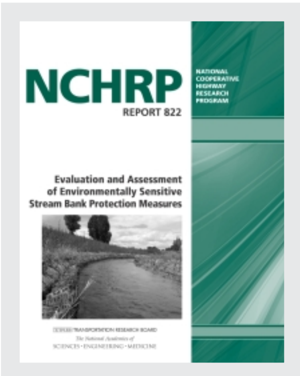
THE NATIONAL ACADEMIES PRESS

This PDF is available at http://nap.edu/23540 SHARE



Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

DETAILS

264 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-44414-9 | DOI 10.17226/23540

BUY THIS BOOK

FIND RELATED TITLES

AUTHORS

P. F. Lagasse, P. E. Clopper, C. I. Thornton, F. D. Shields Jr, J. McCullah, and W. J. Spitz; National Cooperative Highway Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

Visit the National Academies Press at NAP.edu and login or register to get:

- Access to free PDF downloads of thousands of scientific reports
- 10% off the price of print titles
- Email or social media notifications of new titles related to your interests
- Special offers and discounts

Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press. (Request Permission) Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.

Copyright © National Academy of Sciences. All rights reserved.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 822

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

P. F. Lagasse
P. E. Clopper
Ayres Associates Inc
Fort Collins, Colorado

C. I. Thornton
Colorado State University
Fort Collins, Colorado

F. D. Shields, Jr.
Shields Engineering LLC
Oxford, Mississippi

J. McCullah
Salix Applied Earthcare
Redding, California

W. J. Spitz
Ayres Associates Inc
Fort Collins, Colorado

Subscriber Categories
Environment • Hydraulics and Hydrology

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2016
www.TRB.org

Copyright National Academy of Sciences. All rights reserved.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP REPORT 822

Project 24-39
ISSN 0077-5614
ISBN 978-0-309-37540-5
Library of Congress Control Number 2016938262

© 2016 National Academy of Sciences. All rights reserved.

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FRA, FTA, Office of the Assistant Secretary for Research and Technology, PHMSA, or TDC endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

NOTICE

The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the National Academies of Sciences, Engineering, and Medicine.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; or the program sponsors.

The Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet by going to

http://www.national-academies.org

and then searching for TRB

Printed in the United States of America

Copyright National Academy of Sciences. All rights reserved.

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Ralph J. Cicerone is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

Copyright National Academy of Sciences. All rights reserved.

C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

CRP STAFF FOR NCHRP REPORT 822

Christopher W. Jenks, *Director, Cooperative Research Programs*
Christopher Hedges, *Manager, National Cooperative Highway Research Program*
David A. Reynaud, *Senior Program Officer*
Megan A. Chamberlain, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Scott E. Hitchcock, *Editor*

NCHRP PROJECT 24-39 PANEL
Field of Soils and Geology—Area of Mechanics and Foundations

Michael T. Long, *Eugene, OR* (Chair)
Jon K. Zirkle, *Tennessee DOT, Nashville, TN*
Michael Fazio, *City of Bluffdale, Bluffdale, UT*
Wayne Gannett, *New York State DOT, Albany, NY*
Kristin A. Schuster, *Michigan DOT, Lansing, MI*
Neil VanBebber, *Illinois DOT, Springfield, IL*
Richard Y. Woo, *Maryland State Highway Administration, Baltimore, MD*
Larry A. Arneson, *FHWA Liaison*
Christine Gerencher, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration (FHWA), and was conducted in the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Academies.

The research reported herein was performed under NCHRP Project 24-39 by Ayres Associates, Fort Collins, Colorado. Dr. Peter F. Lagasse, Senior Water Resources Engineer, served as Principal Investigator. Mr. Paul E. Clopper of Ayres Associates and Dr. Christopher I. Thornton of Colorado State University served as Co-PIs. They were assisted by Dr. F. Douglas Shields, Jr. of Shields Engineering LLC, Mr. John McCullah of Salix Applied Earthcare, and Mr. William J. Spitz of Ayres Associates. The laboratory testing performed under this project was conducted at the Colorado State University Engineering Research Center. The authors wish to acknowledge the efforts of the CSU graduate students in hydraulic engineering who worked under the direct supervision of Mr. Allen J. Chestnut, an MS candidate from the U.S. Army Corps of Engineers, who reported on the testing results in partial fulfillment of the requirements of his degree program. A special acknowledgement is due Mr. William M. deRosset of Ayres Associates who supervised the implementation of the laboratory testing phase of this study for the research team and developed the HEC-RAS models which supported the detailed hydraulic analyses of the testing program results. We also wish to thank Ms. Sue Paquette, City of Fort Collins, who provided access to and assisted in the harvesting of the willows for the testing program.

Copyright National Academy of Sciences. All rights reserved.

In conducting field site visits in the Southeast Dr. Shields was ably supported by Drs. David Derrick and Andrew Simon, who were involved with the original design and/or installation and monitoring of most of the sites, and Mr. Brad Maurer of the Nature Conservancy who supported the visits to the Buttahatchee River sites. Similarly, we wish to thank Dr. Don Gray of the Department of Civil and Environmental Engineering of the University of Michigan for suggesting the Ann Arbor, MI, sites in the upper Midwest and supporting Dr. Shields with expert advice and detailed knowledge of the sites. Mr. Bob Grese, Arboretum Director, accompanied the visits to the Huron River sites of the Nichols Arboretum. Special thanks are due to all of these "volunteers" who contributed to the success of the site visit program.

The authors also acknowledge the contributions of Mr. Thomas W. Smith, Geotechnical Engineer, RiverSmith Engineering Inc. who accompanied Mr. McCullah on the California site visits and reviewed the geotechnical sections of this report, Dr. David Zachmann, Vista Computational Technology LLC who formulated the Compendium in a searchable database format, and Dr. William Miller, Miller Ecological Consultants, Inc. who reviewed the aquatic habitat sections of this report. We also acknowledge the contribution of Dr. Peggy Johnson, Professor and Head, Department of Civil and Environmental Engineering, Pennsylvania State University, whose suggestions during the early stages of this study helped set the direction for this research. Finally, the participation, advice, and support of NCHRP panel members throughout this project are gratefully acknowledged.

Copyright National Academy of Sciences. All rights reserved.

FOREWORD

By David A. Reynaud
Staff Officer
Transportation Research Board

NCHRP Report 822: Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures evaluates and assesses existing guidelines for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank stabilization and protection measures, and develops quantitative engineering design guidance for selected treatments. Updated design guidelines for three widely used treatments are presented: live siltation and live staking with a rock toe, vegetated mechanically stabilized earth, and vegetated rip rap. This report would be of interest to hydraulic and environmental engineers

---

There was a reluctance on the part of many engineers to utilize biotechnical approaches to stream bank stabilization techniques. This was due, in part, to a lack of technical training, experience, and definitive hydraulic engineering design guidance. In particular, there was a lack of knowledge about the properties of the vegetative materials being used in relation to the force and stress generated by flowing water. There was also concern regarding the difficulties in obtaining consistent performance from countermeasures that rely on living materials. In addition to the laboratory testing, Ayres Associates conducted a synthesis and survey of current practice and found that the available hydraulic design criteria are drawn from a variety of sources and vary in quality from qualitative anecdotal rules of thumb to isolated spot measurements of velocity.

For the engineer involved in the multidisciplinary design of an environmentally sensitive treatment, this report also includes current guidance from the Federal Highway Administration on the use of biotechnical treatments in proximity to transportation infrastructure. In addition, for the Professional Engineer (PE) on a design team, the report explores aspects of professional liability in environmentally sensitive design.

As a result of this research, updated quantitative guidance and more detailed documentation and guidelines for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank protective measures are now available. This research produced practical, implementable guidance that will enhance the ability of practitioners to utilize environmentally sensitive treatments as an alternative to, or in conjunction with, more traditional "hard engineering" approaches.

Copyright National Academy of Sciences. All rights reserved.

CONTENTS

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

Copyright National Academy of Sciences. All rights reserved.

SUMMARY

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Overview

In 2005, the results of NCHRP Project 24-19 were published as *NCHRP Report 544: Environmentally Sensitive Channel- and Bank-Protection Measures* (McCullah and Gray 2005). After conducting an extensive literature review and evaluation of commonly used environmentally sensitive techniques, McCullah and Gray identified 44 techniques for study. Technique descriptions and guidelines for their application were developed. In many respects the work by McCullah and Gray (2005) can be viewed as a starting point and foundation for this project, NCHRP Project 24-39.

Even with the guidance provided by *NCHRP Report 544*, there was reluctance on the part of many engineers to utilize biotechnical approaches to stream bank stabilization techniques. This was due, in part, to a lack of technical training, experience, and definitive hydraulic engineering design guidance. In particular, there was a lack of knowledge about the properties of the vegetative materials being used in relation to the force and stress generated by flowing water, and there was concern regarding the difficulties in obtaining consistent performance from countermeasures that rely on living materials. Thus, the objectives of NCHRP Project 24-39 included evaluating and assessing existing guidelines for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank stabilization and protection measures. In addition, quantitative engineering design guidance was developed for selected treatments.

Research Approach

The research approach for NCHRP Project 24-39 involved the following steps:

1. Completion of a literature review to update the 2005 findings of *NCHRP Report 544* and evaluation of current practice with a survey of practitioners.
2. Development and implementation of a laboratory test plan, which involved installing and growing two environmentally sensitive treatments under controlled greenhouse conditions and moving the mature treatments to a large outdoor hydraulic flume for testing and detailed hydraulic data acquisition at prototype scale.
3. Identification of field sites and implementation of a field site visit program to evaluate current practice and performance of environmentally sensitive treatments under a range of geophysical and geomorphic conditions.
4. Compilation of the data acquired from 16 field site visits into a Compendium in a searchable database format to permit practitioners to access a wide range of design, installation, and performance data on commonly used treatments.

Copyright National Academy of Sciences. All rights reserved.

5. Development of two detailed case studies that illustrate the integration of hydraulic engineering analysis and design with the multidisciplinary approach necessary to achieve project success when employing environmentally sensitive treatments.
6. Presentation and appraisal of the results of laboratory testing in a standalone format for ease of access by both the researcher and the practitioner (Chapter 3).
7. Presentation of detailed design guidance in a standalone format (Chapter 4) for the vegetative components of the two environmentally sensitive treatments that were tested in the laboratory, and an overview and update of design guidance for a third widely used treatment.
8. Suggestions for implementation activities to enhance the state of practice for environmentally sensitive stream bank protection measures, and discussion of potential areas for additional investigation and research.

Appraisal of Research Results

Starting with the published results of NCHRP Project 24-19, 16 treatments from the river training and bank armor and protection categories of *NCHRP Report 544* were selected for further consideration. Budget and time constraints indicated that only two treatments could be grown and tested in the laboratory flume. For these, certain physical constraints both for growing the treatment in a greenhouse and for transporting the mature treatment to the large outdoor hydraulic flume had to be observed. In addition, in selecting the two treatments for rigorous hydraulic flume testing consideration was given to treatments or treatment components that would have the widest applicability nationwide. One treatment included a stone (riprap) toe, live siltation, and live staking. The hydraulic data from testing this treatment has broad applicability to either multi-component systems or treatments using just individual components (i.e., using live siltation or willow staking, alone) for stream bank protection.

The second treatment [Vegetated Mechanically Stabilized Earth (VMSE) without a hard toe] recognizes that many resource agencies tend to discourage, and in some cases prohibit, the use of rock in stream bank protection. Thus, testing the hydraulic limits of a treatment without a hard toe but incorporating fabric-encapsulated soil (FES) lifts with live brush layering between the lifts could have wide potential applicability and interest. It should be noted that the laboratory testing task of this project represents a technological breakthrough in developing quantitative hydraulic engineering design guidance for environmentally sensitive treatments. The in-channel roughness characteristics of living plants had been tested (by others) in a laboratory flume, primarily to investigate the influence of vegetation on channel roughness characteristics under varying flow conditions. However, the testing of the vegetative components of selected stream bank treatments following recommended design criteria, including fabricating the structural component(s), planting the vegetative component(s) and growing them to maturity, and, finally, moving them to a flume for fully instrumented hydraulic testing at prototype scale under a range of flow conditions represents a “first” in the development of quantitative guidance for environmentally sensitive treatments. The results of these tests are presented in a standalone format in Chapter 3.

The treatments tested under NCHRP Project 24-39 were designed to respond to specific hydraulic research needs identified by McCullah and Gray in 2005, including:

- Live Siltation—Research into velocities that this technique can withstand would be helpful.
- Live Staking—Studies would be valuable regarding the effect live staking has on increasing the ability of other measures to withstand higher velocities and shear stresses.
- VMSE—Some uncertainty exists at present as to the exact permissible shear stresses and velocities for VMSE interfaces.

Copyright National Academy of Sciences. All rights reserved.

The laboratory testing task does not represent the only contribution of this study. The synthesis and survey of current practice accomplished as part of this NCHRP Project 24-39 study updated the 2005 findings from *NCHRP Report 544* and concluded that hydraulic design criteria were still scarce and, with few exceptions, rely on the literature that was summarized within NCHRP Project 24-19. The available hydraulic criteria were drawn from a variety of sources and varied in quality at that time from qualitative anecdotal rules of thumb to isolated spot measurements of velocity.

Sixteen site visits to existing field installations of a variety of treatment types in three geographic regions (Southeast, upper Midwest, and the West Coast) were also completed. A highly detailed site visit data form was developed and completed for each site, and significant additional effort was applied to gathering design and monitoring information, reports and specifications, cost data, and photographic documentation for each site. Additional effort was devoted to obtaining hydrologic and hydraulic data that supported the design and influenced the level of functionality achieved at each site. While much of this information was qualitative and anecdotal, observations from each site visit provided insight into best management practices, and, in several cases, into failure mechanisms and lessons learned that will improve the state of practice. Moreover, the site visit reports and data obtained were assembled into a one of a kind Compendium of information to provide easy access for the practitioner to a wealth of experiential information on environmentally sensitive treatments. The Compendium is presented in a searchable database format to permit the practitioner to employ structured query language (SQL) in searching the database.

General hydrologic, hydraulic, and geomorphic considerations and site-specific physical processes that influence the design, installation, and monitoring of any environmentally sensitive stream bank protection treatment are presented in a standalone format in Chapter 4. The site-specific physical process topics include bankfull discharge and conveyance; assessing the stage of evolution for incising channels; analyzing aggradation, degradation, and lateral channel stability; predicting meander migration; guidance for protecting the upstream and downstream "flanks" and "toe" of a stream bank treatment; and estimating toe down requirements and hydraulic stress on a bendway. Geotechnical considerations, guidance for monitoring the success of the vegetative component(s) of environmentally sensitive treatments, and aquatic habitat issues that can influence the design and installation of any treatment are also discussed in Chapter 4.

Detailed, updated design guidelines for three widely used treatments are the focus of Chapter 4. These include the two treatments tested under this study and an overview and updated guidance for vegetated riprap. These design guidelines are presented in a format that addresses the following specific topics: (1) purpose and advantages, (2) design and hydraulic design parameters, (3) materials and equipment, (4) construction and installation, (5) cost, (6) maintenance and monitoring, and (7) common reasons for failure. Of the two treatments tested in the laboratory, one (live siltation and live staking with a stone toe) met or exceeded all performance expectations. The second treatment (VMSE without a hard toe) exhibited vulnerabilities to damage and soil loss under the same conditions of discharge and longitudinal slope.

In addition, two detailed case studies of the application of environmentally sensitive stream bank protection measures employed in conjunction with stream channel restoration projects are presented in Chapter 4. One example involves the application of environmentally sensitive techniques on an arid region perennial stream. The second example deals with a smaller stream in a humid region with significant infrastructure issues. The examples illustrate the integration of hydraulic engineering analysis and design with the multidisciplinary approach necessary to achieve project success and include, by example, additional guideline

Copyright National Academy of Sciences. All rights reserved.

4 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

topics such as hydrologic and hydraulic design parameters, performance and longevity, and ecological issues.

For the engineer involved in the multidisciplinary design of an environmentally sensitive treatment, Chapter 4 also provides current guidance from FHWA on the use of biotechnical treatments in proximity to transportation infrastructure. In addition, for the Professional Engineer (PE) on a design team aspects of professional liability in environmentally sensitive design are explored.

As a result of this research, updated quantitative guidance and more detailed documentation and guidelines for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank protection measures are now available. This research produced practical, implementable guidance that will enhance the ability of practitioners to utilize environmentally sensitive treatments as an alternative to or in conjunction with more traditional "hard engineering" approaches.

Copyright National Academy of Sciences. All rights reserved.

CHAPTER 1

Introduction and Research Approach

1.1 Scope and Research Objectives

1.1.1 Background

Vegetation is the most natural method for protecting stream banks and it provides ecosystem services such as habitat, water quality protection, and aesthetic benefits. Vegetation can effectively protect a bank in two ways. First, the root system helps to hold the soil together and increases overall bank stability by forming a binding network. Deep root structures increase soil strength by imparting an "apparent cohesion" to soils, stabilizing banks from mass-wasting types of geotechnical slope instability. Second, the exposed stalks, stems, branches and foliage provide resistance to flow, causing the flow to lose energy by deforming and exerting drag on the plants rather than by removing soil particles. Above the water line, vegetation prevents surface erosion by absorbing the impact of falling raindrops and reducing the velocity of overbank flow and rainfall runoff.

Terms describing the techniques that combine the use of vegetation with structural (hard) elements include biotechnical engineering, biotechnical slope protection, bioengineered slope stabilization, and biotechnical revetment. The terms soil bioengineering and biotechnical engineering are most commonly used to describe stream bank erosion countermeasures and bank stabilization methods that incorporate vegetation (*Hydraulic Engineering Circular No. 23*, Third Edition, Lagasse et al. 2009). Where riprap constitutes the "hard" component of biotechnical slope protection, the term vegetated riprap is also used (McCullah and Gray 2005).

Due to a lack of technical training, experience, and design guidance there is a reluctance on the part of many engineers to utilize soil bioengineering/biotechnical engineering techniques and stability methods. In addition, bank stabilization systems using vegetation have not been standardized for general application under particular flow conditions. There is a lack of knowledge about the properties of the materials being used in relation to force and stress generated by flowing water and there may be difficulties in obtaining consistent performance from countermeasures that rely on living materials. Nonetheless, stabilization of eroding stream banks using vegetative countermeasures has proven effective in many documented cases in Europe and the United States.

Design of biotechnically engineered countermeasures to minimize stream bank erosion requires accounting for hydrologic, hydraulic, geomorphic, geotechnical, vegetative, construction, and maintenance factors. Although most of the literature dealing with biotechnical engineering on rivers is associated with stream bank stabilization relative to channel restoration and rehabilitation projects, it is also generally applicable to bank stabilization associated with highway facilities.

While many biotechnical bank-protection measures have been deployed and have survived for a number of years, there remains considerable skepticism within the engineering community

Copyright National Academy of Sciences. All rights reserved.

regarding performance of these measures when subjected to flood event magnitudes typical of DOT designs for stream bank protection. Very little information is available regarding the durability and service life expectations as well as the maintenance requirements of these measures. The applicability of individual measures to varying stream hydraulic and site conditions, the long-term structural integrity of the measure, and the anticipated maintenance and inspection costs are all critical elements that must be understood in order to support sound engineering decisions.

Existing NCHRP guidance for environmentally sensitive stream bank protection measures (McCullah and Gray 2005) was developed more than ten years ago. Although the products from that project provide a wealth of information, several important developments have occurred during the past decade. Among these are attempts by others to summarize and codify design guidance for biotechnical measures [e.g., Li and Eddleman 2002, Admiraal et al. 2007, NRCS (Natural Resources Conservation Service) 2007a, b, c], detailed case studies (e.g., Barrett et al. 2006), development of risk-benefit analyses for comparing biotechnical measures (Niezgoda and Johnson 2012), advances in understanding the behavior, properties, and architecture of plant roots, incorporation of vegetation into stream bank stability models (Simon et al. 2011), improved representations of vegetation interaction with the flow field in numerical simulation, and the development of a unique, prototype-scale facility (described below) at Colorado State University (CSU) for subjecting various types of vegetation to the erosive forces of flowing water. The research work plan for this project was designed to capitalize on these and other developments in this evolving field.

1.1.2 Objectives

The objectives of this research were to produce guidelines for appropriate selection, design, installation, and maintenance of environmentally sensitive stream bank stabilization and protection measures. The guidelines are intended to address:

- Performance data/failure mechanisms;
- Stabilization structure selection guidelines;
- Structural guidelines and standard designs;
- Construction and maintenance best practices;
- Hydraulic design parameters such as shear stress and velocity;
- Hydrologic design parameters such as regional climate, topography, and stream morphology;
- Structure and geotechnical design parameters such as composite interaction of soil, rock, geosynthetic materials, and/or vegetation;
- Longevity issues such as performance under peak flood conditions, material durability, and vegetation viability;
- Cost and availability issues such as installation, maintenance, and materials, including commercial products; and
- Ecological issues such as fish species and aquatic organisms habitat enhancement, and vegetation suitability for climatic conditions.

This research provided the opportunity to develop hydraulic design parameters for critical "hard" (engineered/structural) and "soft" (vegetation) components of biotechnical countermeasures. By addressing life-cycle issues for environmentally sensitive bank-protection measures, this research provided countermeasure alternatives that can be designed and installed with the same level of confidence and reliability achieved with more traditional "hard" engineering approaches to stream bank stabilization.

Copyright National Academy of Sciences. All rights reserved.

1.2 Research Approach

Successfully achieving the objectives outlined above required the integration of multiple disciplines to produce practical guidelines that can be reliably and consistently implemented by practitioners. The following sections present an overview of the research team's approach to this research.

The approach to this research project included not only the identification and assessment of existing field sites where environmentally sensitive stream bank protection measures have been implemented, but extended the current state of the practice with quantitative methods that can be used for design, specification, installation, and maintenance of these measures. In addition to field work, prototype-scale laboratory testing of selected biotechnical engineering treatments was conducted in the large (20 ft wide by 110 ft long) outdoor flume at CSU.

Two treatments were installed in large trays and nurtured in CSU's climate-controlled greenhouses, which provide customized light, temperature, and humidity conditions for year-round establishment and growth of many different types of vegetation. When vegetation was established to a predetermined condition, the trays were moved to a large outdoor flume for testing under the desired hydraulic conditions. Figure 1.1 provides an example of the greenhouse facility and vegetated trays used in hydraulic testing.

Guidelines developed under this research project would not meet the objectives without inclusion of practical and implementable guidance involving cost, constructability, and maintenance requirements in a life-cycle context. While information on these issues was gleaned from this project's Phase I literature review (Task 1) and survey of practitioners (Task 2), additional guidance came from the experience of the research team members. Research team members have provided design, specification, and construction observation (and in some cases, the actual construction and post-construction maintenance) for a number of notable environmentally sensitive stream bank protection projects.

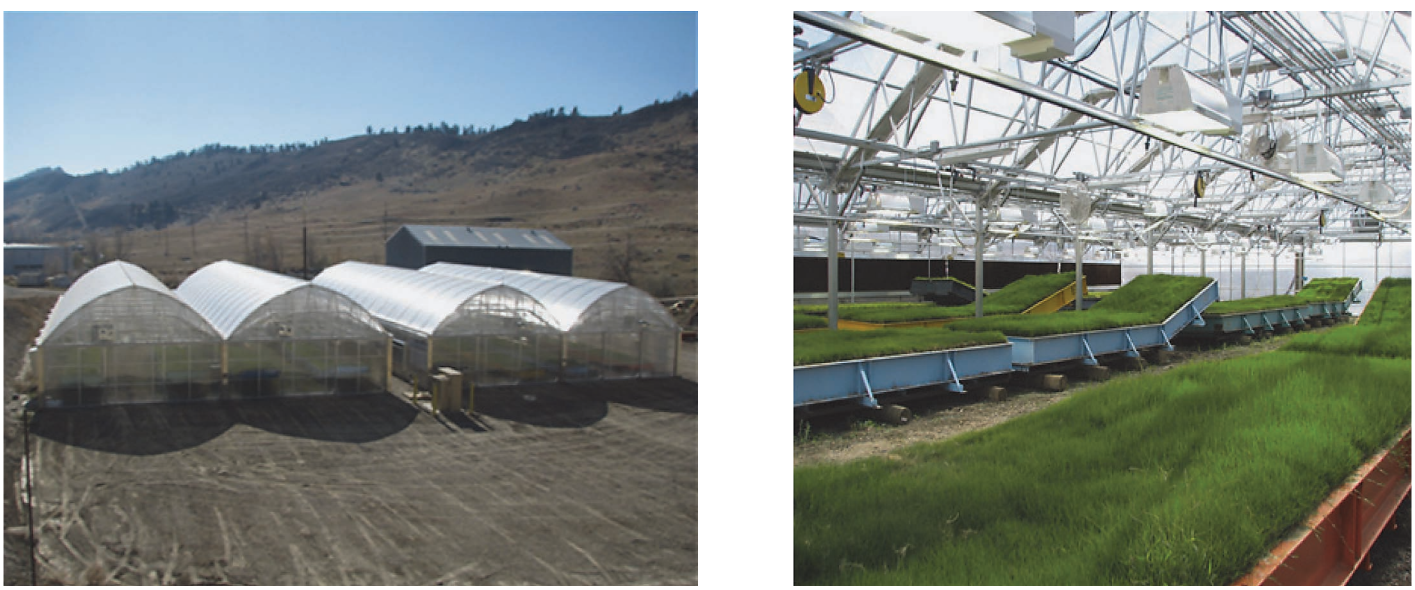


Figure 1.1. (Left) Climate-controlled greenhouses at CSU's Hydraulics Laboratory. (Right) Turf grass grown in large trays for subsequent hydraulic testing.

Copyright National Academy of Sciences. All rights reserved.

In summary, the research approach was designed to take advantage of the data that was obtained from a comprehensive field investigation program, but also offered the singular opportunity for growing and testing critical components of biotechnical treatments in a controlled laboratory setting. This methodology provided a quantitative, repeatable measure of vegetation condition and viability for biotechnical treatments to support inspection activities and maintenance decisions. The overall approach provided specific and detailed hydraulic design and life-cycle guidance for a range of environmentally sensitive stream bank protection measures.

1.3 Research Tasks—Phase I

Considering the research approach discussed above, the following specific tasks were completed to accomplish project objectives. These tasks incorporate NCHRP project panel guidance and parallel, with some modifications, the tasks established in the original research work plan.

1.3.1 Task 1—Review the Technical Literature

The research team conducted a thorough review of technical literature from foreign and domestic sources to assess adequacy and extent of existing information on environmentally sensitive stream bank protection measures. The literature review identified research in progress as well as completed work.

Under Task 1 of the Research Work Plan, a complete and thorough literature search on environmentally sensitive stream bank protection measures was conducted. The search began with a major search engine that included most peer-reviewed online journals of Europe and America's largest scholarly publishers, plus scholarly books and other non-peer-reviewed journals, in addition to GeoRef and TRB's TRID. As necessary, secondary searches were conducted online using reference search engines provided by the American Society of Civil Engineers (ASCE), International Association of Hydrological Sciences (IAHS), United States Geological Survey (USGS), Geological Society of America (GSA), American Geophysical Union (AGU), and the Institute of Civil Engineers (ICE) in the United Kingdom. The key words used in the search included:

- Stream stability
- Stream bank protection
- River training
- Bank armor/protection
- Riparian buffer
- Slope stabilization
- Laboratory studies (countermeasures)
- Field studies (biotechnical countermeasures)
- Case studies (biotechnical countermeasures)
- Channel restoration/rehabilitation

Combinations of these key words also helped refine the search.

The remaining secondary search sites contain reference lists for their respective publications. Almost all of the sites contain references to literature that has been published since the early 1970s. After primary and secondary lists were compiled, references not relevant to the study were removed from all the compiled reference lists. The lists were then compared and evaluated for duplicates. The remaining references were evaluated for appropriateness and usefulness and submitted to the NCHRP project panel for review.

Copyright National Academy of Sciences. All rights reserved.

1.3.2 Task 2—Survey of Relevant Agencies

In consultation with the NCHRP project panel the research team developed, distributed, and evaluated a survey of agencies that have implemented existing guidelines for environmentally sensitive bank protection. The survey was designed to support development of a Compendium of photographs and case studies and provide information to assist in identifying field sites.

Permitting and regulatory agencies were included in the survey. State and federal resource and regulatory agencies were also included in the survey [such as state Departments of Natural Resources (DNRs), Departments of Environmental Conservation (DECs), Departments of Environmental Protection (DEPs), etc.]. For the survey, spreadsheets were used to allow rapid screening and organization of the response data set.

1.3.3 Task 3—Identify Field Evaluation Sites

Based on the information obtained in Tasks 1 and 2, candidate sites for field investigation during Task 6 (Phase II) were identified and proposed to the NCHRP project panel.

At the outset of this study, 31 sites where environmentally sensitive bank-protection measures have been installed across the country were identified. Each of those sites had either been designed, constructed, and/or monitored by one or more research team members. During Phase I of the project, additional field sites were identified as potential candidate sites for field investigation.

The research team discussed at length the costs vs. benefits of field site investigations, which will provide a synoptic "snapshot in time" of a particular site's condition. That condition must then be compared to a quantitative assessment of the "history" of the site. The length of time since construction, its design/installation records, and its post-construction monitoring and maintenance records all figured into the final selection process. It was noted that the cost of visiting field sites to obtain one "snapshot" would yield valuable, but limited, quantitative data compared to the cost of performing controlled laboratory testing.

The research team worked closely with the NCHRP project panel through the Quarterly Progress and Interim Report process to select the final "short list" of field sites during Phase I. The final short list of sites for the Interim Report (Task 5) included a diversity of protection measures and geographic locations including the upper Midwest (Michigan), Southeast (Mississippi), and the West Coast (Northern California).

1.3.4 Task 4—Develop Laboratory Test Plan

Under this task, a detailed description was developed for the Phase II (Task 7) laboratory experiments proposed. The primary purpose of the experiments was to develop hydraulic design data for critical components of biotechnical stream bank treatments. Data from these experiments would supplement and expand existing databases, and would support the development of detailed design guidelines. Based on NCHRP project panel review of the Interim Report, the laboratory test plan was refined and revised.

A wealth of literature and documentation is available regarding environmentally sensitive stream bank protection measures. Much of this material is summarized or cited by *NCHRP Report 544* (McCullah and Gray 2005) and additional references were obtained during Task 1. However, most of the information regarding biotechnical measures consists of case studies of particular sites that, in many cases, have limited general applicability. Furthermore, these case studies usually have a shortage of quantitative data regarding the hydraulic, hydrologic, climatic,

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

and geotechnical conditions surrounding the sites. Recent advances in understanding the performance of nonliving bank-protection materials and structures have included laboratory flume tests that allow greater control and data acquisition than for field sites, but few of these experiments involved plant materials. Some tests have been conducted with grass-lined channels or with artificial plants made of wooden dowels, plastic strips, or other materials to investigate interactions between plants and the flow field. However, due to the difficulty of conducting scaled tests with real plants in available hydraulic laboratory flumes, only limited work has been done with real plants (see Section 2.2.5).

During this project, this deficiency was addressed by conducting well-planned, carefully controlled flume tests in the unique facilities at CSU described in Section 1.2.1 (see Figure 1.1). Tests would focus on a few selected but representative biotechnical measures that could be constructed with real plants in deep planter boxes. Plant materials would be given time to establish prior to installation on the banks of the experimental trapezoidal channel. Measurements of the flow field conducted during flume runs would then be used to calibrate an appropriate one-dimensional computer model.

The approach to prototype-scale laboratory testing of selected bank-protection measures was outlined in some detail in the Interim Report. Figure 1.2 provides a conceptual sketch of a typical bank-protection measure that could be investigated under Task 7.

The steps involved in testing and evaluating a bank-protection treatment such as the one shown in Figure 1.2 would involve the following:

1. The soil, rock, and stream bed materials required for each specific treatment will be installed in large planter trays in the CSU climate-controlled greenhouse (see Figure 1.1). Various treatments will be installed at the beginning of the Phase II program, selected in consultation with the NCHRP 24-39 project panel.
2. The vegetative component(s) will be installed and allowed to establish over a 5- to 6-month period. Periodic measurement of the root structure for the vegetation will be performed to ensure that a representative canopy and root system has developed prior to testing.
3. The planter trays will be moved by crane and placed in the outdoor River Engineering Flume at CSU with associated upstream and downstream transition sections. Cross-section surveys at predetermined locations will be performed prior to testing.
4. The discharge and tailgates will be adjusted to achieve the desired flow conditions. It was anticipated that three discharges would be examined: (a) a relatively low "mean annual" discharge, (b) an intermediate flow rate, and (c) a "design" discharge. Each flow rate will be run for a period of 2 to 3 hours to allow detailed velocity and depth measurements to be recorded. At each flow rate, both cross-sectional and vertical velocity profiles will be recorded.

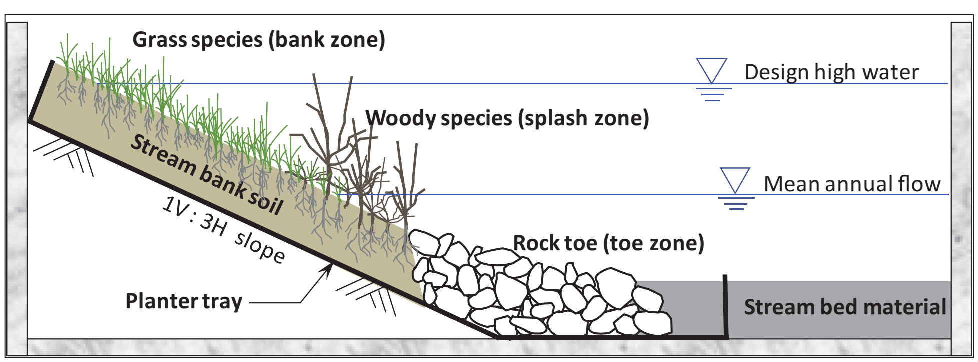


Figure 1.2. Typical bank-protection measure proposed for testing at CSU.

Copyright National Academy of Sciences. All rights reserved.

5. After each flow, the treatment will be examined for any damage to its various components (e.g., loss of vegetation, movement of rock, or soil loss) and cross-section surveys and longitudinal profiles will be repeated.

1.3.5 Task 5—Interim Report

The research team prepared and submitted an Interim Report documenting the information developed in Tasks 1 through 4. The Task 5 revised work plan for completing Phase II was included as an attachment to the Interim Report.

The Interim Report (Task 5) provided all findings and recommendations, including suggestions for field site visits and a recommended laboratory test plan for Phase II. The principal investigator (PI) and co-PIs met with the NCHRP Project 24-39 panel in Fort Collins, Colorado to discuss the Interim Report and the revised work plan. The Interim Report meeting included a visit to the CSU laboratory to observe the selected treatments for testing growing in the greenhouse and the outdoor flume where testing would be conducted during Phase II.

1.3.6 Task 6—Field Investigations

The research team planned, coordinated, and implemented field site visits to evaluate design, performance, and maintenance issues for selected biotechnical treatments. Site visits were completed at 16 individual sites in three regions (upper Midwest, Southeast, and West Coast).

Site visit teams were organized so that most disciplines on the research team (hydraulic engineer, geomorphologist, Geotechnical Engineer, vegetation specialist, and construction/maintenance engineer) had the opportunity to visit sites in one of the three geographic regions recommended under Task 3. Each site visit included comprehensive photographic documentation, a search for design or as-built drawings, supporting calculations, and performance and monitoring history. The goal was to integrate the data acquired from the site visits with the results of the Task 7 laboratory testing and obtain sufficient design, construction, monitoring, and maintenance information to produce several detailed case studies for the design guidelines and substantial supporting information for the Task 8 Compendium. As recommended by the NCHRP project panel, a uniform field protocol/data collection form was developed and used for all site visits.

1.3.7 Task 7—Laboratory Studies

Using the testing program and configurations discussed and approved during the Interim Report meeting, the research team conducted the laboratory experiments according to the approved work plan. Two specific treatments for the laboratory testing program were approved by the panel during Phase I.

For Task 7, the extensive laboratory facilities and hydraulic modeling expertise of CSU were available. These included the unique greenhouse facilities where biotechnical treatments can be grown/installed to meet particular specifications for later testing at prototype scale in a large outdoor flume (see Figure 1.1). These tests provided specific hydraulic design parameters for the selected biotechnical treatments. The outdoor flume was made available on a priority basis at the appropriate time in the testing sequence. Testing included two representative biotechnical measures that were constructed with real plants in large planter boxes (6-ft wide by 20-ft long by either 12 or 18 in. deep). Plant materials were given time to establish prior to installation on the banks of the experimental trapezoidal channel.

A variety of environmentally sensitive bank-protection measures were considered as potential candidates for testing at prototype scale at CSU. Due to cost considerations, only two treatments

Copyright National Academy of Sciences. All rights reserved.

could be accommodated under this research project. Various treatments were carefully evaluated from the perspective of having wide applicability across the nation, as well as practical issues of:

- Constructability,
- Physical testing requirements,
- Quantitative measurements of key hydraulic variables, and
- Monitoring the condition of each component before testing and after each test flow event.

The two biotechnical bank-protection treatments selected for testing were:

1. Live siltation with live staking and rock toe at a 3H:1V slope, and
2. VMSE (sometimes referred to as FES lifts) at a 2H:1V slope.

The vegetative components of these treatments were harvested locally in Fort Collins, Colorado, and consisted of *Salix exigua* (also known as sandbar willow or narrowleaf willow), a shrub-type willow that is common to riparian corridors throughout most of the United States.

1.3.8 Task 8—Develop Compendium of Photographs and Case Histories

Based on the data acquired from the Task 2 survey and photographic and case history documentation from the Task 6 field investigations, a Compendium of biotechnical treatments in a searchable database format was developed. In addition, two detailed case studies were developed to support the design guidelines:

- Application Example—Arid Region (Rio Grande Bank Protection, Santa Ana Reach, near Bernalillo, New Mexico).
- Application Example—Humid Region (Bank Protection and Erosion Control on Malletts Creek near Ann Arbor, Michigan).

1.3.9 Task 9—Develop Detailed Design Guidelines

Based on the results of Tasks 7 and 8 and the field data assembled under Task 6, detailed design guidelines for the life cycle of selected environmentally sensitive stream bank protection measures were developed. These guidelines address appropriate selection, design installation, and maintenance requirements.

Using the Task 8 Compendium, 16 site visit folders were assembled to supplement the design guidelines. The site visit examples illustrate the hydrologic/geomorphic application of the techniques for various scenarios in a range of physiographic conditions across the country.

1.3.10 Task 10—Submit Final Report

The research team submitted a Final Report that documents the entire research effort, including a companion summary. Standalone design guidelines (Chapter 4) document in detail how to implement the findings of this research.

1.4 Points Addressed by the Research Plan

The NCHRP 24-39 Problem Statement listed ten specific points to be addressed in this study. These points are shown below with the addition of a reference to the location/task of the final research work plan where these topics were addressed along with relevant observations by the research team.

- **Performance data/failure mechanisms**—Performance and failure experience data were requested in the Task 2 survey of relevant agencies. Additional information at selected sites

Copyright National Academy of Sciences. All rights reserved.

was obtained during the field investigations (Task 6). Performance/failure issues were investigated during the laboratory investigations (Task 7). Photographic evidence and case history experience assembled for the Compendium (Task 8) were also used to address this topic in the design guidelines (Task 9).

- **Stabilization structure selection guidelines**—*NCHRP Report 544* (McCullah and Gray 2005) includes selection guidelines in the form of the Greenbank Decision Support Tool (developed by members of NCHRP Project 24-19 research team). Review of this expert system approach to selection guidance resulted in the proposal, which was accepted by the project panel, that updating or revising this tool would not be necessary. The Greenbank Decision Support Tool as published with *NCHRP Report 544* provides a viable approach to screening a range of alternative treatments for a specific application.
- **Structural guidelines and standard designs**—Standard designs were requested in the Task 2 survey of relevant agencies. Additional information on structural guidelines and standard designs at selected sites was obtained during the field investigations (Task 6). Hydraulic data to support design was developed during the laboratory investigations (Task 7). Case history experience assembled for the Compendium (Task 8) was also used to address this topic. The guidelines include structural guidelines and standard designs for the treatments selected (Task 9).
- **Construction and maintenance best practices**—Based on evaluation of case study information (Task 8) and the combined experience of the research team, construction and maintenance best practices are included in the detailed guidelines (Task 9).
- **Hydraulic design parameters such as shear stress and velocity**—Developing detailed hydraulic design parameters was the primary objective of the Task 7 laboratory studies. With the unique greenhouse and flume facilities at CSU, a test plan was implemented that provides hydraulic design data for biotechnical techniques that had not been available from field experience and case studies alone. These results were integrated with hydraulic design guidance compiled for the detailed design guidelines (Task 9).
- **Hydrologic design parameters such as regional climate, topography, and stream morphology**—These components of the design approach are addressed in the Task 9 design guidelines and in two application examples.
- **Structure and geotechnical design parameters such as composite interaction of soil, rock, geosynthetic materials, and/or vegetation**—The research team included Professional Civil Engineers with the design experience necessary to address the structural and geotechnical issues related to design of environmentally sensitive treatments. In addition, a Geotechnical Engineer was added to the research team as suggested by the panel. Several research team members have broad experience with design, construction, and monitoring of a variety of biotechnical treatments.
- **Longevity issues such as performance under peak flood conditions, material durability, and vegetation viability**—One research team member's experience at both the United States Army Corps of Engineers' (USACE) Engineering Research and Development Center (ERDC) and the Agricultural Research Service (ARS) National Sedimentation Laboratory includes the longevity and durability of materials for large woody debris structures and various vegetative treatments such as willow post plantings. These topics are addressed in the Task 9 design guidelines (Task 9).
- **Cost and availability issues such as installation, maintenance, and materials, including commercial products**—Cost information, where available, was considered as a component of the design guidelines (Task 9).
- **Ecological issues such as fish species and aquatic organism habitat enhancement, and vegetation suitability for climatic conditions**—A consultant was included on the research team to address ecological and habitat issues/opportunities for environmentally sensitive stream bank protection measures (Tasks 8 and 9).

Copyright National Academy of Sciences. All rights reserved.

CHAPTER 2

Findings

2.1 *NCHRP Report 544*

In 2005, the results of NCHRP Project 24-19 were published as *NCHRP Report 544: Environmentally Sensitive Channel- and Bank-Protection Measures* (McCullah and Gray 2005). After conducting an extensive literature review and evaluation of commonly used environmentally sensitive techniques, McCullah and Gray identified 44 environmentally sensitive channel- and bank-protection techniques for study. The channel- and bank-protection techniques were grouped into four major categories: (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. In many respects the work by McCullah and Gray (2005) can be viewed as a starting point and foundation for the present study.

2.2 Synthesis of Current Practice

2.2.1 Introduction

Since publication of McCullah and Gray (2005), numerous reviews, handbooks, and measure-specific guidance documents for environmentally sensitive bank protection have been published by federal, state and local agencies. These documents emphasize the steps describing various measures and provide construction or installation guidance. Similarly, large numbers of case studies of biotechnical bank-protection projects have appeared, but few contain hydraulic data. Hydraulic design criteria are scarce and with few exceptions rely on the literature that was summarized within NCHRP Project 24-19. The data underlying the hydraulic criteria are drawn from a variety of sources and vary in quality from qualitative anecdotal rules of thumb to detailed laboratory measurements. Many are based on isolated spot measurements of velocity. Considerable progress has been made in recent years in understanding the biology of riparian plants and developing technology for improving planting success. Limited but important advances have been made in understanding and simulating the complex fluid mechanics of open-channel flows adjacent to vegetated banks. Slope stability models have been modified to include contributions of roots to soil strength, and such models are becoming more widely employed.

2.2.2 Environmentally Sensitive Channel- and Bank-Protection Measures

State departments of transportation (DOTs) are seeking ways to incorporate environmental criteria into projects that impact streams in order to comply with legislation and cooperate

Copyright National Academy of Sciences. All rights reserved.

with conservation agencies and interests. Environmentally sensitive measures for controlling erosion of channel banks, beds, and floodplains have been described by many authors and usually feature use of living and nonliving plant materials in combination with stone, geotextiles, and soil. However, guidance for design, construction and maintenance of such measures is often qualitative, forcing agencies to rely on individual experience or accept high levels of risk and liability. Further, documented experience with many types of measures is in short supply.

In response to this situation, NCHRP Project 24-19 was initiated. The effort was targeted at compiling existing information on measures for controlling channel erosion that simultaneously provided benefits to terrestrial habitat, aquatic habitat, or aesthetics relative to traditional bed and bank erosion control measures. The final report from this effort (McCullah and Gray 2005) contains detailed descriptions including typical design drawings along with as much design criteria as could be gleaned from the literature extant as of 2001–2002. Data assembled for each technique included allowable hydraulic loadings, dominant modes of failure, and research needs (see Appendix A of this report for a summary).

In addition, a rule-based technique selection system was also developed for *NCHRP Report 544.* The selection system is presented as an interactive software program titled "Greenbank," which can be found on the CD-ROM that accompanied *NCHRP Report 544* (CRP-CD-58). The user is queried regarding environmental objectives, dominant erosion processes at the site in question, hydraulic conditions, and other site characteristics. A short list of suggested techniques or measures is then provided, along with links to additional information. Related content useful to designers was published by McCullah (2006). The following sections synthesize results of a literature review focused on developments subsequent to the NCHRP Project 24-19 effort.

2.2.3 Literature Prior to NCHRP Project 24-19

The review presented by McCullah and Gray (2005) includes an annotated list of key documents and websites, and the CD that accompanied *NCHRP Report 544* contained a compilation of .pdf versions of many of the documents. Accordingly, this section presents only a very brief overview of the pre-2002 literature dealing with environmentally sensitive bed- and bank-protection measures.

Earliest work in stream bank erosion and protection did not differentiate between standard and environmentally sensitive measures, as practitioners then were largely agnostic about ecological impacts. However, basic principles underlying river engineering in general and stream bank erosion and its control were considered relevant. For example, the extensive national research and demonstration program in stream bank protection conducted by the USACE in the late 1970s and early 1980s ("Section 32 Program") produced a wealth of information that is often overlooked because little of it appeared in the open literature. Results (summarized in Table 2.1) highlighted the need for designers to consider both geotechnical and hydraulic processes and to think about erosional processes across a wide range of spatial scales.

Noteworthy items within the early literature are the texts by Schiechtl (1980) and Schiechtl and Stern (1994) that provide rather comprehensive overviews of European bioengineering practice, which has a very long history (Evette et al. 2009). Bache and Coppin (1989) present similar material from a U.K. perspective, while Gray and Leiser (1982) and Gray and Sotir (1996) write for a U.S. audience. Henderson and Shields (1984) and Henderson (1986) also provided an early review of environmental features for stream bank erosion control in use within the U.S. Although case studies and project reports may be found in the early literature, scientific research to support development of design criteria for environmental channel erosion control measures

Copyright National Academy of Sciences. All rights reserved.

Table 2.1. Lessons learned from the Section 32 program.

Section 32 refers to Section 32 of Public Law 93-251, the "Streambank Erosion Control Evaluation and Demonstration Act of 1974," which authorized $50 million for a national program of demonstration and research. The program, which ended in September 1982, included:

- Laboratory demonstrations,
- Construction of demonstration projects at 125 bank-miles of eroding bank line at 68 legislated and selected sites,
- Observation of 50 existing projects, and
- Extensive literature surveys.

The final report, *U.S. Army Corps of Engineers, 1981. Final Report to Congress, The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251. Main Report, Supplemented by Appendices A-H in separate volumes. U.S. Army Corps of Engineers, Washington, D.C.*, contains a summary of the program findings, including the items below.

Causes

- The causes of stream bank erosion are complex and varied. Erosion along major rivers may involve different processes than for small streams, and dominant processes frequently vary from one site to another along the same stream. In most cases, erosion at a site is the result of several causes, and each cause may require a specific cure.
- Prediction of future bank erosion is beyond the current state of the art. Although the basic processes are understood, the complex interactions between many variables in natural systems make prediction of erosion indeterminate. Streams displaying very active tendencies to erode their banks often seem to reverse themselves and display periods of relative stability.
- Selection and design of effective bank protection often depends on a good understanding of the geotechnical characteristics of the site and the fluvial geomorphology of the reach and the watershed.

Cures

- Where bank failure is due to bed degradation, grade control structures may be needed to restore stability.
- There is no universal method that offers low-cost solutions for all stream bank erosion problems. Low-cost methods are best suited for short-term protection on small streams. There are no cheap solutions, but good understanding of the important processes can yield cost-effective projects.
- Much erosion can be prevented with toe protection, especially with vegetation on the upper bank. In fact, the final report stated that "…the most important conclusion is to provide effective protection at the toe of the bank." Bank shaping and vegetation planting without providing toe protection is usually ineffective.
- Bank-protection materials (rock, stone, armor blocks, etc.) in river reaches subjected to high velocities, waves, or high levels of turbulence must be placed on appropriate granular or geotextile filters to prevent the loss of bank material to penetrating currents. In low-energy environments, however, a blanket of quarry-run riprap of sufficient size and thickness performs well.
- Riprap blanket is generally the most cost effective, flexible, and widely used bank-protection technique. Other structures made of stone riprap such as spurs, jetties, groins, stone toe, and windrow revetment provide adequate protection when properly designed, but some initial erosion should be anticipated before the structures become effective.
- The alignment of bank-protection structures is critical. During periods of high flow, the location of the major point of attack by the current will usually vary from low or moderate flow conditions.
- The most common mistake in designing bank protection for an eroding bank is to extend bank protection too far upstream and not far enough downstream.

is very scarce prior to 1990. Most of the content of the earlier works is composed of photos and drawings of measures under construction or sometime after completion, descriptions of construction techniques, and occasionally cost data.

Laboratory data are available for permissible hydraulic stress on certain types of flexible channel linings, but less is provided for measures that include woody plants. Design guidelines in these works are mostly qualitative and descriptive rather than quantitative, and reflect the experience-based design approaches based on judgment, although the details vary greatly by

Copyright National Academy of Sciences. All rights reserved.

technique. When hydraulic loading criteria are provided they are often based on the author's experience rather than specific test data.

Literature on all types of environmentally sensitive stream treatments has grown rapidly since about 1990. In the late 1990s, Fripp prepared the tabulation of allowable velocities and shear stresses for a variety of channel boundaries, including environmentally sensitive treatments shown in Table 2.2 (personal communication, Jon Fripp, USDA NRCS). The source documents for Table 2.2 vary from peer-reviewed journal papers describing measurements performed under controlled conditions in hydraulic laboratories to rough measurements made under field conditions, to claims made by vendors of various products, to nonspecific reports based on experience. This compilation provided the basis for a modified table published by Fischenich (2001b) (Table 2.3) as part of a series of technical notes issued by the USACE ERDC.

Refinements of these tabulations were used to generate rules for specific measures in the Greenbank selection system (McCullah and Gray 2005). Since definite numerical limits were required for the selection of system logic, allowable shear and velocity values for Greenbank could not be expressed in approximate terms, or as a range of values. Where the source documents provided a range of values, the midpoint of the range was adopted for use in Greenbank. Furthermore, Greenbank contained criteria for all 44 measures described by McCullah and Gray (2005), a much longer list than those presented in Tables 2.2 and 2.3. Techniques based on stone structures such as vanes, bendway weirs, longitudinal stone toe, and Newbury rock riffles were assigned maximum permissible velocities of 11.5 ft/s based on upper limits for well-designed stone structures. Measures intended to address geotechnical slope stability such as drop inlets, chimney drains, and live pole drains were not assigned maximum hydraulic loading values since allowable velocity and shear in such an application depends on the treatment applied to the bank face. In some cases, Greenbank used findings published subsequent to Fischenich (2001b) such as Lipscomb et al. (2001) for vegetated, articulated concrete blocks or the Erosion Control Technology Center (ECTC) (2001) for turf reinforcement mats.

Since the completion of work on NCHRP Project 24-19 and publication of McCullah and Gray (2005), publications dealing with stream erosion control, riparian zone and floodplain restoration, and interactions among plants, slope stability, and stream hydraulics have multiplied prolifically. For purposes of this synthesis, these documents may be categorized as either applied or fundamental literature.

2.2.4 Applied Literature Subsequent to NCHRP Project 24-19

Applied literature includes how-to guides, handbooks, case studies, and studies and documents focused on the performance of a specific measure (e.g., willow stakes or rootwads). A subset of these documents consists of guidelines and research reports on techniques for handling plant materials (e.g., soaking or refrigeration) to improve survival and performance. Most of the applied literature has been published by governmental agencies and is not published in peer-reviewed scientific or engineering journals. Much of the content in these documents is duplicative or redundant.

Handbooks and Reviews

This section places all documents containing catalogs of environmentally sensitive measures in the same category, even though some (e.g., Admiraal et al. 2007, Landphair and Li 2001) are literature reviews while others provide design guidance (e.g., McCullah 2006, Allen and Leech 1997). Handbooks have been produced by the city of Denver (Denver Urban Drainage and Flood Control District 2001a,b,c), King County, Washington (Johnson and Stypula 1993),

Copyright National Academy of Sciences. All rights reserved.

Table 2.2. Permissible shear and velocity data compiled in the late 1990s by Fripp.

Bank Material/Protection	Shear Stress (lb/ft^2)	Velocity (ft/s)	Type of Criteria	Source
Bermuda grass, erosion resistant soils, 0%–5% slope		8	design	USDA 1947 (rev. 1954)
Bermuda grass, erosion resistant soils, 5%–10% slope		7	design	
Bermuda grass, erosion resistant soils, over 10% slope		6	design	
Bermuda grass, easily eroded soils, 0%–5% slope		6	design	
Bermuda grass, easily eroded soils, 5%–10% slope		5	design	
Bermuda grass, easily eroded soils, over 10% slope		4	design	
Grass mixture, erosion resistant soils, 0%–5% slopes		5	design	
Grass mixture, erosion resistant soils, 5%–10% slopes		4	design	
Grass mixture, easily eroded soils, 0-5% slopes		4	design	
Grass mixture, easily eroded soils, 5%–10% slopes		3	design	
Grasses: *Lespedeza sericea*, Weeping lovegrass, Yellow bluestem, Kudzu, Alfalfa, Crabgrass, Common lespedeza; erosion resistant soil, 0%–5% slope unless on side slopes		3.5	design	
Grasses: *Lespedeza sericea*, Weeping lovegrass, Yellow bluestem, Kudzu, Alfalfa, Crabgrass, Common lespedeza; easily erodible soil, 0%–5% slope unless on side slopes		2.5	design	
Dense sod, fair condition growing in moderately cohesive soil	0.35		limit	Austin and Theisen 1994
12.5 cm of excellent growth of grass/woody veg on outside bend	1		limit	Parsons 1963
Flume trials, fabric reinforced veg failed after 50 hrs	5		limit	Theisen 1992
Flume trials, fabric reinforced veg failed after 8 hrs	8		limit	
Sod revetment, short period of attack	0.41		design	Schoklitsch 1937
Wattles (coarse sand between)	0.2		design	
Wattles (gravel between)	0.31		design	
Wattles (parallel or oblique to current)	1		design	
Fascine revetment	1.4		design	
Cribs with stone	30		design	
Reed plantings (immediately after construction)	0.10		limit	Schiechtl and Stern 1994
Reed plantings (after 3-4 seasons)	0.61		limit	
Reed roll (immediately after construction)	0.61		limit	
Reed roll (after 3-4 seasons)	1.22		limit	
Wattle fence (immediately after construction)	0.20		limit	
Wattle fence (after 3-4 seasons)	1.02		limit	
Live fascine (immediately after construction)	1.22		limit	
Live fascine (after 3-4 seasons)	1.63		limit	
Willow brush layer (immediately after construction)	0.41		limit	

Copyright National Academy of Sciences. All rights reserved.

Table 2.2. (Continued).

Bank Material/Protection	Shear Stress (lb/ft^2)	Velocity (ft/s)	Type of Criteria	Source
Willow Brush layer (after 3-4 seasons)	2.86		limit	Schiechtl and Stern 1994 (cont)
Willow mat (immediately after construction)	1.02		limit	
Willow mat (after 3-4 seasons)	6.12		limit	
Deciduous tree plantings (immediately after construction)	0.41		limit	
Deciduous tree planting (after 3-4 seasons)	2.45		limit	
Live stakes in riprap (immediately after construction)	2.04		limit	
Live stakes in riprap (after 3-4 seasons)	6.12		limit	
Coarse gravel and stone cover with live cuttings (immediately after construction)	1.02		limit	
Coarse gravel and stone cover with live cuttings (after 3-4 seasons)	5.10		limit	
Coir fiber roll, single stake, <1:3 slope	0.2 - .8	5	design	Bitterroot Restoration Product Literature
Coir fiber roll, double stake, with brush mat	0.8 - 3.0	8	design	
Turf reinforcement mat, permanent	8	20	design	Rolanka Product Literature
Straw reinforcement mat, temporary	0.45	8	design	
Jute mat	0.45		design	Chen and Cotton 1988
Straw with net	1.45		design	
Curled wood net	1.55		design	
Synthetic mat	2		design	
Rootwads		8.7	observation	Allen and Leech 1997
Rootwads		12	observation	
Willow posts		3.1	observation	
Herbaceous and woody		8	design	
Soil cement		25	limit	Portland Cement Association
Brush mattress w/willows	6.5		limit	Gerstgraser 1999
Wattle fence	1		limit	
Fascine	2.1	9.8	limit	
Cuttings of willows/willow stakes	2.1	9.8	limit	
Articulated concrete mats, unvegetated, USACE block, 40% open	4.3	13.2	limit	Lipscomb et al. 2001
Articulated concrete mats, vegetated, COE block, 40% open	6.1	13.8	limit	

and the states of Alaska (Walter et al. 2005), Arizona (Arizona Department of Environmental Quality 2005), Georgia (Georgia Department of Natural Resources 2007 and 2011), Iowa (Iowa Department of Natural Resources 2006), Maryland (Maryland Department of the Environment 2000), Nebraska (Admiraal et al. 2007), New Jersey (New Jersey Department of Agriculture 2012), New York (Glath et al. 2003), Ohio (Kush 2007, Baker 2007), Oregon (Oregon DOT 2011), Texas (Landphair and Li 2001), Washington (Cramer et al. 2003), and Wisconsin (Wisconsin DOT 2013). In addition, a Canadian province (Donat 1995) and the federal government have produced handbooks for regional (Bentrup and Hoag 1998, Hoag et al. 2001, Hoag and Fripp 2002 and 2005, Yochum 2013) and national [Biedenharn et al. 1997, Fischenich and Allen 2000, Lewis 2000, Federal Interagency Stream Restoration Working Group (FISRWG) 2001, Eubanks and Meadows 2002, Wells 2002a and b] application. Additional guides have been published by nongovernmental organizations (The River Restoration Centre 2002, Schueler and Brown 2004) and the governments of Scotland (Scottish Environmental Protection Agency 2008) and Australia

Copyright National Academy of Sciences. All rights reserved.

20 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Table 2.3. Permissible shear and velocity criteria presented by Fischenich (2001b).

Boundary Category	Boundary Type	Shear Stress lb/ft^2	Velocity ft/s	Source
Vegetation	Class A turf	3.7	6-8	Gray and Sotir 1996, unpub data Fischenich
	Class B turf	2.1	4-7	
	Class C turf	1.0	3.5	
	Long native grasses	1.2-1.7	4-6	Kouwen, Li, and Simons 1980, Norman 1975, Temple 1980, unpub data Fischenich
	Short native and bunch grass	0.7-0.95	3-4	
	Reed plantings	0.1-0.6	N/A	Gray and Sotir 1996, unpub data Fischenich
	Hardwood tree plantings	0.41-2.5	N/A	
Temporary degradable rolled erosion control products	Jute net	0.45	1-2.5	Gray and Sotir 1996, Norman 1975, TXDOT 1999
	Straw with net	1.5-1.65	1-3	
	Coconut fiber with net	2.25	3-4	Gray and Sotir 1996, Texas Department of Transportation (TXDOT) 1999
	Fiberglass roving	2.00	2.5-7	Gray and Sotir 1996, Norman 1975, TXDOT 1999
Non-degradable rolled erosion control products	Unvegetated	3.00	5-7	Gray and Sotir 1996, Kouwen, Li, and Simons 1980,TXDOT 1999
	Partially established	4.0-6.0	7.5-15	
	Fully vegetated	8.00	8-21	Julien 1995, Temple 1980, TXDOT 1999
Soil bioengineering	Wattles	0.2-1.0	3	Gerstgraser 1998, Schiechtl and Stern 1994, Schoklitsch 1937, unpub data Fischenich
	Reed fascine	0.6-1.25	5	Gray and Sotir 1996
	Coir roll	3-5	8	Gray and Sotir 1996, TXDOT 1999, unpub data Fischenich
	Vegetated coir mat	4-8	9.5	
	Live brush mattress (initial)	0.4-4.1	4	Forineth 1982, Gray and Sotir 1996, Schiechtl and Stern 1996
	Live brush mattress (grown)	3.90-8.2	12	Forineth 1982, Gerstgraser 1998, Gray and Sotir 1996, Schiechtl and Stern 1996, unpub data Fischenich
	Brush layering (initial/grown)	0.4-6.25	12	Gray and Sotir 1996, Schiechtl and Stern 1996, Fischenich 2001
	Live fascine	1.25-3.10	6-8	Gerstgraser 1998, Gray and Sotir 1996, Schiechtl and Stern 1996, Schoklitsch 1937
	Live willow stakes	2.10-3.10	3-10	Gray and Sotir 1996, Allen and Leech 1997, unpub data Fischenich

(Torre 2001), although some of these guides cover all types of stream restoration measures as well as bed and bank treatments. Several writers cover slope stabilization using bioengineering approaches with stream bank measures as a subset (e.g., Lewis 2000, Holanda and da Rocha 2011). Almost all reviews present some sort of taxonomy that they use to classify various techniques, and some (e.g., Li and Eddleman 2002, Hagen et al. 2002) emphasize the relative cost-effectiveness of selected measures, but hydraulic data are generally lacking.

Two of the most important national handbooks are the ones produced by the Federal Interagency Stream Restoration Working Group (1998, revised 2001) and the NRCS (2007a, b, and c). The latter contains more engineering design guidance and includes a compilation of allowable velocities and shear stresses (Table 2.4) based upon, but slightly different from the earlier ones by Fripp (Table 2.2) and by Fischenich (2001b) (Table 2.3). The text that accompanies Table 2.4 is worth noting:

Copyright National Academy of Sciences. All rights reserved.

Table 2.4. Permissible hydraulic loadings for bioengineering measures from NRCS (2007b).

Practice	Permissible Shear Stress (lb/ft^2)	Permissible Velocity (ft/s)
Live poles (depends on the length of the poles and nature of the soil)	Initial: 0.5 to 2 Established: 2 to 5+	Initial: 1 to 2.5 Established: 3 to 10
Live poles in woven coir (depends on the installation and anchoring of coir)	Initial: 2 to 2.5 Established: 3 to 5+	Initial: 3 to 5 Established: 3 to 10
Live poles in riprap (joint planting) (depends on riprap stability)	Initial: 3+ Established: 6 to 8+	Initial: 5 to 10+ Established: 12+
Live brush sills with rock (depends on riprap stability)	Initial: 3+ Established: 6+	Initial: 5 to 10+ Established: 12+
Brush mattress (depends on soil conditions and anchoring)	Initial: 0.4 to 4.2 Established: 2.8 to 8+	Initial: 3 to 4 Established: 10+
Live fascine (very dependent on anchoring)	Initial: 1.2 to 3.1 Established: 1.4 to 3+	Initial: 5 to 8 Established: 8 to 10+
Brush layer/branch packing (depends on soil conditions)	Initial: 0.2 to 1 Established: 2.9 to 6+	Initial: 2 to 4 Established: 10+
Live cribwall [depends on nature of the fill (rock or earth), compaction and anchoring]	Initial: 2 to 4+ Established: 5 to 6+	Initial: 3 to 6 Established: 10 to 12
Vegetated reinforced soil slopes (VRSS) (depends on soil conditions and anchoring)	Initial: 3 to 5 Established: 7+	Initial: 4 to 9 Established: 10+
Grass turf—bermuda grass excellent stand (depends on vegetation type and condition)	Established: 3.2	Established: 3 to 8
Live brush wattle fence (depends on soil conditions and depth of stakes)	Initial: 0.2 to 2 Established: 1.0 to 5+	Initial: 1 to 2.5 Established: 3 to 10
Vertical bundles (depends on bank conditions, anchoring, and vegetation)	Initial: 1.2 to 3 Established: 1.4 to 3+	Initial: 5 to 8 Established: 6 to 10+

Sources: NRCS (1996), Hoag and Fripp (2002), Fischenich (2001b), Gerstgraser (1999), Nunnally and Sotir (1997), Gray and Sotir (1996), Schiechtl and Stern (1994), Allen and Leech (1997), Forienth (1982), and Schoklitsch (1937).

> Recommendations for limiting velocity and shear vary widely. . . . The designer should proceed cautiously and not rely too heavily on these values. Judgment and experience should be weighed with the use of this information. The recommendations in [Table 2.4] were empirically determined and, therefore, are most applicable to the conditions in which they were derived. The recommendations must be scrutinized and modified according to site-specific conditions such as duration of flow, soils, temperature, debris and ice load in the stream, plant species, as well as channel shape, slope and planform. Specific cautions are also noted in the table. However, there are anecdotal reports that mature and established practices can withstand larger forces than those indicated in this table. (NRCS 2007b)

Although not a handbook or review, work by Niezgoda and Johnson (2012) should be mentioned here because it lays a foundation for an important new aspect of applied practice: risk analysis. These authors present a quantitative approach for weighing risks of failure for specific practices against economic, environmental, and social benefits. A weakness of the approach is the lack of objective criteria for quantifying failure risk and benefits.

Guidelines for a Specific Measure

Another class of documents consists of guidelines for designing or constructing a single type of environmentally sensitive bank-protection technique. Although guidance may be gleaned from case studies that feature a specific technique, single-measure guidelines are primarily directive in nature and do not relate experience at a single site or group of sites. Several local, state,

Copyright National Academy of Sciences. All rights reserved.

Table 2.5. List of selected bank treatment guidelines available from two web sources.

Institute for Water Resources, USACE	Ohio Department of Natural Resources*
1. Bank Cover and Current Deflector with Sand Bag and Cellular Confinement System	07 Restoring Streambanks with Vegetation
2. Bank Crib with Cover Log	
3. Bank Shaping and Vegetation	11 Tree Kickers
4. Bioengineering and Bioengineering Techniques	
5. Branch packing and Brush layering	12 Evergreen Revetments
6. Cable Concrete	
7. Coconut Fiber Roll, Coir Rolls, Coir Mats and Coir Netting	13 Forested Buffer Strips
8. Dormant Posts or Dormant Cuttings	
9. Erosion Control Blanket	14 Live Fascines
10. Grout-filled Mattress	
11. Gabion and Gabion Mattresses	17 Live Cribwalls
12. Grass Rolls	
13. Hedge-Brush Layering	19 Deflectors
14. Joint Planting/Vegetative Riprap	
15. Live Cribwalls	20 Eddy Rocks
16. Live Fascines and Wattlings	
17. Live Siltation	22 Gravel Riffles
18. Live Staking	
19. Log and Brush Shelter	
20. Log Cribbing	
21. Native Material Revetment (Log, Rootwad, and Boulder Revetment)	
22. Overhanging Bank Cover	
23. Placement of Boulders	
24. Riprap	
25. Rootball or Rootwad Placement	
26. Straw Rolls	
27. Stream Bank Debrushing, Brush Bundles, and Brush Mats	
28. Training Fences	
29. Vegetated Geogrids	
30. Vegetation/Revegetation	
www.pmcl.com/mmdl/MM.asp?ID=1	www.dnr.state.oh.us/tabid/4178/default.aspx

***The numbers preceding the Ohio Department of Natural Resources treatment types are the guide numbers assigned by the department.**

and federal agencies have published series of these documents in print or on the web. McCullah and Gray (2005) note several examples of websites that disseminated such guidelines. Since conclusion of their research project, additional guidelines have appeared. For example, the USACE's Institute for Water Resources maintains a website with guidelines for 30 techniques, while a smaller number of techniques are available from the Ohio Department of Natural Resources (Table 2.5) and numerous other sources.

Typically, such guidelines focus on construction details: how to prepare the site and materials and assemble or plant them to produce a finished project. Hydraulic design criteria familiar to designers who work with riprap revetment (e.g., Lagasse et al. 2006) or even similar to those produced for grassed channels (e.g., Killgore and Cotton 2005) are usually absent. Printed guidance documents have also been published. Examples of measure-specific guidelines, most either from the USACE ERDC or the state of Ohio Department of Natural Resources, are provided in Table 2.6.

Case Studies

The literature contains a large number of reports of the success or failure of bank-protection measures applied to a given site (a segment of bankline or a stream reach), and even more have been published recently (Goldsmith et al. 2014). Many case studies describe projects

Copyright National Academy of Sciences. All rights reserved.

Table 2.6. Typical guidance documents for individual bank-protection measures.

Measure	Hydraulic Design Criteria	Content/Remarks	Reference
Willow spilling	yes	Summary of performance of 140 projects. Criteria modified from Fischenich (2001b) and Sotir and Fischenich (2007).	Anstead and Boar 2010
Brush mattress	yes	Guidance for fabrication and installation. Hydraulic criteria from Fischenich (2001b) supplemented with Schietchl and Stern (1997) and experience by Fischenich.	Allen and Fishenich 2001, American Society for Testing and Materials (ASTM) 2003
Live fascines, "vertical bundles"	yes	Hydraulic criteria from Fischenich (2001b). Limits are "empirical information collected from constructed projects." Guidance for fabrication and installation.	Sotir and Fishenich 2001, Ervin 2007, ASTM 2014
Live stakes and joint planting	yes	Example contract specifications. Guidance for preparation and installation. Hydraulic loading limits based on empirical information collected from constructed projects.	Shafer and Lee 2003, Sotir and Fishenich 2007, ASTM 2013, Hoag 2009b
Rootwads	yes	Design methodology for use with a computer spreadsheet and/or a family of empirical curves that can quantify the amount of ballast required to stabilize a rootwad for a variety of load conditions. Safety factor computations.	Sylte and Fishenich 2000, Wood and Jarrett 2004
Tree revetments	no	Guidance for site selection, fabrication, and installation.	Bishop et al. 2007
Live cribwalls	no	Guidance for site selection, fabrication and installation.	Ervin and Fulmer 2007
Willow and cottonwood	no	Guidance for using cuttings or clumps in a variety of ways and for constructing stable banks by placing poles or bundles under riprap.	Hoag 2007, Hoag and Sampson 2007
Coir logs	yes	Allowable velocity and shear from vendors or constructed projects.	Allen and Fischenich 2000
VMSE	yes	Limits based on empirical information collected from constructed projects.	Sotir and Fischenich 2003
Flexible channel linings	Qualitative	Guidance on use of manufacturer's reported allowable velocity and shear stress for rolled erosion control products, turf reinforcement mats, erosion control blankets, etc.	Miller et al. (2012)

that employ several types of measures in adjacent bankline segments or combined along the same bank.

To date, case studies have provided a higher level of reality than model studies or laboratory experiments, but are difficult to generalize for application to other sites due to site-specific conditions, short periods of observation, or insufficient data to fully characterize the hydraulic and geotechnical processes operating on the constructed site. Most common are studies that describe the appearance or geometry of an eroding site before and after treatment and provide details on design, construction, and costs, but little if any hydraulic data. For example, only 10 of the 35 case studies presented by Goldsmith et al. (2014) are for sites for which discharge data are available, and near field measurements of flow depths and velocities are much less common. In some cases, practitioners infer shear stresses acting on installed biotechnical measures using 1-D or 2-D models. Key facts regarding recently published case studies are summarized in Table 2.7.

Handling Plant Materials

Most of the handbooks and several of the guidelines for individual measures contain sections about selecting, harvesting, and handling plant materials (e.g., NRCS 2007b). Guidelines that

Copyright National Academy of Sciences. All rights reserved.

Table 2.7. Recently published case studies of environmentally sensitive bank-protection projects.

Measure(s)	Locale	Remarks	Reference
Willow spilling	Two sites, East Anglia, U.K.	One yr observation, successful.	Anstead et al. 2012
Live poles, stakes, fascines	Mill Creek, Cincinnati, OH	Five yr observation, successful. Protecting landfill	Barrett et al. 2006
Large wood structures, brush mattress, VMSE	Redwood and Corte Madera Creeks, California	Three and six yrs of observation, mostly successful	Blomberg et al. 2006
Rootwads, brush layers, coir logs, transplanted vegetation mats	19 sites on flowing waters or lakes in Matanuska-Susitna Borough, Alaska, 10 of which involved bank restoration	A few evaluations of plant survival, structure condition and bank stability within one to three yrs of construction. Several opportunities for improved practice noted	Davis and Davis 2005 and 2007
Slope flattening, boulder grade control structures, VMSE, coir logs at toe, brush layering, turf reinforcement mat, fascines, live siltation	Willow and Sand Creeks, Denver, CO	Two yr observation, deemed successful	Denver Urban Drainage 2001a and 2001b
Various combinations of wood, planting cuttings, coir, rock	10 sites, Western WA	Various periods of observation. All reported as successful	Federal Emergency Management Agency (FEMA) 2011
Brush layers with stone toe recommended, but not constructed since this is a planning-level report	Four reaches of Cazenovia Creek, NY	Reach-mean velocity and shear stress computed using uniform flow equations and compared to Fishenich 2001b	Frothingham 2008
Wattle fence	Huaijiu River, Beijing, China	*Salix alba* recommended.	Gu et al. 2012
Rootwads, brush layering	Ketnai River, Alaska	Root wads experienced ice damage, brush layers protected upper banks well	Karle 2007
Rootwads, live staking, brush layers, coir logs	11 sites, Alaska	1-D model used to compute average bed and bank shear stresses under 50-year and 100-year events. Bioengineering measures not reliable in channels with high shear stresses	Karle et al. 2003
Vegetated cribwall	Two southern Ontario watersheds, 12 cribwalls in all. Age of structures not specified	Cribwall and vegetation characteristics, sediment sampling, erosion pin monitoring and computer generated stream power analysis. Vague about performance	Krymer and Robert 2013
VMSE—with geogrids and willow cuttings. Dormant willow posts—combined with stone toe and protection of surface between posts with reinforced turf	Cottonwood Creek, Hutchins, TX	Three yr observation. Successful stabilization with 90% survival of cuttings. Questionable approach used to monitor velocity at a single point.	Li 2006
Reinforced turf VMSE Vegetated riprap Jute netting and large wood	Four sites in Oregon	Four yr observation. Quantitative measurements of stream stage, velocity, and discharge. No bank erosion observed. Vertically averaged velocity continuously logged using acoustic instruments at two points.	Mabey 2009

Copyright National Academy of Sciences. All rights reserved.

Table 2.7. (Continued).

Measure(s)	Locale	Remarks	Reference
Vegetated riprap	South central and interior Alaska	"…specific hydrologic and hydraulic characteristics need to exist for a riprap armored stream bank to allow and sustain vegetative growth."	Maniaci and Nolen 2005
Vegetated cribwalls	Nicaragua	Three of the four native species evaluated are recommended for future use. Economics attractive.	Petrone and Preti 2008
12 types of structures including vegetated crib walls, debris jams, log bank structures	Guadalupe Creek, San Jose, CA	Five yr observation. Crib walls and debris jams successful; log bank structures stabilized banks but did not maintain undercut habitats	Seville and MacKay 2006
Boulders at toe with VMSE on upper bank	Three reaches of Fort Branch Creek, Austin, TX	Period of observation short and unspecified, successful.	Byars and Renfro 2012
Vegetated gabions	Manchester River at golf course, Manchester, NH	Six months observation. After only one growing season, the vegetation is generally well established where it was planted. Some areas where the plants were too small or not properly placed during the installation have some problems with establishment in the structure.	Brunet and Shuey 2005
Reinforced turf with anchors	Anthony Creek and Cow Creek, WV	No post-construction observations reported.	Merritt et al. 2010
Large wood structures, plantings of willow poles and stiff grasses	Topashaw Creek, MS	Five yr observation. Measurements of flow, depth and velocity. Unsuccessful due to ongoing channel incision.	Shields et al. 2008
Coir logs, erosion control blankets	Nineveh Creek, Edinburgh, IN	Very brief period of observation	USACE 2006
VMSE: Lifts of soil are encapsulated in geotextile that is wrapped over the exposed face of each lift, creating a "stair-step" appearance. Vegetation is planted between lifts. This is a well-established bioengineering technique widely employed with variations in the types of vegetation and geotextile used. Other terms used for this technique include "vegetated reinforced soil slope," "vegetated soil lifts," and "vegetated geogrids."			

focus specifically on handling plant materials include Fischenich (2001a), Luna et al. (2006), Darris (2006), Bergdorf (2007), Hoag (2007) and Balch (2008). Additional guidance is available on irrigation (Fischenich 2000a), soil compaction (Goldsmith et al. 2001), and soil amendments (Fischer 2004). Other researchers have experimented with special equipment and techniques to make woody cutting planting on banks, typically a labor-intensive task, more efficient (Hoag et al. 2001, Hoag 2009a, Hoag and Ogle 2011). Furthermore, the literature contains results of applied research on techniques for handling and installing plant materials to ensure acceptable levels of survival and growth vigor. Many of these deal with propagation of woody species from cuttings. Greer et al. (2006a and 2006b) found that the diameter of *Salix nigra* cuttings interacted with soil moisture regime in a complex fashion; they recommended planting both large (10 cm) and small (1 cm) diameter cuttings. Although willow (*Salix* sp.) and cottonwood (*Populus* sp.) species are most often used due to ease of rooting from cuttings, Hunolt (2012) and Hunolt et al. (2013) compared performance of silky dogwood (*Cornus amomum*) and Virginia sweet-spire (*Itea virginica*) as live stakes to two willow species and found they were able to survive and establish if harvested during dormancy.

Several practitioners have tested the effect of soaking woody cuttings before they are planted on survival and growth. Soaking cuttings before planting for periods as long as 14 days was beneficial if cuttings were dormant (Schaff et al. 2002, Martin et al. 2004, Tilley and Hoag 2008).

Copyright National Academy of Sciences. All rights reserved.

Results for nondormant cuttings were less favorable (Pezeshki et al. 2005). Martin et al. (2004) showed cuttings responded positively to soaking water oxygen concentration, giving credence to anecdotal guidelines for soaking plant materials in moving waters. Hunolt (2012) and Hunolt et al. (2013) found soaking cuttings of four woody species for 48 hours before planting had minimal effects, but dormancy was important. Survival rates were 100% for all species when stakes were harvested and planted during the dormant season, but three of the four had 0% survival when harvested during the growing season. Tilley and Hoag (2008) found fall willow cutting plantings did better than spring plantings. Because some regions have short dormant seasons, Landphair and Li (2002) and Li et al. (2005) experimented with extending dormancy by storing cuttings in refrigerated chambers and achieved field survival rates for *Salix nigra* cuttings in Texas of 44% to 81%.

2.2.5 Advances in Fundamental Science Subsequent to NCHRP Project 24-19

Plant Characteristics

Considerable research has been done in recent years to characterize aspects of woody riparian species that are important in bioengineering applications. Species tolerances to various environmental stresses and habitat preferences have been better defined for some species (Evette et al. 2012, Liu et al. 2010, Pezeshki and Shields 2006). Work on *Salix nigra* (Schaff et al. 2003, Li et al. 2004, Pezeshki et al. 2007) and *S. exigua* (Caplan et al. 2012) has shown that soil texture and soil moisture are key characteristics, with best performance within rather narrow ranges of these two interrelated variables. A few researchers have attempted to define plant characteristics (e.g., root biomass per unit soil volume) that correlate with erosion rates (Gyssels et al. 2005). Work by Beasley (2011) and Beasley et al. (2010) on levee slopes subjected to overtopping is noteworthy in this regard. Slope stability models that account for contributions of plant roots to soil strength require information about root density, morphology, and tensile strength, which must be painstakingly measured (Adhikari et al. 2013). These characteristics vary by species and with environmental variables, but at least one report indicates that engineered slopes can produce superior plant characteristics (biomass and root tensile strength) to natural slopes (Ying et al. 2011).

Fluid Mechanics

In order to design and manage systems with bank-protection measures that feature vegetation, engineers need robust tools to simulate channel flow conveyance, bank shear stresses, and habitats. Riparian vegetation interacts with channel flow in complex ways, such as modifying flow resistance locally and at the reach scale, governing near-bank turbulent structure and shear stresses, momentum exchange, and, in some cases, concentrating flows by displacing threads of higher velocities either away from the bank or underneath the canopy and closer to the bank (Kean and Smith 2004, McBride et al. 2007, Czarnomski et al. 2012). Fluid mechanics for flows in channels with vegetated banks may be categorized based on flexibility of vegetation (flexible or rigid) and relative flow depth (vegetation submerged or emergent) (Rahmeyer and Werth 1996, McKay and Fischenich 2011, Aberle and Järvellä 2013). Rigid plants that protrude above the free surface, for example, offer much greater flow resistance than flexible ones that are fully submerged. The density of the plant stems and branches is also quite important as the flow field responds to plant density in a highly nonlinear fashion (Kean and Smith 2004). For deciduous plants, the presence or absence of leaves is important (Freeman et al. 2000 and 2004, Wunder et al. 2011, Czarnomski et al. 2012, Aberle and Järvelä 2013).

Research on interactions between rivers and terrestrial vegetation has been advancing rapidly over the past 10–15 years, and a range of approaches has been used. Both floodplain and stream

Copyright National Academy of Sciences. All rights reserved.

bank vegetation have been studied; the latter is of primary interest here. Some workers have used dowels or other manmade objects as artificial plants in laboratory flumes (e.g., Czarnomski 2010, Czarnomski et al. 2012), but artificial plants do not deform in flows as real ones do (Järvelä 2006, Wunder et al. 2011). Others have used small, real plants in laboratory flumes or wind tunnels (Freeman et al. 2000, Wunder et al. 2011). Laboratory flumes allow high-frequency, spatially-detailed measurements of the velocity field in prismatic channels under steady flow. Most of these flume experiments (and associated numerical modeling) have assumed a uniform stand of bank vegetation that does not vary its characteristics in the lateral direction (e.g., Kean and Smith 2004, Bledsoe et al. 2011) even though natural riparian vegetation and biotechnical bank-protection measures usually feature different types of protection for bank toe, mid bank, and upper bank. Interactions between riparian vegetation and stream channel morphology have been studied at larger scales using statistical approaches by fluvial geomorphologists (e.g., Bledsoe et al. 2011). Increasingly sophisticated numerical models (e.g., computational fluid dynamics) have been used to extend and complement field and laboratory results across a range of spatial scales (e.g., Wilson et al. 2006, Jahra et al. 2011).

Some of the most interesting work in this area has been directed toward forested floodplains: stands of woody vegetation on flat surfaces. For example, Chen et al. (2009) conducted a series of flume studies examining the flow resistance and soil erosion rates for flat surfaces composed of bare soil, and for soil surfaces planted with uniform stands of four California native floodplain plant species. For vegetated surfaces, flow resistance declined as a linear function of Reynolds' number, with linear slopes and intercepts varying according to plant characteristics. When mean flow velocities exceeded 3 ft/s, erosion rates under plant canopy were less than 30% of those observed for bare soil. The following explanation was offered:

> Observations demonstrate that these floodplain-adapted species lay over under higher flows creating a laminar break in the velocity profile where the soil/water interface is essentially insulated and protected from the scour forces of higher velocities. The bare soil vertical velocity gradient was quite uniform whereas the velocity gradients in the plant tests were S shaped, being slow at the soil surface and accelerating over the top of the plant canopy as the plants bent over.

In another example, Rahmeyer and Werth (1996) and Freeman et al. (2000 and 2004) reported results of over 220 flume experiments involving 27 different real plant types and groupings. In-channel (not stream bank) vegetative flow resistance was found to decrease with velocity and depth for submerged plants but to increase with depth for emergent plants. Flexible, submerged plants with leaves formed a streamlined (teardrop) shape that reduced the flow forces on the plants, protecting leaves and smaller stems from breakage. Minimum plant velocity limits of 3 to 4 ft/s were observed for leaf failure, and most of the leaf and stem failures were the result of impact with bed material and debris. Stands with more or less uniform canopy geometry concentrated flow underneath the canopy, resulting in general scour.

In a field (rather than flume) study, Manners et al. (2013) used terrestrial laser scan images of clumps of tamarisk shrubs to characterize stage dependence of hydraulic roughness. The resulting models were extrapolated to reach-scale, two-dimensional hydraulic models built with aerial LiDAR data.

The studies cited above on floodplain vegetation and similar works have made important contributions, but key differences exist between flows across vegetated floodplains and flows in channels with vegetated banks (e.g., turbulence peaks at the interface between the main channel and riparian zone and near the toe of sloping banks) (McBride et al. 2007, Czarnomski et al. 2012). Bank slope influences spatial distributions of Reynolds stresses (Czarnomski et al. 2012). Despite considerable effort devoted to studying flow forces on vegetation (Fischenich and Dudley 2000, Wunder et al. 2011) and associated effects of vegetation on flow resistance (e.g., Fischenich 2000b, McKay and Fischenich 2011, Aberle and Järvelä 2013), almost no work has been done

Copyright National Academy of Sciences. All rights reserved.

since that reported by McCullah and Gray (2005) to define the ability of biotechnical measures to withstand flow forces. Criteria for selecting and designing environmentally sensitive measures are usually qualitative or based on experience of a few individuals. Much of the hard data that does exist is derived from smaller-scale flume experiments in prismatic channels with highly uniform vegetation or artificial vegetation.

Slope Stability

Stream banks erode or retreat due to fluvial erosion processes, sliding or mass wasting, and combinations of these processes. Scientists have long realized the links between vegetation and bank slope stability (Gray and Leiser 1982, Gray and Sotir 1996), but since publication of McCullah and Gray (2005), several important advances have been made in development of analytical techniques. Both beneficial and detrimental effects of vegetation on bank stability have been observed: plant roots reinforce soils and remove moisture by evapotranspiration, increasing matric suction; however, very large trees impose weight loading on banks and woody vegetation may also enhance infiltration of precipitation (Simon and Collison 2002, Gray and Barker 2004, Pollen et al. 2004). Earlier models of root reinforcement of soils ignored the effects of soil type and moisture on root-soil bonds; root tensile strength was simply added to soil strength and roots were assumed to be oriented perpendicular to failure planes. Work by Pollen (2007) has advanced understanding of temporal and spatial variability in root reinforcement due to variations in soil type and moisture, and work by her team (Pollen et al. 2004, Pollen and Simon 2005) has shown that soil-root matrices are better simulated by fiber-bundle models that allow progressive failure of roots (weakest first) rather than the "all-roots-break-instantaneously" assumption of the older perpendicular models. The fiber-bundle model algorithm has been incorporated into the Bank Stability and Toe-Erosion Model (BSTEM), a spreadsheet tool used to simulate stream bank stability. The user supplies bank geometry, soil properties, vegetation cover, and bank water-table levels, and the model outputs factors of safety. If banks fail or erode, new bank geometry is generated. Fluvial erosion of material at the bank toe is simulated using a simple excess-shear stress approach (Simon et al. 2011).

Fluvial Geomorphology

At the river reach scale, geomorphologists have produced stronger explanations for the mutual adjustment of bank vegetation and channel width, depth, and slope including physically based models that account for vegetation effects on slope stability, sediment transport, and flow resistance (Millar and Eaton 2011, Bledsoe et al. 2011). Some effects are non-intuitive: Trimble (2004) presented data from a Wisconsin watershed that showed grass on banks promotes a smaller bankfull cross-sectional area than forested banks. Opposite effects were reported by Bledsoe et al. (2011), who found that channels narrower than 65.6 ft (20 m) have shear stress distributions quite sensitive to bank vegetation. Streams with banks covered with woody vegetation should be narrower and deeper.

Environmental Effects

Research is emerging on ecological effectiveness of a range of ecosystem rehabilitation and restoration strategies and measures. Roni et al. (2008) present a global review of literature on the effects of stream habitat rehabilitation measures; 142 of the 345 papers analyzed report effects of instream habitat measures that include various bank treatments. However, few of the bank treatments can be classified as erosion controls: riparian silviculture, fencing, and instream habitat structures are the focus. Frequently the literature reports a lack of data on restoration success or projects that have no measurable ecological benefit (Doyle and Shields 2012). Within this literature there is a small subset relevant to environmentally sensitive bank-protection measures.

Copyright National Academy of Sciences. All rights reserved.

For example, Everaert et al. (2012) reported on analysis of 82 (macroinvertebrate) and 112 (macrophyte) "records" from Dutch projects involving "ecologically sound banks." In general, the projects contributed to diverse macroinvertebrate and macrophyte communities, but site selection, design, and maintenance were crucial to success. Conversely, Cooperman et al. (2007) were unable to detect differences in habitat or macroinvertebrate abundance between stream bank restoration sites and untreated reference sites along salmon streams in southern British Columbia. A recent textbook notes that while bank protection can be a legitimate component of an ecological restoration project, bank stabilization constructed with the main objective of protecting infrastructure is unlikely to achieve habitat improvement since natural channel processes require some lateral channel migration (Roni and Beechie 2013).

2.3 Survey of Current Practice

2.3.1 Survey Form and Distribution

A copy of the final survey instrument for Task 2 is included in Appendix B. In early November 2013, the survey questionnaire was distributed by email to 319 individuals representing all 50 state highway agencies (DOTs) and other federal, state, and local government agencies. Selected Native American nations, consultants, and academic institutions involved in stream bank protection measures were also included in the survey outreach effort. In addition to the DOTs, the distribution list included:

- FHWA:
  - Resource Centers
  - Federal Lands Divisions
- USDA:
  - NRCS Plant Materials Centers
  - Forest Service
  - ARS
- U.S. Department of the Interior (USDI):
  - USGS
  - Bureau of Land Management
  - Bureau of Reclamation
  - Fish and Wildlife Service
- USACE
- National Oceanic and Atmospheric Administration (NOAA)
  - National Marine Fisheries Service (NMFS)
- AASHTO Standing Committee on the Environment (SCOE)
- Muckleshoot Tribe
- Lower Elwha Klallam Tribe
- Quinault Indian Nation
- Selected universities, counties, and cities

In terms of response, many recipients/respondents indicated that they had not only received the request for information, but had distributed the survey to many of their colleagues. For example, a single Pennsylvania Department of Transportation (PennDOT) contact on the initial email list solicited, and received, responses to the survey from all 11 of the PennDOT districts. From PennDOT District 11 alone, 140 files of photos and site reconnaissance/monitoring documents were received. The California Department of Transportation (Caltrans) also provided a wealth of valuable information on stream bank protection sites that are currently being evaluated through a cooperative study with California State University, Humbolt (CSU-H).

Copyright National Academy of Sciences. All rights reserved.

As a direct result of the survey a number of sites in the Ann Arbor, MI, area were suggested for field work by a co-author of *NCHRP Report 544* in his response. Follow-up discussion revealed that most of these sites would be included in a text on bioengineering treatments and, as such, are very well documented (Goldsmith et al. 2014). Many of these stream bank projects are located within a mile of the University of Michigan campus in Ann Arbor and are (1) easily accessible, (2) have USGS stream gaging information, and 3) are well documented. Based on these factors it was proposed under Task 3 that sites in the Ann Arbor area be included in the Task 6 field evaluation program as the upper Midwest region (see Section 2.4).

2.3.2 Summary of Survey Results

The purpose of the survey was to gather information on the current state of practice with respect to a variety of topics related to environmentally sensitive stream bank protection, and included detailed performance-related issues/questions for 16 specific protection treatments (see Appendix A).

In total, 35 completed questionnaires were received. Eighteen states, the District of Columbia, and British Columbia are represented by the completed questionnaires, with eight states located west of the Mississippi River (12 responses) and 10 states located east of the Mississippi (23 responses). Most of the individuals responding were from state DOTs (30 responses). Several federal and state agencies responded (one each from FHWA, NOAA, U.S. Forest Service, and California Department of Fish and Wildlife), as well as one consulting firm.

The distribution of and number of responses by state are shown in Figure 2.1. It should be noted that 12 of the 35 responses were received from PennDOT, with each of its districts providing a response across that state's diverse physiography. Also note that the responses from South Dakota and Missouri are labeled "n/a" because the respondents from these two DOTs indicated that they did not have any experience with any of the 16 treatments listed in the survey.

The physiographic regions included in the responses across the U.S. are indicated in Figure 2.2 by a check mark next to the legend. Sixteen of the 25 physiographic regions defined by the USGS (Fenneman and Johnson 1946) are represented by the survey responses.

Because of the many responses received from PennDOT, physiographic regions 2 (Appalachian Plateau) and 24 (Valley and Ridge) are well represented. Also well represented is region 6

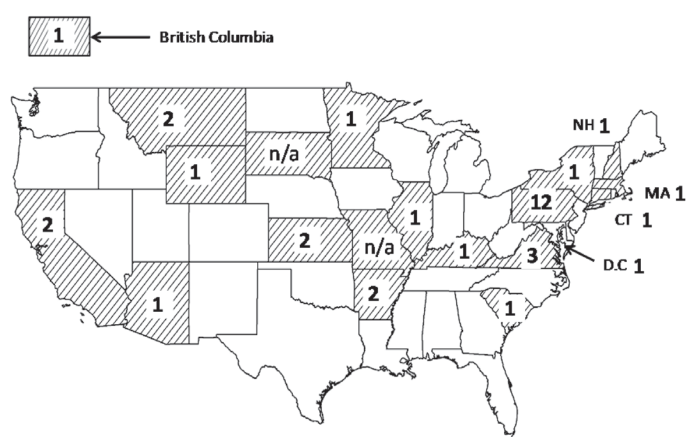


Figure 2.1. Survey responses by state.

Copyright National Academy of Sciences. All rights reserved.

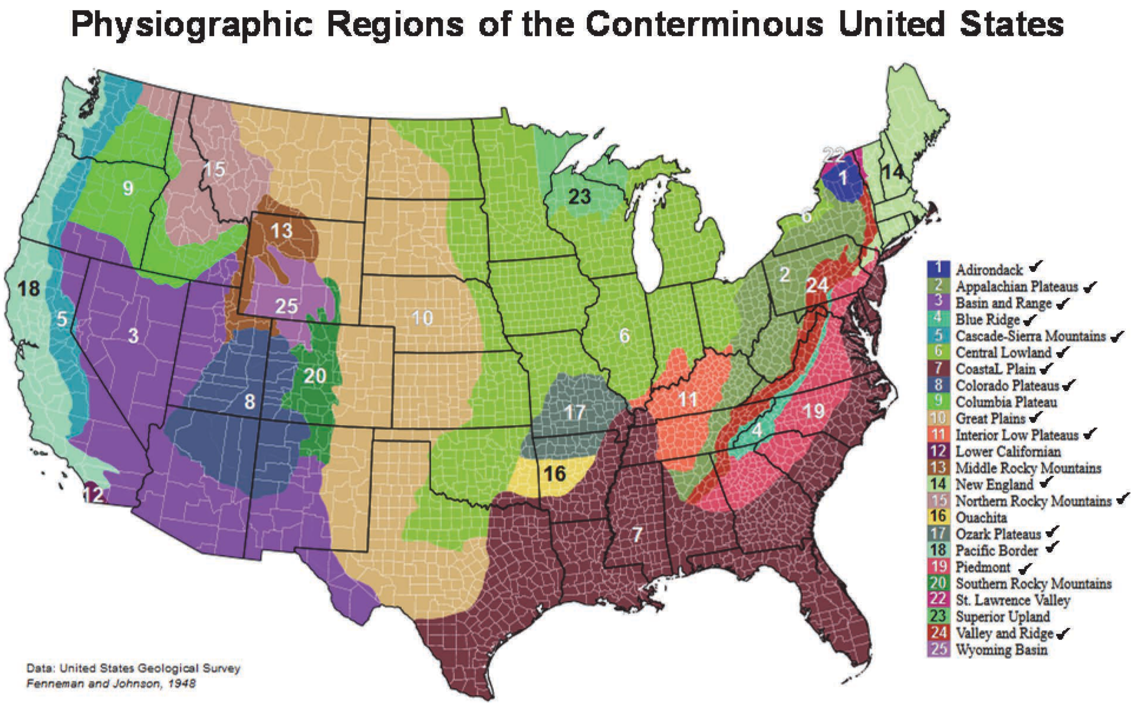


Figure 2.2. Survey responses by physiographic region.

(Central Lowland) owing to the number of responses received from Illinois, Kansas, Minnesota, and New York. It should be noted that many responses represent multiple physiographic regions corresponding to a particular agency's area of jurisdiction.

A detailed listing of responses by state is provided in table format and shows the responses and frequency of use reported for the 16 treatments listed in the survey. Also shown are the physiographic regions associated with each response. The above-mentioned tabled and detailed response spreadsheets for each of the 16 treatments are included in the Compendium that accompanies this report. These spreadsheets tabulate performance, monitoring, and failure mode information for each of the 16 treatments.

The survey was constructed to elicit specific information regarding the relative frequency of use of the various types of environmentally sensitive bank-protection treatments, and their performance. Table 2.8 provides a numeric tabulation of the frequency of use of the 16 bank-protection measures for which specific information was requested.

Table 2.8. Bank-protection treatments: frequency of use.

Live brush layering	7	Live brush mattress	7
VMSE	9	Vegetated articulating concrete blocks (ACBs)	6
Large woody debris	12	Vegetated riprap	17
Vegetated gabions	6	Vegetated gabion mattress	2
Live staking	27	Soil/grass-covered riprap	10
Willow posts/poles	11	Live fascines	13
Live siltation	5	Coconut fiber roll	12
Rootwad revetment	16	Turf reinforcement mats	12
		Other (describe):	0

Copyright National Academy of Sciences. All rights reserved.

By far, the most popular treatment currently in use is live staking (27 out of 35 responses). The survey responses indicated that vegetated riprap (17 responses) and rootwad revetments (16 responses) were the second-most popular treatments in current practice.

In terms of performance, respondents were asked to qualitatively assess their experience with a particular treatment using the following scale:

1 = Failure
2 = Satisfactory
3 = Good
4 = Excellent

This ranking scheme revealed that, in general, environmentally sensitive bank-protection measures typically result in satisfactory to good performance at most installation sites. The average value of the numerical rankings ranged from a low of 2.2 to a high of 3.0, indicating that there is not much differentiation between treatments. Table 2.9 provides the averaged rankings along with a summary of the comments and observations received from the surveys.

Only two treatments received more than one response indicating "excellent" performance: soil/grass-covered riprap (3 "excellent" ratings) and coconut fiber rolls (2 "excellent" ratings). On the other hand, none of the treatments received more than one response indicating "failure."

The two most common causes of substandard performance were drought and erosion of the bank slope. These factors were a recurring theme across nearly all of the 16 bank-protection measures listed in the survey. Protection measures incorporating live cuttings tended to indicate that improper plant selection or improper installation resulted in poor performance. Protection measures that incorporated a "hard" or "engineered" component such as rootwad revetment, large woody debris, articulated blocks, gabions, etc. exhibited failure modes associated with toe or edge scour, undermining, flanking, or geotechnical slope instability.

2.4 Field Site Evaluations

2.4.1 Site Selection Criteria

Initially, 31 sites where environmentally sensitive bank-protection measures have been installed across the country were identified. Each of those sites had either been designed, constructed, and/or monitored by one or more of this project's research team members. Based on the information obtained during Phase I (Tasks 1 and 2), additional candidate sites for field investigation during Task 6 (Phase II) were identified and screened. The final "short list" of sites included a diversity of protection measures and geographic locations.

The schedule and budget allowed site visits to 16 field evaluation sites in three geographic regions:

- Southeast (Mississippi)
- Upper Midwest (Michigan)
- West Coast (Northern California)

Priorities were to visit sites where measurements have or can be made and where those measurements can be correlated to original design intent and hydrologic/hydraulic history.

The following section discusses the screening process and the schedule for field investigations completed during Task 6. The "short list" of field sites considered site groupings to maximize the return on Task 6 activities and also considered the desire to strike a balance between investment in field visits and Task 7 laboratory studies.

Copyright National Academy of Sciences. All rights reserved.

Table 2.9. Bank-protection treatments: qualitative performance assessments.

Protection Measure	Avg. Score (1 = Failure, 4 = Excellent)	Comments
1. Live brush layering	2.8	Seven respondents indicated experience with multiple sites and reported generally good performance. Montana reported some poor performance due to improper installation, and California noted both slope erosion and drought as factors leading to instances of substandard performance.
2. VMSE	2.7	Generally good performance reported by nine respondents. Montana reported some poor performance due to improper installation, while California and D.C. noted both slope erosion and drought as factors leading to substandard performance.
3. Large woody debris	2.9	Generally good performance. California noted failure modes associated with undermining and/or flanking as well as slope erosion and drought. Pennsylvania reported damage associated with herbivory leading to poor condition of the vegetation.
4. Vegetated gabions	2.8	Only six responses, generally reporting good performance. California noted toe scour, geotechnical slope instability, flanking, slope erosion, and drought as factors leading to failure.
5. Live staking	2.5	Because of the large number of responses for this treatment, performance ranged from "failure" to "excellent." Most respondents indicated experience with multiple sites and reported generally satisfactory performance. When mortality was indicated, the cause was typically lack of moisture, poor soil conditions, poor quality of cuttings, or a combination of these factors. California indicated that they do not use this as a standalone measure but incorporate a hard armor toe.
6. Willow posts/poles	2.5	Generally satisfactory performance. Wyoming reported failure due to improper plant selection. Drought was mentioned by five respondents as a factor leading to substandard performance.
7. Live siltation	2.5	Generally satisfactory performance, but not much usage reported (only five responses).
8. Rootwad revetment	2.4	Generally satisfactory performance, with toe scour/undermining being the leading cause of performance problems.
9. Live brush mattress	3.0	Generally good performance, but not much usage reported (seven responses). California noted that slope erosion, drought, and beaver damage resulted in some performance problems.
10. Vegetated ACBs	2.2	Satisfactory performance, but not much usage reported (six responses). Slope erosion and geotechnical slope stability problems were noted as factors leading to substandard performance.
11. Vegetated riprap	2.8	Generally good performance. Slope erosion and drought were the most commonly reported causes of substandard performance.
12. Vegetated gabion mattress	3.0	Only two responses for this treatment. South Carolina reported "excellent" performance, while Arizona reported "satisfactory" performance.
13. Soil/grass-covered riprap	3.0	Good performance. Slope erosion and drought were noted as factors causing less than desired performance.
14. Live fascines	2.7	Generally satisfactory to good performance. Bank and toe scour were noted as failure mechanisms, along with slope erosion and drought.
15. Coconut fiber roll	2.8	Generally good performance. Toe scour was reported as the most common cause of problems. Montana noted that this treatment is "expensive, but always works."
16. Turf reinforcement mats	2.8	Generally good performance. Bank scour, toe scour, and drought most often mentioned as factors leading to substandard performance.

Copyright National Academy of Sciences. All rights reserved.

2.4.2 Screening, Schedule, and Initial Observations—Field Site Visits

Screening of the field evaluation sites included 31 field sites identified initially, review of responses to the Task 2 survey and follow-up discussion with several survey respondents, and the experience of research team members with specific sites in various geographic regions. The regional coverage listed in Section 2.4.1 provided the desired geographic diversity to obtain relevant information on a national basis from both humid and less humid regions and regions that experience significantly different climatic conditions (e.g., the upper Midwest sites experience a freeze/thaw cycle, while the Southeast sites do not). Regional selection was also influenced by the grouping of sites in reasonable proximity so that a maximum number of sites could be visited in a two- or three-day field trip.

Additional considerations in site selection included:

- Well-documented sites with a detailed photographic record.
- Availability of detailed site design and installation data.
- Access to a wide range of treatment types as classified by *NCHRP Report 544* (see Appendix A).
- Providing specific information on research needs identified in *NCHRP Report 544* as listed in Appendix A.
- Flood history, monitoring history, and availability of quantitative hydrologic and hydraulic data.
- Availability of a person involved in design, construction, and monitoring of a site to guide the team during the site visit(s) and provide access to historic and current site data.

The screening process and field evaluation sites recommended to the panel are discussed briefly below. Site photographs, construction date, and details of the treatment components for each site are provided in the following sections. The schedule for site visits during Task 6 and initial observations from each region are also summarized.

Southeast (Mississippi)

Site MS1: Buttahatchee River, near Columbus, MS (1.5 miles northeast)

- Stone toe.
- Erosion control blanket.
- Rootwads.
- Willow trenches—live staking.
- VMSE in some locations.

Site MS2: Buttahatchee River, near Columbus, MS (0.5 miles due north)

- Willow posts and poles.
- Bendway weirs with embedded large wood "locked" logs.

Site MS3: Goodwin Creek near Batesville, Mississippi (northern Mississippi)

- Stone toe.
- Bendway weirs.
- Rock riffles.
- Live staking.
- Live willow posts.
- Containerized plantings.

Site MS4: Harland Creek, near Lexington, MS (west-central Mississippi)

- Stone toe.
- Bendway weirs.
- Live willow posts.

Copyright National Academy of Sciences. All rights reserved.

Site MS5: Hotophia Creek near Batesville, Mississippi (northern Mississippi)

- Stone toe.
- Stone spurs.
- Live willow posts.
- Live siltation.

Sites MS1 through MS5 were suggested as typical of biotechnical stream bank treatments installed by many agencies throughout the Southeast (see Figure 2.3). A member of the research team has a unique historical perspective on these installations and notes that there are a number of open literature reports available covering design, installation, and monitoring of several of these sites. The research team member noted the following with reference to his knowledge and proximity to these sites:

Buttahatchee River. 600 ft reach, 85 miles away from Oxford, MS. Construction 2012. Erosion control blanket, stone toe, willow stakes, rootwads, VMSE. No transportation infrastructure. Limited description of project design details available. Continuous stage and discharge record at USGS gage about 20 miles upstream.

Goodwin Creek. 330 ft reach, 20 miles away from Oxford, MS. Construction 2007. Bendway weirs, stone-toe protection, cuttings (poles and stakes), and container plants. No transportation infrastructure. Design details and performance described in open literature. Heavy geotechnical analysis in design. Continuous discharge record from gage at nearby meteorological station, immediately downstream.

Harland Creek. 11,000 ft reach, 125 miles away from Oxford, MS. Construction 1994. Bendway weirs, willow posts, stone toe. Bridge downstream. Design details and performance described in open literature. USGS stage, discharge, and suspended sediment records through 2000 for gage about 4 miles downstream.

Hotophia Creek. 3,000 ft reach, 30 miles away from Oxford, MS. Construction 1992. Stone toe, stone spurs, post plantings, and post plantings above stone toe in a fashion similar to "live siltation." Centered on highway bridge. Design details and performance described in open literature. USGS stage and discharge record through 1997.

Sites representative of the Southeastern U.S. were visited September 9–10, 2014. Typical site photos are shown in Figure 2.3. Value was added to these site visits by the presence of the original project designers and planners within the visit party at all sites. One site included two projects in the same reach of the Buttahatchee River, so a total of five projects were inspected, with construction dates ranging from 1992 to 2012. Treatments included stone toe, bendway weirs, rootwads, erosion control blanket, willow posts and poles (planted in a variety of ways), live staking, rootstock plantings, VMSE, and bank resloping. All projects were subjected to significant high flows within two years of construction. Banks at all project sites were stable with little damage or outstanding maintenance observed. However, one project (Site MS1 on the Buttahatchee) exhibited very poor performance of planted vegetation due to infertile, droughty soils exposed by bank grading. Older projects tended to have lush bank vegetation and a high level of ecological functionality within the riparian zone, but planted willow (primarily *Salix nigra*) had given way to planted or volunteer river birch (*Betula nigra*) and sycamore (*Platanus occidentalis*). The dominance of sycamore was impressive. Success of woody vegetation at one site was severely limited by the exotic vine, kudzu (*Pueraria lobata*). Design and construction best practices were noted at all sites. For more details on a typical Southeast site see Section 2.5.

Copyright National Academy of Sciences. All rights reserved.

Site	Typical Before Project	Typical 2014 Conditions
Buttahatchee River Site MS1		
Buttahatchee River Site MS2		
Goodwin Creek Site MS3		
Harland Creek Site MS4		
Hotophia Creek Site MS5		

Figure 2.3. Task 6 field site visits—southeastern field sites.

Copyright National Academy of Sciences. All rights reserved.

Upper Midwest (Ann Arbor, Michigan)

Site MI1: Huron River (Nichols Drive), Ann Arbor, Michigan

- Rock vanes.
- VMSE.
- Chimney drains.
- Revegetation.

Site MI2: Huron River (Nichols Arboretum/River Landing) Ann Arbor, Michigan

- Vegetated riprap.
- Live fascine.
- ECB (erosion control blanket).
- Revegetation.

Site MI3: Huron River (Argo Cascades) Ann Arbor, Michigan

- ECB w/grass seeding.
- Boulder spurs.
- Stepped pools.

Site MI4: Fleming Creek, Northfield, Michigan

- Rock Vanes.
- Willow Pole planting.

Site MI5: Malletts Creek, Ann Arbor, Michigan

- Rock vanes.
- Coir logs.
- ECB w/live stakes.

The upper Midwest sites were suggested by a co-author of *NCHRP Report 544* in his response to the Task 2 survey. Follow-up phone conversations revealed that most of these sites are included in a text on bioengineering treatments and, as such, are very well documented. The text is entitled *Bioengineering Case Studies: Sustainable Stream Bank and Slope Stabilization* (Goldsmith, Gray, and McCullah 2014). The co-author noted that there are a total of 35 project case studies that are described and evaluated in the book from a retrospective point of view. Over a third of the case studies are stream bank protection or repair projects. At least five of these stream bank projects are located within a mile of the University of Michigan campus in Ann Arbor, and are (1) easily accessible, (2) have USGS stream gaging information, and (3) are well documented. For example:

Fleming Creek has substantial stream bathymetry data. The velocity field around the rock vanes was measured using an acoustic Doppler velocimeter.

Malletts Creek has a treated reach that is 1-½ miles long and consists of both conventional and bioengineered measures.

River Landing and Nichols Drive are both large projects located on the Huron River, a major river that runs through the city of Ann Arbor. Both sites can be accessed by a road that runs parallel and adjacent to the river.

Argo Cascades is also on the Huron River near Ann Arbor and provides the opportunity to document in-channel structures including boulder spurs and stepped pools.

One of the *NCHRP Report 544* coauthors volunteered to assist the research team in visiting and inspecting the Ann Arbor sites. Representative photographs from each site are shown in Figure 2.4.

Copyright National Academy of Sciences. All rights reserved.

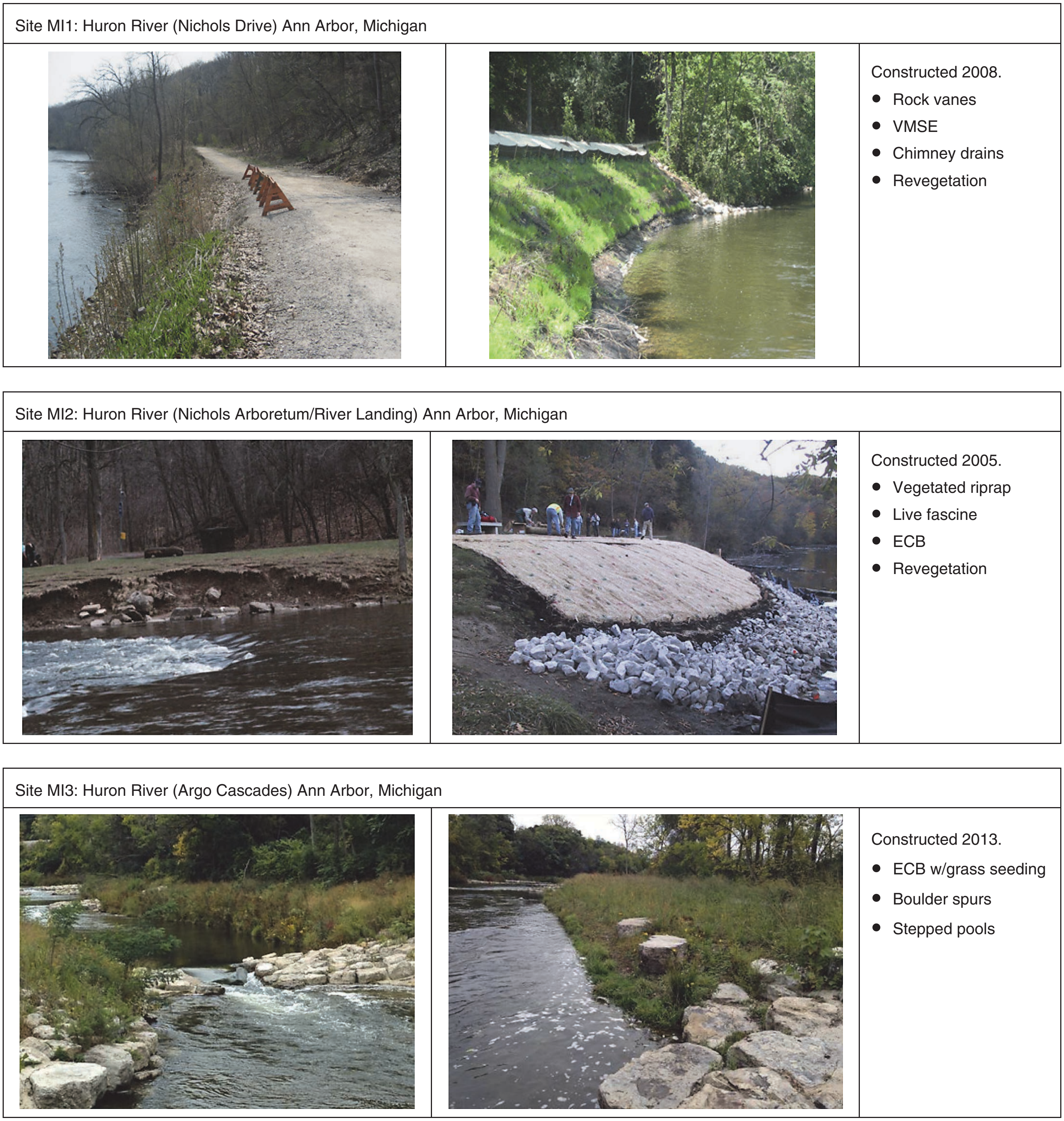


Figure 2.4. Task 6 field site visits—upper Midwest, Michigan field sites.

Copyright National Academy of Sciences. All rights reserved.

Site MI4: Fleming Creek, Northfield Township, Michigan

Constructed 2006.

- Rock vanes
- Willow pole planting

Site MI5: Malletts Creek, Ann Arbor, Michigan

Constructed 2011.

- Rock vanes
- Coir logs
- ECB w/live stakes

Figure 2.4. (Continued).

Five site visits were completed during the period October 1–2, 2014, for locations representative of the upper Midwest. All sites are in Ann Arbor, MI.

Conditions at Site MI2 on the Huron River are typical of those encountered during the Michigan site visits (see Figure 2.4). This site is also referenced as River Landing at Nichols Arboretum. The Nichols Arboretum project was intended to replace concrete rubble on the bank with a natural, less visually intrusive treatment with the help of trainees and volunteers. Another goal was to provide visitor access to the river at the site. Concrete rubble was removed from the site and the bank graded back to a stable 2H:1V slope. This project involved design of an environmentally sensitive, stream bank repair approach that also provides access to the river. The project provided hands-on opportunities for volunteer participation and training. Steps built into the bank at two locations in the protected reach now provide ready access to water's edge. For more details on the upper Midwest sites see Sections 2.5 and 4.4.

West Coast (Northern California)

Site CA1: Sacramento River at Sacramento, California (RM 47.0L and RM 62.5R)

- Large woody debris.
- Willow posts and poles.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

- Vegetated riprap.
- Soil and grass-covered riprap.

Site CA2: Lower American River (LAR) at Sacramento, California (RM 2.0L)

- Large woody debris.
- Willow posts and poles.
- Vegetated riprap.
- Soil and grass-covered riprap.

Site CA3: LAR at Sacramento, California (RM 6.9L)

- Willow posts and poles.
- Vegetated riprap.
- Soil and grass-covered riprap.

Site CA4: Alamitos Creek near San Jose, California

- Willow posts and poles.
- Live siltation.
- TRMs (turf reinforcement mats).

Site CA5: Guadalupe River near San Jose, California

- Willow posts and poles.
- Live siltation.
- Coconut fiber roll.
- Longitudinal logs at toe.

Site CA6: Russian River at Highway 128 (Geyserville Bridge)

- Large woody debris.
- Willow posts and poles.
- Live siltation.
- Longitudinal stone toe.
- Rock vanes.

The CA1 sites were implemented as part of the Sacramento River Bank-Protection Project on the Sacramento River and the LAR, California. Specific guidance was also provided for erosion sites located on the LAR, a tributary to the Sacramento River (Sites CA2 and CA3).

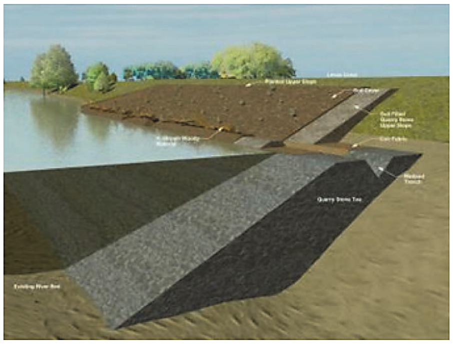
A special report on the "Guadalupe River Restoration Project: Biotechnical Channel Stabilization Solutions" (McCullah and Dettman 2004) was published and thus, the Guadalupe River site (CA5) is very well documented. In addition, the evolution of treatments at this site includes initial construction of treatment alternatives in 2002, failure of the initial approach, and reconstruction in 2003 using different techniques (which survived a large flood in 2004).

The Alamitos Creek and Russian River sites (Sites CA4 and 6), while some distance away from the Guadalupe River sites, offered the opportunity to evaluate alternative treatments (rock toe and rock barbs with willow siltation and staking), and TRMs in a different geomorphic setting. Representative photographs from each site are shown in Figure 2.5.

Six site visits were completed during the period October 21–22, 2014 for sites representative of the West Coast (Northern California).

Copyright National Academy of Sciences. All rights reserved.

Site(s) CA1: Sacramento River, California (two priority erosion sites downstream of Sacramento)



Constructed 2006.

- Rock toe with scalloped bench
- Instream woody material
- Live staking
- Container plantings
- Beaver fence (temporary)

Sites CA2 and CA3: LAR, Carmichael, California (two sites)

Constructed 1998.

- Rock toe with scalloped bench
- Instream woody material
- Live staking
- Container plantings
- Beaver fence (temporary)

Site CA4: Alamitos Creek near San Jose, California

Constructed 2010.

- Willow posts and poles
- Live siltation
- TRM
- Coir netting

Figure 2.5. Task 6 field site visits—West Coast (Northern California) field sites.

(continued on next page)

The Sacramento River and LAR sites represent a unique design that balances the need to upgrade protection at critical erosion sites on the Sacramento levee system with the requirement to enhance environmental/ecological values.

Regarding the Guadalupe River site, it was concluded in McCullah and Dettman (2004) that the restoration work performed in 2003 was extremely successful in stabilizing the slope. In April of 2004, the bank was becoming vegetated and the willows were successfully established at the toe. Combining techniques such as cobble revetment, live staking, pole planting, live siltation, hydroseeding, and coir blankets provided the stability, habitat, and aesthetic value needed for the site. For more details on a typical California site see Section 2.5.

Copyright National Academy of Sciences. All rights reserved.

Site CA5: Guadalupe River at Alma Road, San Jose, California

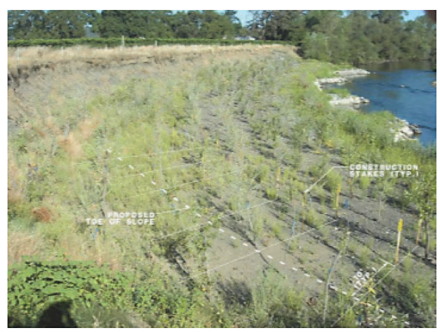
Constructed 2002.

- Log toe
- Coir wattle
- ECB
- Native grass vegetation
- Failed in 2002, redesigned and rebuilt

Reconstructed 2003.

- Rock toe
- Live siltation
- ECB
- Native grass vegetation
- Coir wattles and cutoff trenches
- Survived large flood in 2004

Site CA6: Russian River at Geyserville Bridge, SR 128, Geyserville, California



Constructed 2010.

- Rock toe
- Rock barbs
- Live siltation
- Live staking

Figure 2.5. (Continued).

2.5 Compendium of Field Data, Documentation, and Photographs

2.5.1 Introduction

Based on the data acquired from the Task 2 survey, and photographic and case history documentation from the Task 6 field investigations, a Compendium of biotechnical treatments in a searchable database format was developed. The Compendium represents a collection of the 16 field data forms from the site visits described in Section 2.4. The Compendium provides access to the full site visit report from each of the 16 site visits in addition to a variety of supporting data and documentation gathered during the site visits and could include (where available for a specific site):

- Design information,
- Presentations,
- Reports and published articles,
- Specifications,

Copyright National Academy of Sciences. All rights reserved.

- Spreadsheet files,
- Cost data, and
- Hydraulic and/or hydrologic data.

The Compendium has a graphical user interface (map) which directs the user to a specific site location and is presented in a searchable database format. Tables 2.10 and 2.11 illustrate the topics available for searching the Compendium database by both treatment type (Table 2.10) and site information available (Table 2.11).

The Compendium is provided with this Final Report as a companion to the detailed design guidelines in Chapter 4. As an introduction to the Compendium, the following section provides extracts of the information contained in a typical site visit report from each of the three regions referenced in Section 2.4. In addition, data and documentation from the Mallets Creek site visit in the upper Midwest region (see Figure 2.4, Site MI5) have been expanded to provide one of two application examples/case studies in Section 4.4.

2.5.2 Selected Findings on Environmentally Sensitive Treatments

Upper Midwest Region (Michigan)
Huron River, Nichols Arboretum Near Ann Arbor, Michigan

1. Purpose and Selection

The Huron River, which drains into Lake Erie, has a drainage area of 730 sq. miles, a daily mean stream flow of 380 cfs, and maximum recorded peak discharge at the site of 5,840 cfs (1918). Dams immediately upstream and downstream of the site tend to regulate flow and suppress peaks in this reach of stream. The river is also quite wide at the site, which tends to decrease velocity and depth of flow.

The Nichols Arboretum site (see Figure 2.4, Site MI2) is also referenced as the River Landing site. The site in question was one of the most heavily used and degraded sites in the University of Michigan Arboretum. It traditionally provides one of the main access and viewing points on the river. Bank erosion was a perennial problem at this site. Concrete rubble was placed on the bank in the 1970s in an attempt to control erosion. The rubble was unsightly, had exposed rebar, and was largely ineffective. Effective repair and restoration required removal of the rubble and replacement with a more natural bank-protection system.

The bank-protection project was completed with amenities that create a gathering place. Stone steps provide access to the water's edge. A rail fence along the top bank separates the heavily vegetated bank from a grassed picnic area with tables and shade trees.

The local USDA NRCS was looking for sites on streams that could be used as training exercises for county road department personnel. Cost for this site was reduced by this program and by use of project construction as an exercise for a training course offered by the arboretum.

The project was completed in October 2005. The project was tested by a flow of about 4,000 cfs in May 2011, which was the 14-year event based on the annual series.

The project was intended to replace the concrete rubble on the bank with a natural, less visually intrusive treatment. Another goal was to provide visitor access to the river at the site. Measures selected for implementation were compatible with construction (planting) by training course participants.

2. Design of System Components

The concrete rubble was removed and the bank graded back to a stable 2H:1V slope (see Figure 2.6).

Copyright National Academy of Sciences. All rights reserved.

Table 2.10. Treatment types.

Site Number	Site Name	Short Name	1 Live brush layering	2 VMSE	3 Large woody debris	4 Veg. gabions	5 Live staking	6 Willow posts and poles	7 Live siltation	8 Rootwad revetment	9 Live brush mattress	10 Veg. ACBs	11 Veg. riprap	12 Veg. gabion mattress	13 Soil and grass covered riprap	14 Live fascines	15 Coconut fiber roll	16 TRMs & ECBs
			Table 2.10. Treatment Types.															
1	Alamitos Creek - San Jose CA	Alamitos CA4						✓	✓									✓
2	Buttahatchee River - US HWY 45 - Columbus MS	Buttahachee MS1		✓			✓			✓			✓				✓	
3	Buttahatchee River - US HWY 373 - Columbus MS	Buttahachee MS2			✓			✓										
4	Fleming Creek - Dixboro MI	Fleming MI4						✓										
5	Goodwin Creek - Batesville MS	Goodwin MS3					✓	✓										
6	Guadalupe River - San Jose CA	Guadalupe CA5			✓			✓	✓								✓	
7	Harland Creek - Howard MS	Harland MS4						✓										
8	Hotophia Creek - Batesville MS	Hotophia MS5						✓										
9	Huron River - Argo Cascades - Ann Arbor MI	Huron MI3																✓
10	Huron River - Nichols Arboretum - Ann Arbor MI	Huron MI2					✓						✓			✓		✓
11	Huron River - Nichols Dr - Ann Arbor MI	Huron MI1		✓			✓											
12	Lower American River - RM2.0L - Sacramento CA	LAR CA2			✓			✓					✓		✓			
13	Lower American River - RM6.9L - Sacramento CA	LAR CA3						✓					✓		✓			
14	Malletts Creek - Ann Arbor MI	Malletts MI5					✓										✓	✓
15	Russian River - Geyserville CA	Russian CA6			✓			✓	✓									
16	Sacramento River - RM47.0L & RM62.5R - Sacramento CA	Sacramento CA1			✓		✓	✓					✓		✓			✓

Copyright National Academy of Sciences. All rights reserved.

Table 2.11. Site information available.

Site Number	Name	Short Name	Table 2.11. Site Information Available.						
			1	2	3	4	5	6	7
			Design Info	PowerPoint (in PDF format)	Reports	Specifications	Excel file (in PDF format)	Cost Data	Hydraulics and Hydrology
1	Alamitos Creek - San Jose CA	Alamitos CA4	✓	✓	✓				
2	Buttahatchee River - US HWY 45 - Columbus MS	Buttahachee MS1	✓	✓	✓	✓		✓	✓
3	Buttahatchee River - US HWY 373 - Columbus MS	Buttahachee MS2	✓	✓	✓			✓	✓
4	Fleming Creek - Dixboro MI	Fleming MI4	✓	✓	✓				✓
5	Goodwin Creek - Batesville MS	Goodwin MS3	✓	✓	✓			✓	✓
6	Guadalupe River - San Jose CA	Guadalupe CA5	✓		✓	✓			
7	Harland Creek - Howard MS	Harland MS4	✓		✓	✓		✓	✓
8	Hotophia Creek - Batesville MS	Hotophia MS5	✓		✓	✓			✓
9	Huron River - Argo Cascades - Ann Arbor MI	Huron MI3	✓	✓	✓	✓			✓
10	Huron River - Nichols Arboretum - Ann Arbor MI	Huron MI2	✓	✓	✓			✓	✓
11	Huron River - Nichols Dr - Ann Arbor MI	Huron MI1	✓	✓	✓			✓	✓
12	Lower American River - RM2.0L - Sacramento CA	LAR CA2	✓		✓				✓
13	Lower American River - RM6.9L - Sacramento CA	LAR CA3	✓		✓	✓			✓
14	Malletts Creek - Ann Arbor MI	Malletts MI5	✓	✓	✓			✓	✓
15	Russian River - Geyserville CA	Russian CA6	✓		✓	✓		✓	
16	Sacramento River - RM47.0L & RM62.5R - Sacramento CA	Sacramento CA1	✓		✓	✓	✓	✓	✓

Copyright National Academy of Sciences. All rights reserved.

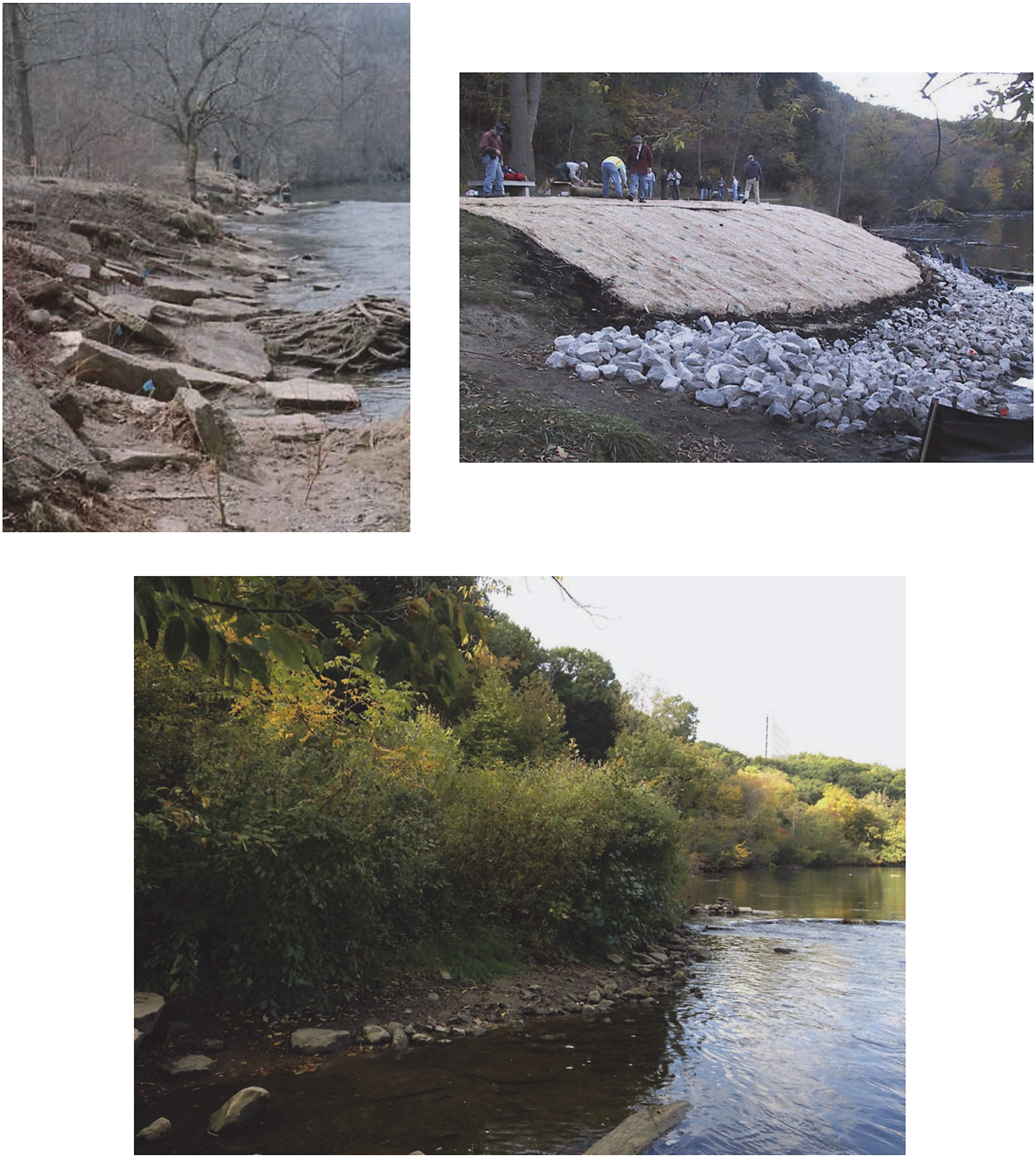


Figure 2.6. Huron River at Nichols Arboretum.

Copyright National Academy of Sciences. All rights reserved.

Vegetated riprap. The bank toe was armored with riprap. The riprap was vegetated using the joint-planting method, i.e., live stakes representing six to eight woody tree and shrub species were inserted between openings or interstices in the riprap: sandbar willow, red osier dogwood, ninebark, silky dogwood, and native roses. Not all stakes were dormant when planted. Some non-native white willow was also used, but the project coordinator said he would like to avoid using non-native species in the future.

Live fascine. A single fascine was placed above the riprap toe, running longitudinally. The bottom of the ECB was run into the fascine trench, and the fascine was anchored in the trench using both live stakes and lumber construction stakes.

ECB. An ECB was placed on the bank and up over the top. The blanket was anchored to the bank using staples and pegs. Topsoil was placed and spread over the bank before placing the ECB.

Revegetation. A seed mix of native grasses and plants was spread on the bank before placing the ECB.

3. Structural and Installation Guidelines:

Plant materials were harvested from nearby parks and soaked in barrels of water for about one week. Except for bank resloping and rock placement, all construction was completed in one day. Compost was spread on the new bank slope to fill the trench that was excavated to receive the live fascines. Teams of workers trimmed the plant materials, bound fascines on a rack made from lumber (like a sawhorse), and carried the material down the bank for installation. Considerable plant mortality occurred due to driving stakes through riprap. Many stakes were damaged (skinned, split) in that way.

After planting, no irrigation was provided for plantings. Fascines and stakes were on a lower bank, where soil moisture was higher. Plantings resulting from live fascines have required some cutting to maintain the view of the river from the recreation area on the top bank.

4. Construction and Maintenance Best Practices:

Some concern was expressed about the bank vegetation limiting access to the river. This concerned was allayed by constructing a set of stairs consisting of granite blocks from the top of the bank to water's edge. In addition, the top of the bank was planted with grass, and picnic tables were provided so visitors could enjoy riverine views.

Plants growing on this site have been used as a source of cuttings for other work. The vegetated bank has been maintained by some selective removal of large individual and invasive species to maintain plant diversity and views of the river from the picnic area on the top bank.

5. Performance, Failure Mechanisms, and Longevity

Vegetative establishment beneath the ECB and in the fascine has generally been excellent. The bank is now stable.

The live stakes in the riprap have not fared as well (see Table 2.12). Many stakes were damaged when driven through the rock blanket to plant them in interstices. A year after installation only

Table 2.12. Vegetative survival rates for 2006.

GENUS	RIPRAP (%) No. of Surviving Stakes (% of Planted Stakes)	FASCINE (%) No. of Surviving Stakes (% of Planted Stakes)
Cornus (dogwood)	26 (48)	14 (78)
Salix (willow)	13 (24)	3 (16)
Sambucus (elderberry)	15 (28)	1 (6)

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

about 30% of the live stakes survived and sent out shoots. The bent willow pole or willow bundle method, which eliminates many of the problems associated with the joint-planting method, should be considered in the future (see Section 4.3.3).

Red osier dogwood was the most successful species planted and was quite prolific when the site was inspected in 2014.

The riprap toe has survived several high-water events but has not been tested by floods approaching peak flows of record.

This project is a good example of an environmentally sensitive, stream bank repair approach that also provides access to the river. The project has provided hands-on opportunities for volunteer participation and training. Steps built into the bank at two locations in the protected reach now provide ready access to water's edge.

The project resulted from planning and cooperation on the part of personnel from the University of Michigan, the city of Ann Arbor, Washtenaw County Road Commission, a private consulting firm, and the NRCS.

6. Cost and Availability

Only ~$30,000 due to the magnitude of in-kind contributions and NRCS assistance.

7. Ecological Issues

Exotic European alder becoming a nuisance.

8. Assessment of Functionality During October 2014 Site Visit

Aquatic ecosystem functionality and recovery is limited by a dam located up- and downstream from this site. However, these dams ensure vertical channel stability and sharply limit water-level fluctuations, which greatly facilitates revegetation of treated stream bank. The river level fluctuates only about 3 ft. Minor sediment deposition was noted where a large gully system entered the channel. Invasive exotic woody species (buckhorn, honey suckle, European alder, black locust) compete with planted native species. The site was evaluated as "functional at risk" with an upward trend (improving) in functionality.

9. Published Documentation/Sources/Citation

Goldsmith, W., Gray, D.H., and McCullah, J., 2014. *Bioengineering Case Studies: Sustainable Stream Bank and Slope Stabilization*, Springer Verlag, New York.

Lawson, R., Bouma, D., Olsson, K., Rubin, L., and Powell, E., 2008. *Watershed Management Plan for the Huron River in the Ann Arbor—Ypsilanti Metropolitan Area*, prepared on behalf of and with funding support from Janis A. Bobrin, Washtenaw County Drain Commissioner, Huron River Watershed Council, Ann Arbor, MI.

Southeast Region (Mississippi)
Buttahatchee River Near Columbus, Mississippi

1. Purpose and Selection

At this site, bendway weirs were selected as a robust but cost-effective way to protect the eroding bank along a very narrow strip of land dividing the channel of the Buttahatchee River, which provides valuable habitat, from a large, abandoned gravel pit (see Figure 2.3 Site MS2). Several old floodplain gravel pits have captured portions of the river in this reach, to the detriment of habitat quality and overall channel stability. The project was constructed under a United States Fish and Wildlife Service (USFWS) program in 2012.

Copyright National Academy of Sciences. All rights reserved.

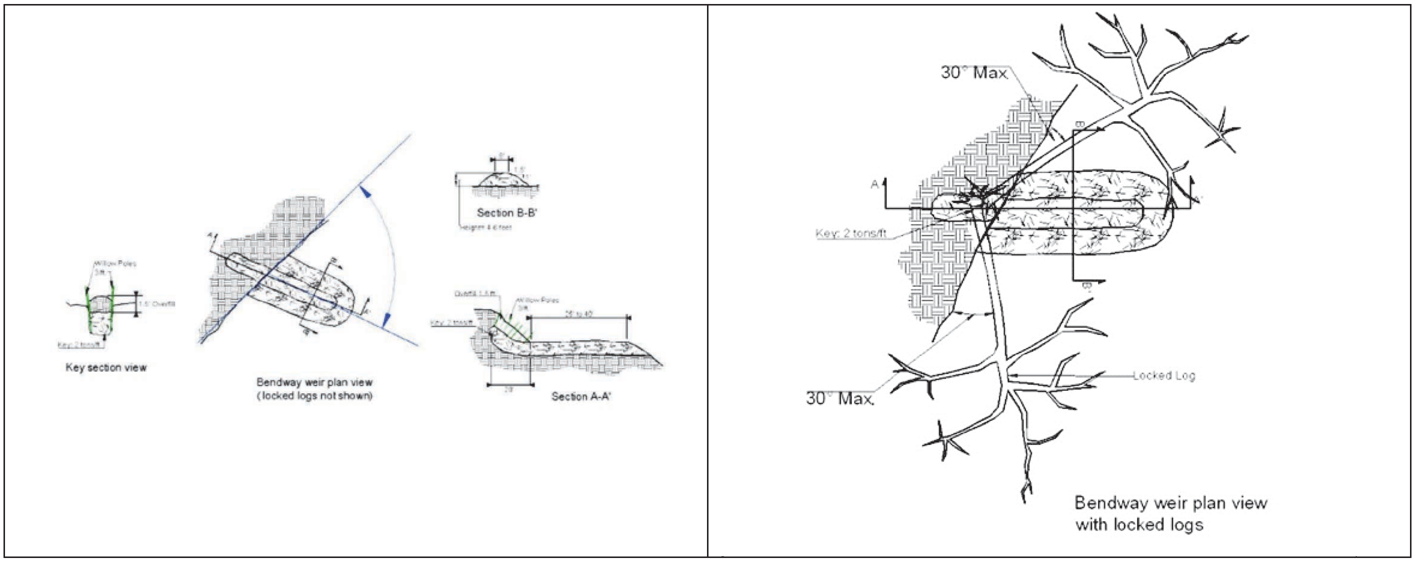


Figure 2.7. Bendway weirs with locked logs at Buttahatchee River site.

2. Design of System Components

The functionality of the bendway weirs at this site was enhanced by the addition of embedded large wood “locked” logs (Figure 2.7).

- Weir crest width = 4 D_{100} (8–10 ft), where D_{100} is the maximum stone size. Some of the crests here were even wider to allow machine access down the crest for stone placement during construction.
- Gage records show water near the top bank during January, March, and April 2011 (Figure 2.8). The January 18, 2013, peak flow of 15,100 cfs was slightly greater than one-year discharge from USGS Streamstats of 11,600 cfs.

3. Structural and Installation Guidelines

Start and end protection at stable points—these usually are located at the extreme ends of the bendway.

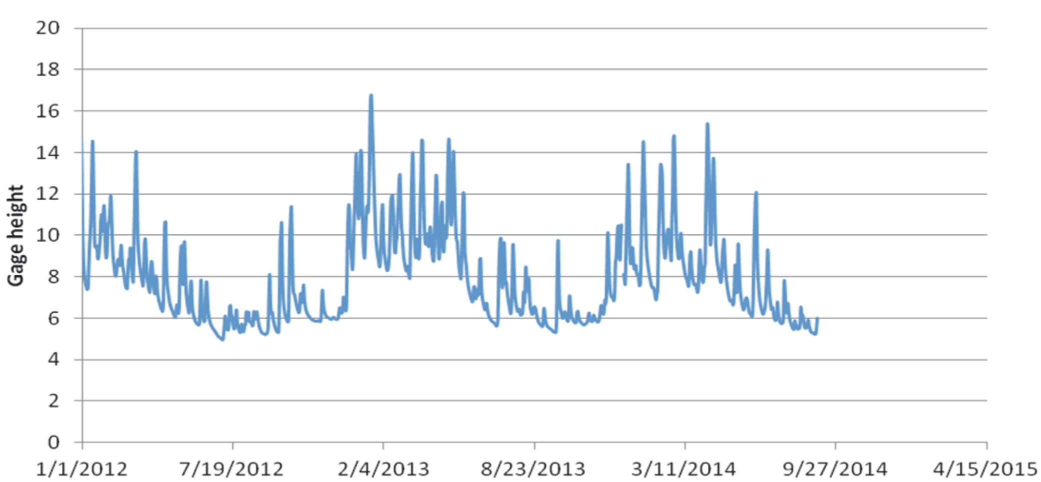


Figure 2.8. Stage hydrograph for Buttahatchee River near Aberdeen. Mean daily stage for inspection of date of September 9, 2014 was 5.44 ft.

Copyright National Academy of Sciences. All rights reserved.

50 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

4. Construction and Maintenance Best Practices

- Construction of weirs should proceed by constructing the weirs located at the upstream and downstream ends and the one in the middle to establish "line of control" riverward tips. Remaining weirs are then constructed from upstream to downstream.
- Avoid wood (locked logs) projecting above waterline that will trap more debris.
- "Locked logs" are constructed by placing logs with rootwad near the location for the bendway key and placing logs pointing downstream at an angle of between 20 and 70 degrees from the bank depending on local conditions. Locked logs were also placed with upstream angles between 20 and 40 degrees (see Figure 2.7). Then stone for the bendway weir is placed on top of the rootwad and lower part of the tree trunk to anchor them securely. These locked logs resist ice removal in northern rivers—ice freezes around them first.

5. Performance, Failure Mechanisms, and Longevity

- Most of the 2012 willow planting did not succeed. Willow cutting survival has been slightly better on the upper and middle banks.
- Hardwood tree rootstock planted in early 2014 with plastic tree protectors. These are cylindrical plastic enclosures about four inches in diameter with perforations in the sides near the top or bottom of the tube. Haul road planted with hardwoods and native grass plugs (mossy oak).
- Rock volume required to complete the project was twice the estimate due to sinking and erosion.

6. Cost and Availability

- Contractor: $102,000.
- Rock; $89,000.
- Design; $13,000.
- Planting; $12,500.
- LiDAR; $22,000.
- Planning, preliminary designs, permits, etc.; $48,160.

TOTAL: $287,520

7. Ecological Issues

The USFWS re-surveyed mussels (earlier done in 1989) finding strong recovery with threatened and endangered species in a riffle just downstream from this site.

8. Assessment of Functionality During September 2014 Site Visit

Bendway weirs and locked logs have provided aquatic habitat diversity and cover, and appear to be stable and functioning well. Bank revegetation is proceeding slowly. A few of the willow cuttings have survived and are growing slowly, perhaps due to herbivory. Planting stock (see Walter et al. 2013 below) on the top bank and haul road are surviving at present, but are less than one year old. The site was evaluated as "functional at risk" with an upward trend (improving) in functionality.

9. Published Documentation/Sources/Citation

Pollen, N., Simon, A. Klimetz, L., and Klimetz, D., 2005. "Stability analysis of the Buttahatchee River Basin, Mississippi and Alabama," Watershed Physical Process Research Unit, National Sedimentation Laboratory, Oxford, MS. Prepared for Mississippi Department of Environmental Quality.

Walter, W. D., Godsey, L. D., Garrett, H. E., Dwyer, J. P., Van Sambeek, J. W., and Ellersieck, M. R., 2013. "Survival and 14-Year Growth of Black, White, and Swamp White Oaks Established as Bareroot and RPM®-Containerized Planting Stock," *Northern Journal of Applied Forestry*, 30(1), 43–46.

Copyright National Academy of Sciences. All rights reserved.

West Coast (Northern California)
Lower American River Near Sacramento, California

1. Purpose and Selection

This project is part of the Sacramento River Bank-Protection Project on the Sacramento River and the LAR, California. This project for the USACE, Sacramento District provided design guidance for bank (levee) protection measures at critical erosion sites to be constructed on both the Sacramento River and the LAR, a tributary to the Sacramento River. This site on the LAR served as a basis for the design of future bank-protection sites along the LAR (Site RM 2.0L—see Figure 2.5 Sites CA2 and CA3). Hydraulic analyses were conducted to provide information necessary for the design of bank-protection measures (velocities, shear stresses) and to analyze the impact of the designs on hydraulic conditions and flood conveyance. A two-dimensional model was created representing the lower 15 km of the LAR. The model was used to analyze both existing and project conditions.

The bank-protection and mitigation design concepts developed represented the state of the art in balancing flood control and environmental needs along the LAR. Innovative features include water-side low berms for the establishment of native terrestrial vegetation and irregular shorelines providing hydraulic variability for fisheries habitat. The result is a highly complex riprap design.

This site is approximately 2,200 ft. in total length and the bank-protection and mitigation features were constructed in 1999. The site is bound by four bridges: N 12th Street/Hwy 160, Lincoln Hwy, Pedestrian, and R/R. Mitigation features include instream woody material (IWM), an undulating, cobble-lined, low-berm soil trench, and plantings on the low-berm, middle-berm, and upper-slope planting surfaces (see Figure 2.9).

The onsite design includes a variety of surfaces capable of supporting vegetation; low river-side berms (small constructed floodplains) with varying berm-surface elevations and shoreline configuration as well as woody materials submerged in constructed embayments or smaller bank scallops (see Figure 2.10). Native woody and herbaceous riparian vegetation was planted on an engineered soil trench placed in the revetment at the site (including a low-berm face, low berm, lower slope, upper slope, and middle berm) with the goal of creating a self-sustaining, mixed canopy riparian forest and riparian scrub habitat, shaded riparian aquatic (SRA) habitat, and valley elderberry longhorn beetle (VELB) habitat.

Project goals included:

- Geotechnical stability for bank and levee,
- Environmentally self-mitigating,

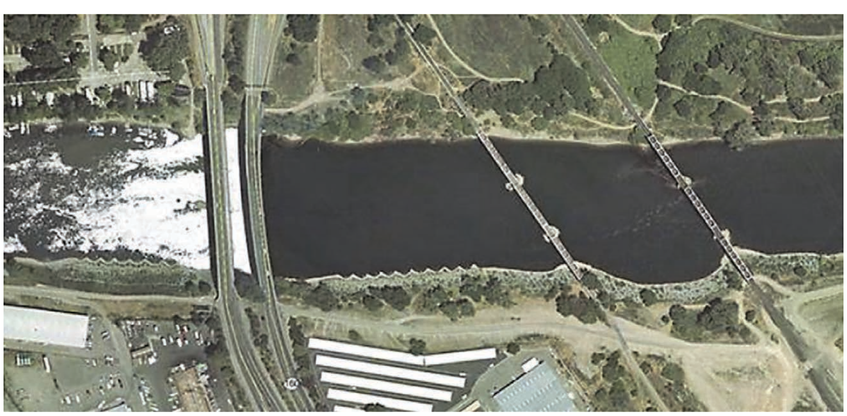


Figure 2.9. 2002 aerial photo of LAR reach RM 2.0L.

Copyright National Academy of Sciences. All rights reserved.

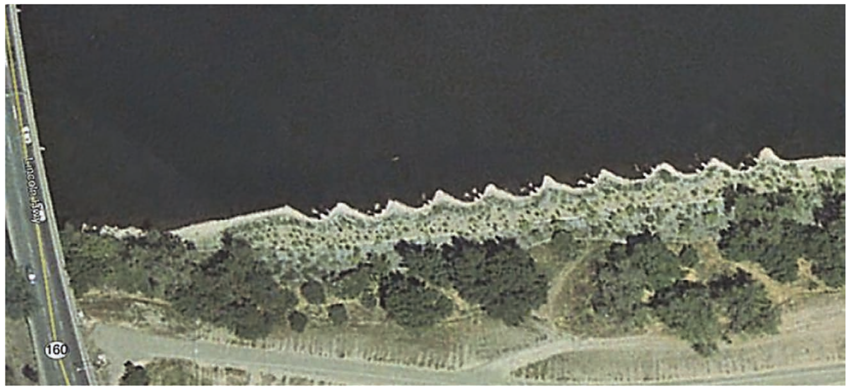


Figure 2.10. 2001 Aerial photo—close-up of embayments with woody material embedded in riprap at LAR Reach RM 2.0L.

- No impact on flood capacity, and
- Erosion protection (high-energy environment).

2. Design of System Components

- 2-D Hydraulic Model (pre- and post-project),
- Topographic and bathymetric surveys,
- Slope stability analysis,
- Multiple benches for habitat enhancement,
- Lower benches submerged at specific environmental flows, and
- Embayments along lower bench for fish habitat (Figure 2.11).

3. Structural and Installation Guidelines

USACE Standard Specifications (included in data and documents folder for this site in the Compendium).

Figure 2.11. 2001 photo looking downstream at LAR reach RM 2.0L.

Copyright National Academy of Sciences. All rights reserved.

4. Performance, Failure Mechanisms, and Longevity

Excellent performance—strong local sponsor [Sacramento Area Flood Control Agency (SAFCA)] ensured adequate follow-up and vegetation maintenance.

Reducing beaver pruning of planted trees (in particular cottonwood) and shrubs on the berm face and low berm remains the greatest challenge to meeting SRA habitat goals. Due to the age of the beaver fence, the fence is becoming brittle, providing easier access to the site by beavers. During 2010, linear beaver fence maintenance and cage installation and relocation continued to be important management actions to minimize beaver damage to vegetation. This strategy proved successful and limited further tree losses or damage at these sites, as well as other sites where cages were previously installed.

5. Cost and Availability

Unknown

6. Ecological Issues

Bank-protection construction resulted in the loss of riparian, SRA, and special-status species habitat. Several mitigation measures were incorporated into project designs, including a variety of surfaces capable of supporting vegetation, low riverside berms (small constructed floodplains) with varying berm-surface elevations and shoreline configuration, and woody materials submerged in constructed embayments or smaller bank scallops. Native woody and herbaceous riparian vegetation was planted on revetment (including a low berm face, low berm, lower slope, upper slope, and middle berm) with the goal of creating a self-sustaining, mixed canopy riparian forest and riparian scrub habitat, SRA habitat, and VELB habitat.

7. Assessment of Functionality During October 2014 Site Visit:

Vegetation at this site continued to grow well and many native plants, including cottonwood, alder, box elder, rose, and sandbar willow are naturally regenerating on the low berm (see Figure 2.12). Protecting the vegetation at this site from beavers has been an ongoing challenge and has required intensive beaver fence maintenance. Maintenance actions include repairing and replacing sections of fence that are in disrepair due to both natural degradation of the fencing over time and vandalism. This site has not received supplemental irrigation since 2004 and yearly monitoring confirms that the plants at this site have successfully established. Colonization by non-native woody vegetation is minimal at this site but was removed when found. This site was evaluated as "functional" during the 2014 site visit.

Figure 2.12. 2011 photo looking downstream at LAR reach RM 2.0L.

Copyright National Academy of Sciences. All rights reserved.

8. Published Documentation/Sources/Citation

SAFCA 2010 Annual Report (December 2010)—Lower American River Sites Year 11, Mitigation Monitoring Report, Bank-Protection Sites: 1–5, Offsite Mitigation Areas: RM 0.9R, RM 3.3R, 11.6R, Sacramento Area Flood Control Agency, Sacramento, CA.

2.5.3 User Guide for the Compendium

A brief step-by-step guide to using the Compendium is provided below:

1. Make sure you have an active connection to the Internet.
2. Insert the accompanying disk into your computer.
3. Open the SiteBrowser by clicking on the Field Site Map (NCHRP-Oct202015.htm) button from the disk menu screen. A map of the United States will pop up with pointers showing the location of each of the 16 field sites.
4. You can use your mouse to pan and zoom in on a group of sites and click on a pointer to see which site it is pointing to. Alternatively, if you have perused Tables 2.10 and 2.11 of this document and know which site you would like to navigate to, you can click on the site name in the pane on the right-hand side of the map and it will take you to the appropriate pointer.
5. Once a site pointer is selected, click on the Data Folders link to gain access that site's comprehensive data. Then, by clicking on the "Docs & Supporting Data" folder, you'll have access to all the available information for that site. By clicking on the "Site Visit Field Form" folder, you can examine the detailed field visit notes, sketches, and assessments performed by the research team for the site visit performed at this site as part of this research project.
6. Alternatively, to access the site data folders directly, click on the Field Site Date Folder (NCHRP_Data) button from the disk menu screen. You'll have access to the "Docs & Supporting Data" folders and the "Site Visit Field Form" folders from here.

To access the Compendium database in Microsoft Access™, click the Field Site Searchable Database (NCHRP_Oct20-2015) button. The database contains the following four tables:

- **Bank-Protection Treatments:** This table simply contains a cross-reference to abbreviations for the 16 different types of treatments used as column headings in other tables.
- **Field Sites:** This table contains the site name, a short name, and the latitude-longitude coordinates of each of the 16 field sites.
- **Site Treatment Types:** This table contains the various types of bank-protection treatments found at any particular field site. Many sites consist of more than one treatment. This table is identical to Table 2.10 in Section 2.5.1.
- **Site Information Available:** This table contains the various types of information available for each site (e.g., design information, PowerPoint presentations, documents from the literature, etc.). This table is identical to Table 2.11 in Section 2.5.1.

By using the database's structured query language (SQL), you can create a specific query to develop a list of sites that have certain attributes of interest. For example, if you wanted a list of sites where live staking AND vegetated riprap was used, AND for which design information AND specifications are available, an appropriately structured query would provide a short list containing the following sites:

Site Number	Name	Short Name
2	Buttahatchee River—US HWY 45—Columbus, MS	Buttahatchee MS1
16	Sacramento River—RM47.0L & RM62.4L—Sacramento, CA	Sacramento CA1

Copyright National Academy of Sciences. All rights reserved.

2.6 Summary of Findings and Observations from Current Practice

2.6.1 Literature Review

Since publication of the results of NCHRP Project 24-19 by McCullah and Gray (2005), numerous reviews, handbooks, and measure-specific guidance documents for environmentally sensitive bank protection have been published by federal, state, and local agencies. These documents emphasize the steps describing various measures and provide construction or installation guidance. Similarly, large numbers of case studies of biotechnical bank-protection projects have appeared, but few contain hydraulic data. Hydraulic design criteria are scarce and with few exceptions rely on the literature that was summarized within the NCHRP Project 24-19 products. The data underlying the hydraulic criteria are drawn from a variety of sources and vary in quality from qualitative anecdotal rules of thumb to detailed laboratory measurements. Many are based on isolated spot measurements of velocity.

Considerable progress has been made in recent years in understanding the biology of riparian plants and developing technology for improving planting success. Limited but important advances have been made in understanding and simulating the complex fluid mechanics of open-channel flows adjacent to vegetated banks. Slope stability models have been modified to include contributions of roots to soil strength, and such models are becoming more widely employed.

Over the past 10 years, publications dealing with stream erosion control, riparian zone and floodplain restoration, and interactions among plants, slope stability, and stream hydraulics have multiplied prolifically. Applied literature includes how-to guides, handbooks, case studies, and other studies and documents focused on the performance of a specific measure (e.g., willow stakes or rootwads). A subset of these documents is composed of guidelines and research reports on techniques for handling plant materials (e.g., soaking or refrigeration) to improve survival and performance. Most of the applied literature has been published by governmental agencies and not in peer-reviewed scientific or engineering journals. Much of the content in these documents is duplicative or redundant.

Another class of documents consists of guidelines for designing or constructing a single type of environmentally sensitive bank-protection technique. Although guidance may be gleaned from case studies that feature a specific technique, single-measure guidelines are primarily directive in nature and do not relate experience at a single site or group of sites. Typically such guidelines focus on construction details: how to prepare the site and materials and assemble or plant them to produce a finished project.

To date, case studies have provided a higher level of reality than model studies or laboratory experiments, but are difficult to generalize for application to other sites due to site-specific conditions, short periods of observation or insufficient data to fully characterize the erosional processes. Most of the flume experiments (and associated numerical modeling) have assumed a uniform stand of bank vegetation that does not vary its characteristics in the lateral direction even though natural riparian vegetation and biotechnical bank-protection measures usually feature different types of protection for the bank toe, mid bank, and upper bank. Interactions between riparian vegetation and stream channel morphology have been studied at larger scales using statistical approaches by fluvial geomorphologists (e.g., Bledsoe et al. 2011). Increasingly sophisticated numerical models (e.g., computational fluid dynamics) have been used to extend and complement field and laboratory results across a range of spatial scales.

In a particularly relevant example, Rahmeyer and Werth (1996) and Freeman et al. (2000 and 2004) reported results of over 220 flume experiments involving 27 different real plant types and groupings. In-channel (not stream bank) vegetative flow resistance was found to decrease with

Copyright National Academy of Sciences. All rights reserved.

velocity and depth for submerged plants but to increase with depth for emergent plants. Flexible, submerged plants with leaves formed a streamlined (teardrop) shape that reduced the flow forces on the plants, protecting leaves and smaller stems from breakage. Minimum plant velocity limits of 3 to 4 fps (0.9 to 1.2 mps) were observed for leaf failure, and most of the leaf and stem failures were the result of impact with bed material and debris. Stands with more or less uniform canopy geometry concentrated flow underneath the canopy, resulting in general scour.

Stream banks erode or retreat due to fluvial erosion processes, sliding or mass wasting, and combinations of these processes. Scientists have long realized the links between vegetation and bank slope stability, but since publication of McCullah and Gray (2005), several important advances have been made in development of analytical techniques. For example, work by Pollen (2007) has advanced understanding of temporal and spatial variability in root reinforcement due to variations in soil type and moisture, and work by her team has shown that soil-root matrices are better simulated by fiber-bundle models that allow progressive failure of roots (weakest first) rather than the "all-roots-break-instantaneously" assumption of the older perpendicular models. The fiber-bundle model algorithm has been incorporated into the BSTEM, a spreadsheet tool used to simulate stream bank stability (see Section 4.2.4).

2.6.2 Observations from Current Practice

Both the survey of practitioners (Task 2) and the site visits conducted under Task 6 of this study provide fertile ground for insights on current practice for environmentally sensitive treatments. For the treatment components tested under Task 7 (live staking, live siltation, rock toe, VMSE) observations on current practice are summarized in Sections 4.5.2 and 4.5.3 in relation to the design guidelines presented in Section 4.3. Additional examples of current practice can be found in the application case studies presented in Section 4.4. Both a humid region example and an arid region example were chosen to illustrate the integration of hydraulic engineering analysis and design with the multidisciplinary approach necessary to achieving success with a river restoration project. The examples involve the cooperative efforts of multiple agencies and the challenges of meeting stakeholder goals and expectations. In both cases monitoring and maintenance issues are addressed and lessons learned are summarized.

Copyright National Academy of Sciences. All rights reserved.

CHAPTER 3

Testing and Appraisal of Testing Results

3.1 Overview and Selection of Treatments for Testing

3.1.1 Overview

As noted in Section 2.6.1, a wealth of literature and documentation is available regarding environmentally sensitive stream bank protection measures. However, most of the information regarding biotechnical measures is composed of case studies of particular sites that have, in many cases, limited general applicability. Furthermore, these case studies usually have a shortage of quantitative data regarding the hydraulic, hydrologic, climatic, and geotechnical conditions surrounding the tested sites. Advances in understanding the performance of nonliving bank-protection materials and structures have been based on laboratory flume tests that allow greater control and data acquisition than for field sites, but few of these experiments involved plant materials. Some tests have been conducted with grass-lined channels or with artificial plants made of wooden dowels, plastic strips, