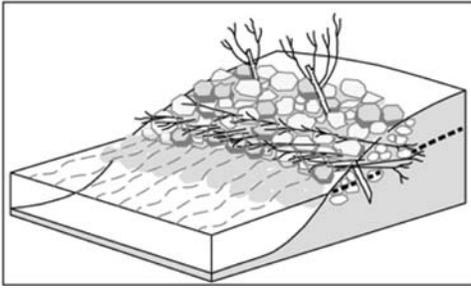
A live brush mattress is a thick blanket (15 to 30 cm [6 to 12 in.]) of live brushy cuttings and soil fill. The mattresses are usually constructed from live willow branches or other species that easily root from cuttings. Brush mattresses are used to simultaneously revegetate and armor the bank. The dense layer of brush increases roughness, reducing velocities at the bank face, and protecting it from scour, while trapping sediment and providing habitat directly along the water's edge. Brush mattresses are an excellent candidate for combining with structural techniques such as rock toe protection.

## VEGETATED ARTICULATED CONCRETE BLOCKS



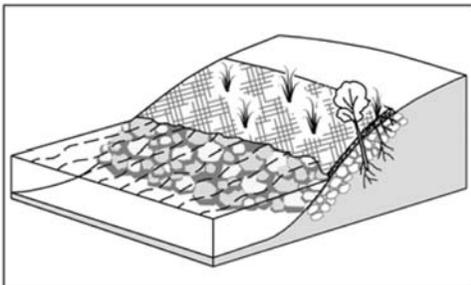
An articulated concrete block (ACB) system consists of durable concrete blocks that are placed together to form a matrix overlay or armor layer. Articulated block systems are flexible and can conform to slight irregularities in slope topography caused by settlement. The blocks are placed on a filter course (typically a geofabric) to prevent washout of fines through the blocks. ACBs provide very little habitat enhancements alone, therefore these systems must be combined with vegetation to be considered environmentally sensitive. Vegetation in the form of live cuttings or grass plugs is inserted through openings in the blocks into the native soil beneath the blocks.

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**VEGETATED RIPRAP**


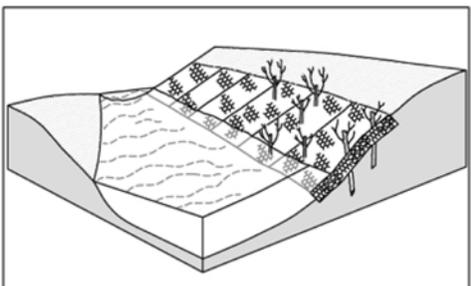
A vegetative riprap is a layer of stone and/or boulder armoring that is vegetated, optimally during construction, using pole planting, brushlayering, and live-staking techniques. The goal of this method is to increase the stability of the bank, while simultaneously establishing riparian growth within the rock and overhanging the water to provide shade, water quality benefits, and fish and wildlife habitat. Vegetative riprap combines the widely accepted, resistive, and continuous rock revetment techniques with deeply planted biotechnical techniques.

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**SOIL AND GRASS COVERED RIPRAP**


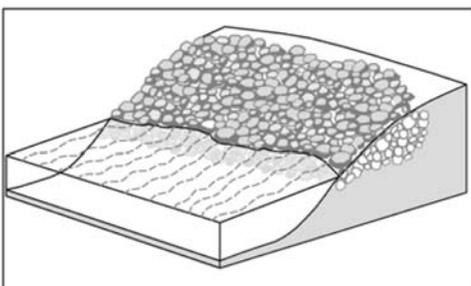
Two configurations have been used: (1) an ordinary riprap blanket is covered with a layer of soil 30 to 60 cm (1 to 2 ft) thick from the top of the revetment down to base flow elevation or (2) a crown cap of soil and plant material is placed over a riprap toe running along the base of a steep bank, effectively reducing the bank angle. Soils used for fill should not be highly erosive. A variety of methods may be used to establish plant materials, including hydroseeding, seeding and mulching, sodding, and incorporation of willow cuttings or root stock in the fill materials.

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**VEGETATED GABION MATTRESS**


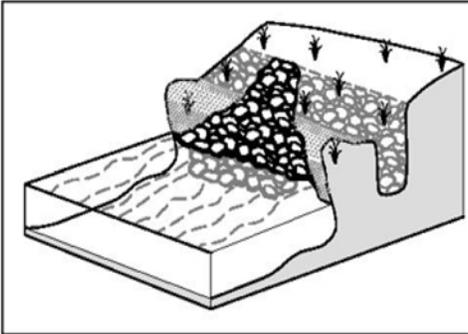
Gabion mattresses differ from gabion baskets as they are shallow (0.5 to 1.5 m [20 to 60 in.] deep), rectangular containers made of welded wire mesh and filled with rock. Gabion mattresses are not stacked but placed directly and continuously on the prepared banks. They are intended to protect the bed or lower banks of a stream against erosion. A gabion mattress can be used as either a revetment to stabilize a streambank or, when used in a channel, to decrease the effects of scour. Live cuttings are introduced through the rock filled mattress and inserted into native soil beneath.

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**COBBLE OR GRAVEL ARMORS**


Cobble or gravel armor is a resistive technique, similar to riprap revetment, that uses naturally occurring rock. Cobbles are natural stones larger than 6.5 cm (2.5 in.) in diameter that have been rounded by the abrasive action of flowing water, while gravel is material smaller than cobble, but larger than sand (larger than about 5 mm [0.2 in.]). Rounded river cobble or gravel blanket presents a more natural appearance and can be as effective as riprap revetment for areas with relatively lower tractive forces and velocities.

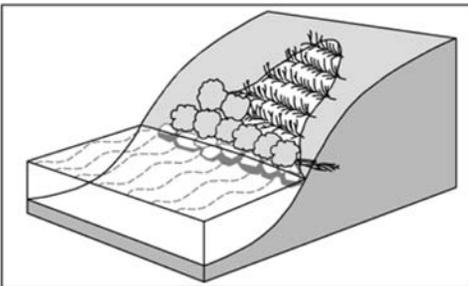
### TRENCH FILL REVETMENT



Trench fill revetments are constructed by excavating a trench along the top of the bank and placing stone riprap in the trench. As the bank erodes, the stone is undercut and “launches” down the bank line, resulting in a more gradual, protected slope. Earth removed for excavation of the trench may be used to cover the riprap, thus completely concealing it until it is launched. This technique might be chosen if access to the stream reach is restricted due to legal or environmental issues.

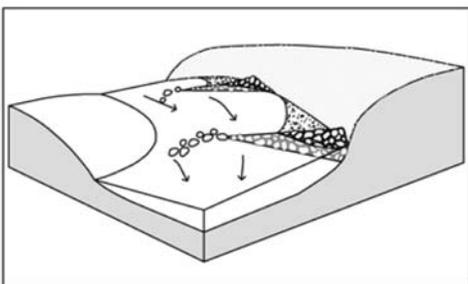
### RIPARIAN BUFFER AND STREAM OPPORTUNITIES

#### LIVE GULLY REPAIR



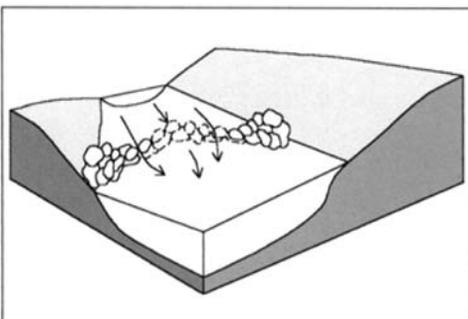
Live gully fill repair consists of alternating layers of live branch cuttings and compacted soil. This reinforced fill can be used to repair small gullies. The method is similar to branch packing (a method for filling small holes and depressions in a slope), but is more suitable for filling and repairing elongated voids in a slope, such as gullies. Gully treatment must include correcting or eliminating the initial cause of the gully as well as the gully itself. Gullies are likely to have tributary gullies that also require treatment.

#### VANES WITH J-HOOKS



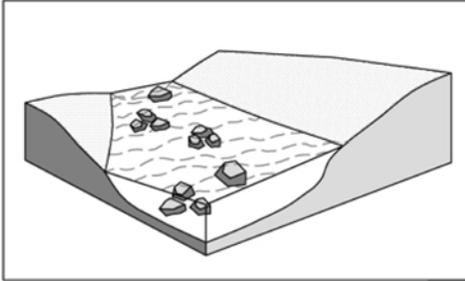
Vanes with J-hooks are actually rock vanes modified to enhance the instream habitat benefits. They are redirective, upstream-pointing deflection structures whose tip is placed in a “J” configuration and partially embedded in the streambed so that it is submerged even during low flows. The rock vanes have demonstrated effectiveness in reducing near-bank velocities by redirecting the thalweg toward the center of the channel. The “J” structures are intended to create scour pools and thereby improve substrate complexity. The scour usually results in a “tail out” deposition of gravel (riffle) which may provide spawning habitat.

#### CROSS VANES



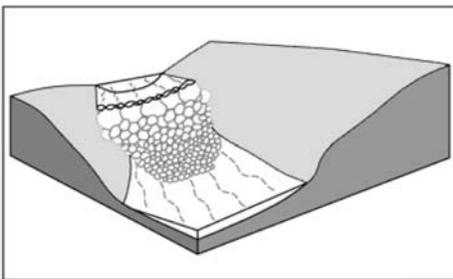
Cross vanes (also known as vortex weirs) are “V” shaped, upstream-pointing, rock structures stretching across the width of the stream. Cross vanes redirect water away from the streambanks and into the center of the channel. This serves to decrease shear stress on unstable banks, as well as create aquatic habitat in the scour pools formed by the redirected flow. Cross vanes are designed to be overtopped at all flows. The lowest part of the structure is the vortex of the “V,” which is at the point farthest upstream. The crests are sloped 3% to 5% with the ends of the vanes keyed into the streambanks at an elevation approximate to annual high water or bankfull stage. This shape forms a scour pool inside the “V.” Cross vanes are particularly useful for modifying flow patterns, enhancing in-stream habitat and substrate complexity, and providing in-grade control. Double cross vanes (W weirs) are a variation suitable for wider channels.

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**BOULDER CLUSTERS**


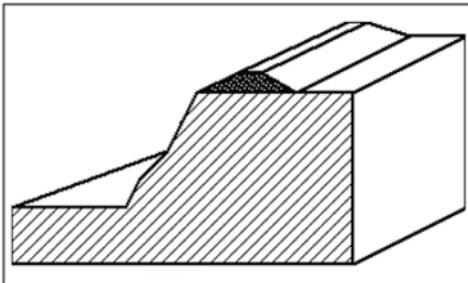
Large boulders may be placed in various patterned clusters within the base flow channel of a perennial stream. Natural streams with beds coarser than gravel often feature large roughness elements like boulders that provide hiding cover and velocity shelters for fish and other aquatic organisms. If a constructed or modified channel lacks such features, adding boulder clusters may be an effective and simple way to improve aquatic habitat.

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**NEWBURY ROCK RIFFLES**


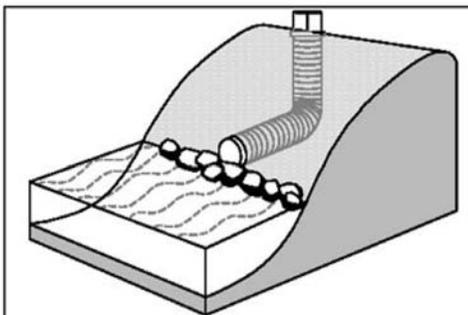
Newbury rock riffles are ramps or low weirs with long aprons made from riprap or small boulders that are constructed at intervals along a channel approaching natural riffle spacing (5 to 7 channel widths). The structures are built by placing rock fill within an existing channel. The upstream slope of the rock fill is typically much steeper than the downstream slope, which creates a longitudinal profile quite similar to natural riffles. These structures provide limited grade control, pool and riffle habitat, and visual diversity in otherwise uniform channels.

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**SLOPE STABILIZATION**
**DIVERSION DIKE**


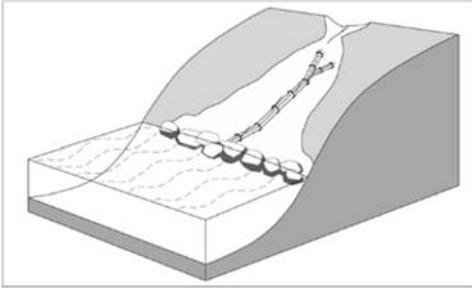
A diversion dike is a low berm (or ditch and berm combination) that is constructed along the crest or top of a streambank. The purpose of a diversion is to intercept and divert concentrated runoff away from the face of a steep slope or streambank. Diversion dikes are constructed from compacted earthen fill and should be used on drainage areas of 2 ha (5 ac) or less. In addition to protecting the face of a streambank from overbank runoff, diversions may also improve general slope stability by preventing runoff from infiltrating into and saturating the bank.

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**SLOPE DRAIN**


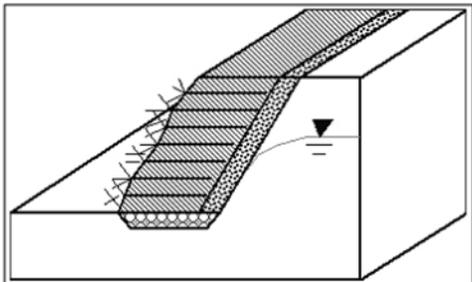
A slope drain is a drainage system used to collect and transport storm runoff down the face of a slope. This system usually consists of a berm at the top of the slope or streambank and a flexible pipe with end sections and outlet protection. A pipe slope drain is constructed with corrugated pipes (polymeric or metallic) and can be temporary or permanent. Slope drains are commonly used to: (1) temporarily convey runoff down the face of a steep slope until permanent protection or cover can be established, (2) prevent further cutting of a gully, and (3) serve as a permanent drainage-way down a steep slope where visual appearance is not a factor.

## LIVE POLE DRAINS



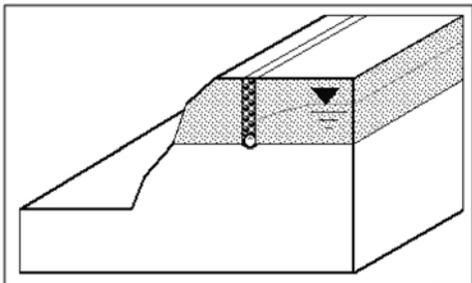
Live pole drains are live, growing, and often long-lived drainage systems composed of bundles (fascines) of live branches (commonly willow). Live pole drains are placed in areas where excess soil moisture results in soil instability. They are also used to treat small drainage gullies. Live pole drains collect subsurface drainage and concentrated surface flow and channel them to the base of the bank. Once established, their drainage function is increased, as the plants absorb much of the water that is conducted along their stems. Because they are long and fibrous, the bundles act like a conduit. As the fascines begin to root and sprout, the root system acts like a filter medium, stabilizing fine particles and reducing piping and sapping. Live pole drains provide drainage and stabilization immediately after installation and, once established, produce roots that further stabilize bank and levee slopes.

## CHIMNEY DRAIN



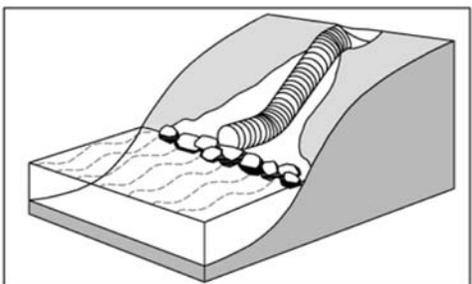
A chimney drain is a subsurface drainage course placed between a natural slope or streambank and an earthen buttress fill or other retaining structure (for example, log crib wall). A drainage blanket, sloped sheet drain, and strip drain are types of subsurface drainage courses. Typically, a chimney drain is a near-vertical drain that feeds into a collection system at its base, whereas a sloped sheet drain is inclined back at an angle. A subsurface drain may be continuous across the slope, or it may consist of discontinuous drainage strips that are placed against the natural slope at periodic intervals.

## TRENCH DRAIN



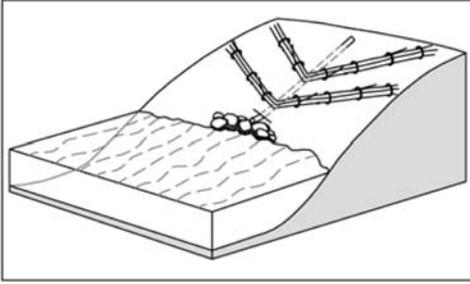
A trench drain is a drainage trench excavated parallel to and just behind the crest of a streambank. Ideally, the bottom of the trench should be keyed into an impermeable layer in the slope. The trench should be backfilled with a coarse graded aggregate that meets filtration criteria; that is, it should allow unimpeded flow of groundwater while excluding fines. Alternatively, the trench can first be lined with a filter fabric that meets the filtration requirements and then be backfilled with a coarse aggregate. The purpose of the trench is to intercept and divert shallow seepage away from the face of the streambank.

## DROP INLET



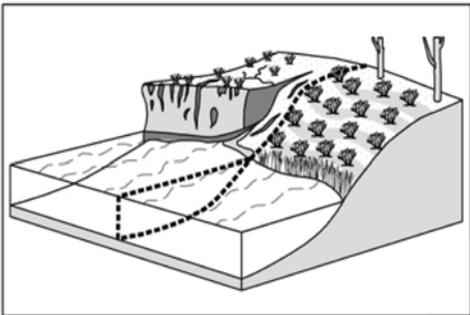
Concentrated overbank runoff can be a major cause of erosion, especially along deeply incised channels. Runoff passing over the top of banks frequently triggers gully development and expansion. Water that is ponded at the top of high, steep banks and infiltrates or seeps into the ground behind the slope face is often a major factor in erosion by piping or slope failure. Gully erosion and downcutting can be addressed using a drop inlet, which is a water control structure that consists of an L-shaped corrugated pipe passing through an earthen embankment placed at the downstream end of the gully.

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**FASCINES WITH SUBSURFACE INTERCEPTOR DRAIN**


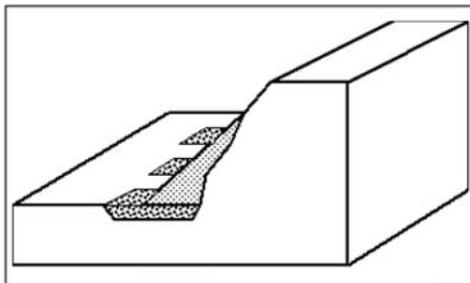
Rows of drainage fascines (also known as live pole drains) are installed off contour along a slope. Drainage fascines are widely used to help dewater landslides or small gullies and on very wet sites where there is evidence of substantial subsurface seepage that is causing piping and slope instability. As the seepage and drainage become concentrated, the fascines can be connected to a subsurface drain, consisting of a perforated pipe wrapped in a geocomposite drainage medium, and placed at the bottom of a trench. The trench is backfilled with clean, coarse aggregate or gravel that is oriented downslope. There is significant evidence that live drainage fascines, usually constructed from willow cuttings, are long lived once established.

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**SLOPE FLATTENING**


Flattening or bank reshaping stabilizes an eroding streambank by reducing its slope angle or gradient. Slope flattening is usually done in conjunction with other bank-protection treatments—including installation of toe protection, placement of bank armor, revegetation, and erosion control—or installation of drainage measures. Flattening or gradient reduction can be accomplished in several ways: (1) by removal of material near the crest, (2) by adding soil or fill at the bottom, or (3) by placing a toe structure at the bottom and adding a sloping fill behind it. Right-of-way constraints may limit or preclude the first two alternatives because both entail either moving the crest back or extending the toe forward.

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**STONE-FILL TRENCHES**


Stone-fill trenches are rock-filled trenches placed at the base of a streambank, usually within a failed section of the toe. A series of trenches are excavated at or within the toe of the slope in a direction perpendicular to the stream. The trenches are backfilled with crushed rock or stone. The toe of the slope is then reconstructed by placing and compacting earthen fill within and atop the stone-fill trenches. A small, longitudinal riverside plug or stone dike should be used between the stone trenches to help contain and protect the toe of the earthen fill placed between and atop the stone trenches.

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## APPENDIX B

# GREENBANK DECISION SUPPORT TOOL USER'S GUIDE

### HOW THIS SOFTWARE WORKS

The Greenbank Decision Support Tool assists users in selecting and learning about environmentally sensitive techniques for protecting transportation infrastructure located adjacent to stream channels. Specifically, Greenbank recommends streambed and bank erosion control measures suitable for a given site. Greenbank screens a master list of several dozen environmentally sensitive bed- and bank-protection techniques using responses the user provides to 12 to 20 questions. These questions deal with key environmental issues associated with the project, the nature of the stream reach where the project is located, key erosion processes, and cost factors. The master list of techniques is narrowed down using the responses until a short list of suitable techniques is derived. Selection criteria are based on the best available information from the literature and sound fundamental principles derived from the collective experience of engineers and scientists working with streams over many decades.

The system eliminates techniques that published sources indicate are not able to withstand forces produced by design flows at the site in question. Additional queries include or eliminate techniques based on cost and on the way the techniques control erosion. For example, continuous measures like stone blanket typically halt erosion entirely, while discontinuous measures like bank barbs or spur dikes deflect flows but may allow limited erosion between structures after construction until a stable, "scaloped" bank line is formed. At the end of a consultation, Greenbank provides a ranked list of the recommended techniques with explanatory notes about each one. For each recommended technique, the user may also request a list of techniques that may be combined with the recommended technique to improve the net environmental outcome. A list of all of the techniques that were not recommended is also available to the user, with notes for each technique explaining why it was not recommended.

### INITIAL INPUTS

#### Environmental Attributes

The user provides responses to a series of multiple-choice questions regarding the importance of various types of environmental attributes for the project in question. Each of 11 specific attributes is rated as very important (2), somewhat important (1), or not important (0). All values are initially set to 0. In order to make dialog more efficient, the user is initially asked for interest in the following four categories:

- Water column habitats
- Benthic habitats
- The riparian zone and related terrestrial habitats or water quality
- Public acceptance

If interest is expressed in any of the first three of these categories, queries regarding the associated attributes appear:

Water column habitats:

- Providing instream or overhead cover for fish and other aquatic organisms
- Providing and enhancing fish rearing habitat
- Providing habitat for adult fish
- Creation of velocity refugia
- Pool and riffle enhancement

Benthic habitats:

- Providing or enhancing quality stream bottom (benthic) habitat
- Decreasing the amount of sediment deposition occurring within the adjacent reach and downstream reaches
- Reducing the frequency of bed movement or the severity of erosion

The riparian zone and related terrestrial habitats or water quality:

- Riparian habitat
- Water quality improvement

These queries ask the user to assign a value of very important, somewhat important, or not important to each of the 10 attributes. If the user indicates public acceptance (the 11th attribute) is of interest, the program automatically assigns a value of very important to that attribute. If the user does not assign a value of very important or somewhat important to at least one of the eleven attributes, then a warning message is displayed.

*"You have not selected any environmental resource or attributes as important. Greenbank is designed to help you select techniques to address environmental issues. You may wish to use the back or restart buttons to revisit previous questions. However, you may continue if you wish."*

#### Erosion processes

Greenbank attempts to select bed and bank erosion control measures that address the dominant erosion processes operative

at the site in question. Through dialog with the user, the system links symptoms with causes and selects important erosion processes from a list of 13. The logic allows for the fact that one process may trigger multiple symptoms and that a given symptom does not always have the same cause. Furthermore, more than one erosion process may be important for a given site.

The dialog begins with Greenbank requesting the user to characterize the erosion problem at the site in question as one of the following:

- Development of gullies or rills
- Erosion or scour by waves or currents
- Bank collapse or mass failure

*Development of Gullies or Rills*

If the user selects “development of gullies or rills,” Greenbank requests the user to specify one or more of the three causes:

- Overbank runoff
- Piping due to steady seepage
- Episodic failures due to piping from sudden drawdown or return of overbank flooding to channel

*Erosion or Scour by Waves or Currents*

If the user selects “Erosion or scour,” Greenbank asks the user to classify the spatial extent of the problem as either local or general. Greenbank also asks where erosion appears to be occurring: on the bed, at the bank toe, on the middle of the bank, or on the top of the bank. Based on these responses, the user is asked to specify important processes. Allowable choices are indicated in Table B-1.

*Bank Collapse or Mass Failure*

If the user specifies that the bank problem is collapse or mass failure, Greenbank asks the user to classify the spatial

**TABLE B-1 Possible processes involved in erosion or scour by waves or currents**

Region where erosion is occurring (specified by user)	Spatial extent of erosion (specified by user)	
	Local (limited to a bank segment a few channel widths long)	General (similar processes appear to be occurring for a considerable distance up- and downstream)
Bed	Local scour due to flow obstruction, constriction, or channel irregularities.  Headcutting.	General bed degradation.  Headcutting.
Toe	Local scour due to flow obstruction, constriction, or channel irregularities.  Removal of noncohesive layers or lenses in stratified alluvium.	Toe erosion and upper bank collapse.
Middle of bank	Local scour due to flow obstruction, constriction, or channel irregularities.  Removal of noncohesive layers or lenses in stratified alluvium.	Middle and upper bank scour by currents.  Ice and debris gouging.
Top of bank	Local scour due to flow obstruction, constriction, or channel irregularities.  Removal of noncohesive layers or lenses in stratified alluvium.	Ice and debris gouging.  Navigation or wind wave wash.

extent of the problem as local (limited to a segment of bank shorter than a few channel widths long) or general.

If the problem is local, the user is asked to specify one of the following three processes as primary:

- Toe erosion and upper bank collapse
- Headcutting
- Piping

If the user selects piping, Greenbank asks if the piping appears to be due to steady seepage or due to sudden draw-down or return of overbank flooding to channel.

If the problem is general (similar processes appear to be occurring for a considerable distance up- and downstream), the user is asked to categorize the problem as follows:

- Toe erosion and upper bank collapse
- General bank instability or susceptibility to mass slope failure

A user who specifies slope instability is asked to specify whether or not the instability is related to subsurface water movement.

## GEOTECHNICAL STABILITY CHECK

If the user specifies that the main reason for bank collapse is general bank instability or susceptibility to mass slope failure, then Greenbank runs a simple geotechnical stability check. First, the user is asked to specify the type of bank material:

- Sand
- Cohesive soil
- Sandy soil
- A mixture of sand and clay
- Alternating sand and clay layers.
- Gravelly
- Noncohesive materials coarser than gravel
- Resistant bedrock

The user is also asked to provide the bank slope, bank height (H), angle ( $\beta$ ), soil density ( $\gamma$ ), friction angle ( $\phi$ ), and cohesion. The following steps are then used for a preliminary geotechnical stability check:

If the user selects sand as the bank material type, Greenbank asks if seepage (subsurface water movement) is a factor in slope instability. If seepage is not a factor, and if bank slope  $> 35$  degrees, an advisory is added to the comments that appear at the end of the run,

*“There is a potential mass instability problem at the site. Possible solutions include techniques that involve flattening the slope, providing internal reinforcement, or supporting the slope with a lateral structure.”*

If seepage or drawdown is a factor and if bank slope  $> 20$  degrees, then the advisory reads,

*“There is a potential mass instability problem at the site. Possible solutions include techniques that reinforce the slope, flatten the slope, support the slope with lateral structure, or improve subsurface drainage.”*

If the user selects *cohesive soil* as the bank material type, Greenbank computes an allowable bank slope angle  $\beta_{crit}$  using these relationships:

$$N_s = H \gamma / c$$

$$\beta_{crit} = -25N_s + 190$$

where  $N_s$  is the stability factor and  $\beta_{crit}$  is the square root of the angle beta.

This formula was obtained by fitting a linear regression to published tabulated values.<sup>1</sup> If the computed  $\beta_{crit} > \beta$ , then the following advisory appears:

*“You have indicated that general bank instability is one of the primary erosion processes operating on your site. However, simple stability checks indicate that the bank height, slope and soil type you have described should be stable. You may continue, but you may wish to use the back or restart buttons to revisit previous questions.”*

If the user specifies the bank material is a sand-clay mixture, Greenbank follows a procedure similar to the one for clay but uses the following relationship for  $N_s$ ,

$$N_s = [0.056684 + 0.0048688 * \text{SQRT}(\beta) * \ln(\beta) - 0.027777262 * \text{SQRT}(\phi)] - 1.$$

This relationship was obtained by fitting a nonlinear regression function to published values<sup>1</sup>. Then  $H_{crit} = N_s(c/\gamma)$ , and if  $H < H_{crit}$ , then the following advisory is displayed:

*“You have indicated that general bank instability is one of the primary erosion processes operating on your site. However, simple stability checks indicate that the bank height, slope and soil type you have described should be stable. You may continue, but you may wish to use the back or restart buttons to revisit previous questions.”*

If the user indicates the bank is alternating sand and clay layers then the following advisory message appears:

*“You have indicated that general bank instability is one of the primary erosion processes operating on your site. Greenbank normally checks bank stability using bank height, angle and soil properties. However, such simple analyses are not*

<sup>1</sup> *Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol. 97, No. SM1, January 1971, pp. 22-23.*

possible for complex stratigraphy (alternating layers of cohesive and noncohesive soils). You may wish to consult a geotechnical engineer for allowable bank heights and angles or run the ARS bank stability model after carefully studying the documentation. You may also use the back or restart buttons to revisit previous questions.”

No simple checks are run if the user specifies gravelly banks or noncohesive materials coarser than gravel. If the user specifies that the banks are *resistant bedrock*, the following message appears:

“You have indicated that general bank instability is one of the primary erosion processes operating on your site. However, you have also indicated the banks are composed of resistant bedrock. It is very unusual for bedrock banks to exhibit general instability. You may continue, but you may wish to use the back or restart buttons to revisit previous questions.”

### ALLUVIAL STREAM TYPE AND EROSION RISK

Elements of a simple stream classification system have been incorporated into Greenbank as an additional tool for assessing the likelihood of significant site erosion. Greenbank queries the user for values of several descriptive variables (for example, flow habit, bed material, bank material, planform, location and size of bars, channel width, and so forth) using a series of multiple-choice questions with largely qualitative answers. These responses are used to place the candidate site in one of five stream type categories defined by Brice et al. (1978).<sup>2</sup> If the site does not fit criteria for any of the Brice categories, it is classified as an unknown type. The five Brice stream types are used to further categorize the site as high, medium, or low erosion risk. Bed- and bank-protection techniques are then eliminated if they are not judged appropriate for the erosional regime of the site.

A similar approach is used to categorize the site according to the incised channel evolution model (CEM) developed by Schumm et al. (1984)<sup>3</sup> (see Figure B-1) and Simon (1989).<sup>4</sup> A stream reach is classified into one of five evolutionary phases or, if none of the phases seem to fit, as a reach where the CEM does not apply. Again, these results are used to classify the risk of instability. CEM stages I, II, III and IV are classified as high erosion risk, while stages V and VI are low risk. Sites that do not seem to fit or that exhibit none of the symptoms of incision upon which the CEM is based are classified as low risk.

<sup>2</sup> Brice, J. C., et al. *Countermeasures for Hydraulic Problems at Bridges*. Report No. FHWA-RD-78-162, FHWA, Offices of Research and Development (1978).

<sup>3</sup> Schumm, S. A., Harvey, M. D., and Watson, C. C., *Incised Channels: Morphology, Dynamics and Control*. Water Resources Publications, Littleton, CO (1984).

<sup>4</sup> Simon, A. “The discharge of sediment in channelized alluvial streams.” *Water Resources Bulletin*, Vol. 25, No. 6, 1989, pp. 1177-1188.

### BUDGET

The user is asked to input the maximum acceptable price for initial construction. However, this input is not a dollar amount but a ratio that represents the price relative to the price for protecting the site with stone riprap blanket. The actual input is therefore a number between 0.5 and 20 that represents the price the user is willing to pay divided by the cost for riprap revetment applied from bank toe to bank top at the site in question.

Maintenance effort may be measured in monetary or other terms. The user is asked to specify the maximum level of maintenance that can be provided in qualitative terms: minimal, moderate, or high.

### MISCELLANEOUS INPUTS

Greenbank asks if the user wishes to compare hydraulic loading at the site with criteria for the techniques under consideration. Local velocity, shear stress, or both may be evaluated, depending upon available criteria.

The user is also asked if additional land loss (due to continuing erosion or bank grading) would be acceptable at their site.

The user is asked for an assessment of the hazard, or consequences, of failure. Choices are extreme (almost certain loss of human life), severe (possible loss of human life and almost certain significant loss of adjacent structures), moderate (possible loss or severe damage to adjacent structures), and light (the probability of loss of life or severe damage to adjacent structures is very small).

### TECHNIQUE SELECTION

The Greenbank system examines each of the techniques using the inputs described above by comparing the user-supplied values with those in a large spreadsheet, or matrix, that contains a row for each technique. Suitability of each technique is encoded within the matrix as follows:

The matrix contains a column for each of the 11 environmental attributes and a column for each of the 11 erosion processes.

Entries in the environmental attribute columns are either 0 (the technique does not contribute positively to the attribute), 1 (the technique has potential for a mild positive impact on the attribute), or 2 (the technique generally has a major, positive effect on the attribute). For purposes of this selection system, simply controlling erosion generally does not constitute positive contribution.

Entries in the erosion processes columns are either 0 (the technique does not address the process) or 1 (the technique does address the process).

The matrix also contains a column giving estimated unit cost relative to riprap stone blanket.

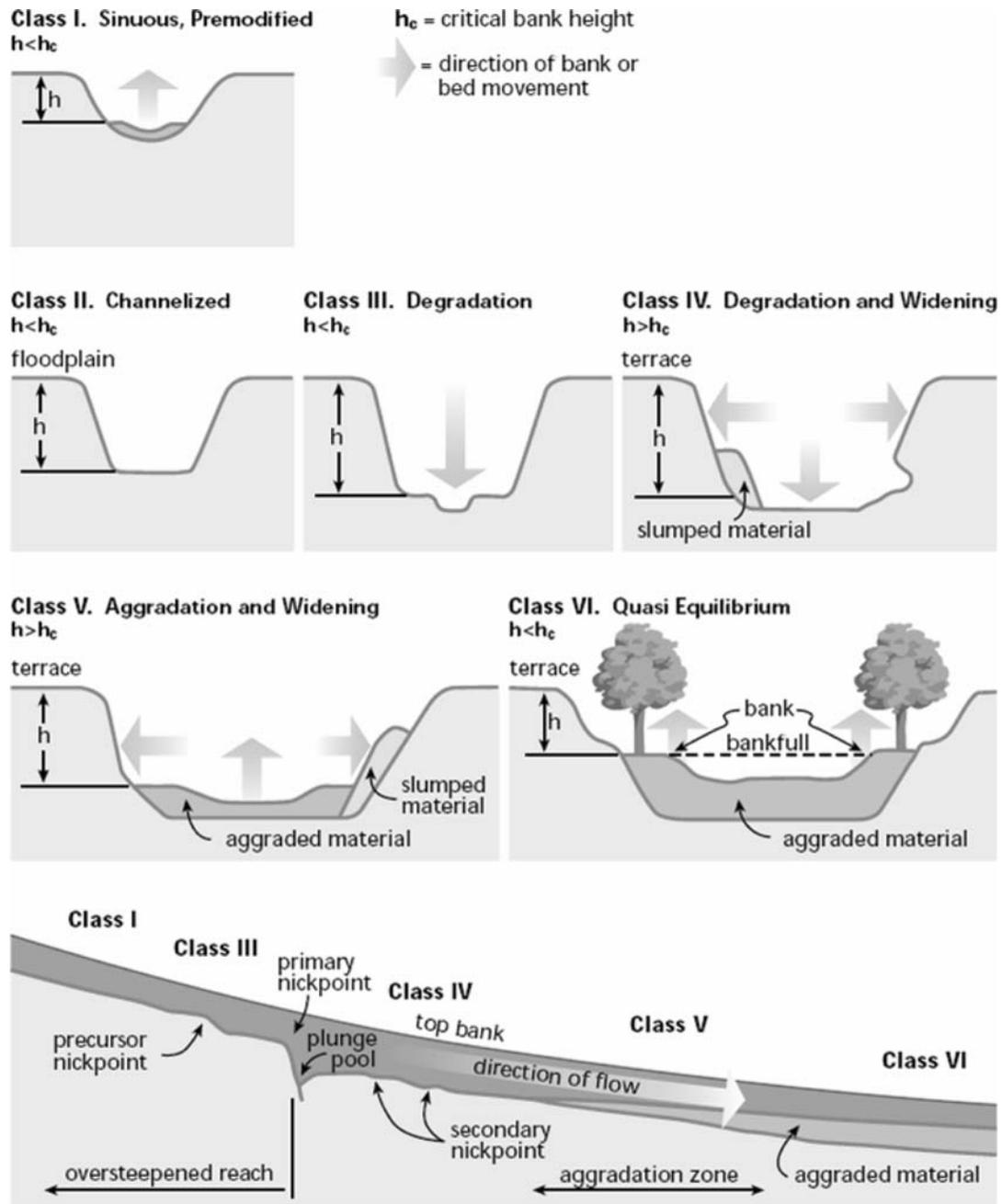


Figure B-1. Schumm's Channel Evolution Model

The matrix contains a column entitled "Level," and each technique is rated as follows:

Level I—well established and widely used, well documented (good performance and monitoring data available), reliable design criteria based on lab/field studies, numerous citations and case studies in technical literature, cost data available from variety of sources.

Level II—used often but lacks the level of detail, quality of information, and reliability that characterizes

Level I, little or no long-term monitoring, fewer case studies and citations in technical literature, cost data scarce or less certain.

Level III—emerging, promising technique. Does not have the track record and level of information characterizing Level I or II. No field or laboratory design or test data, no long-term monitoring or performance data, very few literature citations or case studies, no reliable cost data.

TABLE B-2 Treatment levels

Assignment Criteria	Treatment Level		
	I	II	III
Frequency of Use	Widely and frequently used	Occasional and more limited use	Infrequent use in very limited areas
Availability and Reliability of Lab/Field Test Data	<i>Good</i> ... abundant and reliable data	<i>Fair</i> ... more limited and less reliable	<i>Poor</i> ... little or no data available, mostly anecdotal
Performance and Monitoring Info	<i>Good</i> ... long term and well documented	<i>Fair</i> ... short term and less reliable	<i>Poor</i> ... little to none available
Literature Articles and Case Studies	<i>Many</i> ... in well regarded journals and agency publications	<i>Some</i> ... few if any case studies	<i>Few</i> ... mostly fugitive and obscure publications
Availability and Reliability of Cost Data	<i>Good</i> ...detailed unit costs from several different sources and locations	<i>Fair</i> ... less detailed and fewer sources	<i>Poor</i> ... little available and of limited applicability

Table B-2 summarizes the attributes of the three levels.

The matrix contains a column indicating the potential for additional bank erosion occurring after the technique is installed. For example, intermittent techniques like bendway weirs or bank barbs often create “scalped” banklines due to local erosion between structures. Values of 0, 1, or 2 are assigned for no, moderate, or strong potential, respectively. Values of -99 are found in rows for techniques where this aspect is controlled entirely by site-specific characteristics.

The matrix also contains columns for allowable shear stress and velocity. An adjacent column provides the source for these data (numbers for literature citations in a numbered reference list). If no critical velocity or shear stress values were found in the literature, the entries are -99. Values of 3.5 m/s and 2.5 m/s appear in rows corresponding to structures built with angular and rounded stone, respectively. Clearly these values depend on the size of the rock used, but these values were adopted as

they correspond to the largest size material commonly used for stream and river bed and bank erosion control.<sup>5</sup>

The matrix also contains a series of columns for several key reach characteristics as follows:

The matrix contains columns for each of nine key variables describing reach morphology and other site characteristics. Each technique is given an integer score for each variable. The nine variables are shown as headings in Table B-3, which also provides an explanation of what the integer scores in the matrix mean.

<sup>5</sup>  $D_{50} = 0.75$  m using approach of Maynard (1993) in Escarameia (1998) p. 40.  
Maynard, S. T., “Corps Riprap Design Guidance for Channel Protection.” In *River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone*, C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynard, and K. W. Pilarczyk. (eds.). John Wiley & Sons, Ltd., Chichester, U.K. (1995) pp. 41-42.  
Escarameia, M., *River and Channel Revetments*. Thomas Telford, Ltd., London (1998).

**TABLE B-3 Explanation of matrix scores for site description variables. The Greenbank master matrix contains a row for each erosion control technique. Each technique is given an integer score (shown in first column of this table) for each of the site variables (bold faced in this table). Cells shaded dark gray represent integer scores that do not appear under the given heading**

Entry in matrix	<b>Flow habit</b>	<b>Channel width</b>	<b>Flood plain width<sup>a</sup></b>	<b>Bed material</b>	<b>Bank material</b>	<b>Braiding</b>	<b>Stage of incision</b>	<b>Maintenance requirements</b>	<b>Erosion risk</b>
1		≤ 15 m	≤ 2W <sup>b</sup>	Silt to sand	Cohesive to noncohesive sandy	Not suitable for a braided stream	No incision	Low	Suitable only for sites with low erosion risk
2	Ephemeral or intermittent	≤ 50 m	More than 2W but less than 10W	Sand to gravel	Cohesive to noncohesive gravelly	Possibly suitable for a braided stream	Stage VI or no incision	Moderate	Suitable for sites with low to moderate erosion risk
3	Perennial or no limitations	≤ 500 m	≥ 10W	Gravel to cobble	Cohesive to noncohesive materials coarser than gravel	Suitable for a braided stream	Stage V, VI or no incision	High	Suitable for all sites without respect to risk
4		≥ 500 m	> 2W	Cobble to boulder	No limitations		Stage IV, V, VI or no incision		
5		≥ 15 m		Silt to gravel			Stage III, IV, V, VI or no incision		
6		No limitations		Gravel to boulder			No limitations		
7				Sand to cobble					
8				No limitations					

<sup>a</sup> Area flooded by 50 to 100 year event.

<sup>b</sup> W = active channel width.

**EVALUATION OF A GIVEN TECHNIQUE**

Each of the techniques contained in the Greenbank master matrix is assigned a numerical score that represents the suitability of the technique for the user’s project. Initially, all scores are zero. For each technique the system computes a score as follows:

If an environmental attribute rated as very important or somewhat important has a score in the matrix > 0, the system adds (the entry in the matrix/importance of the attribute) to the score of the technique. Matrix entries are 0, 1, or 2, while importance values are 1, 2 or 3 as shown in Table B-4.

If the maximum relative cost specified by the user is greater than or equal to the relative cost in the matrix, the system adds the quantity (1/relative cost) to the score. If the relative cost is more than the user-specified maximum, then the system adds the quantity (budget – relative cost), which will be a negative number, to the score.

If an erosion process that the user rated as important has an entry of 1 in the matrix, the system adds 5 points to the score of the technique. If an erosion process rated as important has a value of 0 in the matrix, the system subtracts 100 points from the score.

If no additional land loss is acceptable and if the technique is likely to allow some additional erosion to occur after it is installed, the system subtracts 100 from the score. If additional land loss is acceptable and if the technique will require slope flattening to create a slope more gradual than the maximum recommended slope for the technique, the system subtracts 10 points from the score to separate techniques that require bank shaping from those that do not.

The system asks if the user would like to compare the hydraulic loading for the site in question with published

allowable values for the techniques under consideration. A worksheet is available that provides computational assistance in generating velocity and shear stress estimates. After this, the system asks for either the design shear stress or velocity. If the input shear or velocity exceeds the tabulated value in the matrix, 100 is subtracted from the score.

Therefore the score for the *i*th technique is given by:

$$S_i = \left[ \sum_{k=1}^{11} \left[ \frac{EE_{i,k}}{EI_{i,k}} \right] \right] + B_i + \sum_{k=1}^{11} EP_{i,k} + (AEP_i * AEA) + H_i + H_i + \sum_{k=1}^9 SF_{i,k}$$

where

$S_i$  = score for the *i*th technique.

$EE_{i,k}$  = score indicating effectiveness of the *i*th technique in enhancing the *k*th environmental attribute (either 0, 1, or 2).

$EI_{i,k}$  = score indicating the user-specified importance of the *k*th environmental attribute at the site in question (either 1, 2, or 3).

$B_i$  = term based on the unit cost of *i*th technique relative to unit cost for riprap blanket.  $B_i = 1/\text{relative cost}$  if the relative cost is less than the user’s budget. If the relative cost is more than the user’s budget,  $B_i = \text{budget} - \text{relative cost}$ .

$EP_{i,k}$  = score indicating the effectiveness of the *i*th technique in addressing the *k*th erosion process. If the erosion process has been rated as important by the user and if the *i*th technique addresses that process,  $EP_{i,k} = 5$ . If the *i*th technique does not address the *k*th process and it has been rated as important,  $EP_{i,k} = -100$ .

$AEP_i$  = score indicating if the *i*th technique may result in additional land loss due to bank shaping or erosion after con-

**TABLE B-4 Values added to technique score based on environmental attributes of interest and the effectiveness of the technique in addressing the given attribute (shaded area)**

Importance of environmental attribute	Importance score	Value in matrix for effectiveness of technique <sup>a</sup>		
		0—no effect on this attribute	1—mild positive effect	2—major positive effect
Very important	1	0	1	2
Somewhat important	2	0	1/2	1
Not important	3	0	1/3	2/3

<sup>a</sup> Values are computed by dividing the value in the matrix by the importance score.

struction. If there is potential for some additional erosion,  $AEP_i = -100$ , otherwise,  $AEP_i = 0$ .

$AEA$  = score indicating if additional land loss is acceptable at the site in question or not. If so,  $AEA = 0$ , if not  $AEA = 1$ .

$H_i$  = score indicating the capability of the  $i$ th technique to withstand design hydraulic conditions. If the system contains an estimate of allowable velocity or shear for the technique and if the design shear or velocity for the site in question exceeds the allowable, then  $H_i = -100$ . Otherwise,  $H_i = 0$ .

$SF_{i,k}$  = score indicating the suitability of the  $i$ th technique for application to sites with conditions specified by the  $k$ th site factor, as described in Table B-3 above. If the technique is not suitable for the specified site condition, then  $SF_{i,k} = -100$ , otherwise,  $SF_{i,k} = 0$ .

**Reporting Results**

For each technique with a total score  $> -100,000$ , the following formula is used to adjust the total score so that it falls between 0 and 10:

$$\text{Adjusted score} = \frac{10 * (\text{total raw score})}{[(2 * (\text{number of environmental issues of interest}) + 5 * (\text{number of significant erosion processes}) + 5]}$$

The denominator of the right hand side of the above expression represents the maximum score a technique can receive. The first term allows for the fact that 2 is added to the total raw score for each important environmental issue that is fully addressed by the technique (Table B-4). The second term allows for the fact that 5 is added to the score for each significant erosion process that is fully addressed by the technique, and the last term represents a maximum increase that can occur in total raw score due to cost factors.

A similar approach is used to obtain an adjusted score for the environmental performance of each technique. Adjusted scores are converted to letter grades using the scale in Table B-5.

All techniques with grades of D or better (based on total score) are added to a list of recommended techniques. The list is sorted from highest-scoring techniques to lowest.

If no techniques receive scores greater than F, the system displays a message,

*“Based on the information you have provided, Greenbank is unable to recommend any environmentally sensitive channel- or bank-protection techniques. You may wish to reconsider some of your responses. You may inspect and change your inputs by clicking on the back button. Press OK to end this run.”*

If one or more techniques receive grades higher than F, the system displays the name and a brief description of the highest-scoring technique. The brief description includes the letter grades awarded to the technique and its unit cost relative to riprap blanket. The user is then given four choices:

1. See next highest-scoring technique,
2. See a list of techniques suitable for combination with the recommended technique,
3. See a list of all recommended techniques, or
4. See a list of all of the techniques that are not recommended.

Selection of option 1 produces the name and a short description of the next technique, along with a listing of the same four choices unless there are no other techniques in the list of primary recommendations.

Option 2 is provided because best practice usually involves a combination of erosion control techniques. Greenbank suggests primary techniques that address the important erosion processes and address environmental issues of inter-

**TABLE B-5 Relationship of adjusted scores to letter grades**

Adjusted Score Range	Letter Grade
$\geq 8$	A
$8 > \text{adjusted score} \geq 6$	B
$6 > \text{adjusted score} \geq 4$	C
$4 > \text{adjusted score} \geq 2$	D
$< 2$	F

**TABLE B-6 Excerpt from matrix used by Greenbank to suggest secondary techniques to combine with primary recommendations**

Secondary technique	Vegetated earthen spurs	Spur dikes	Vanes	Bendway weirs	Large woody debris structures	Weirs or check dams	Longitudinal dikes with toe spurs	Longitudinal peaked stone toe	Coir rolls	Vegetated gabion basket
Vegetated earthen spurs	0	0	0	0	0	0	0	0	1	1
Spur dikes	0	0	0	0	0	0	0	1	1	1
Vanes	0	0	0	0	0	0	0	1	1	1
Bendway weirs	0	0	0	0	0	0	0	1	1	1
Large woody debris structures	0	0	0	0	0	0	0	0	1	0
Weirs or check dams	0	0	0	0	0	0	0	0	1	1
Longitudinal dikes with toe spurs	0	0	0	0	0	0	0	1	0	0
Longitudinal peaked stone toe	0	0	0	0	0	0	0	0	0	0
Coir rolls	1	1	1	1	1	0	1	1	0	0
Vegetated gabion basket	1	1	0	0	0	0	0	0	0	0

est. However, other techniques that are compatible with the primary technique may be applied at the same site in order to enhance the net environmental outcome. For example, longitudinal peaked stone toe is effective in controlling toe erosion by current or waves, but aquatic habitat may be enhanced by adding spurs or vanes to the toe protection.

If the user requests a list of techniques suitable for combination, another large matrix is searched. This matrix is used in a fashion very similar to the first selection matrix, but the procedure differs in three important ways. First, erosion processes are not considered, because it is assumed that the primary technique will provide erosion control. Second, costs are not considered. Third, the matrix contains additional columns that indicate which techniques are compatible. However, most of the site variables (for example, channel width and bank material) are considered. Each row in the matrix represents a technique and there are also columns for each technique. A small excerpt from the matrix is shown in Table B-6 above. Primary techniques are shown as column heads,

while techniques that might be added to the primary technique for superior environmental performance are shown in the first column. Entries of 1 indicate compatibility, and entries of 0 indicate incompatibility. These entries were composed based on experience and professional judgment. Table B-6 shows that vegetated earthen spurs might be added to coir rolls to improve overall environmental effect, but they are ruled incompatible with vanes (they are too similar to vanes).

Selection of option 3, "See a list of all recommended techniques," provides the most complete set of information. Many of the key inputs are echoed, along with Greenbank's evaluation of the Brice alluvial stream type and erosion risk. A short description of each recommended technique sorted from highest to lowest score is provided. Links are provided to additional information screens. For example, all techniques that involve vegetation are linked to screens giving information about soil compaction, plant handling, propagation, and irrigation and to a document providing information about effects of plants on channel flow conveyance.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation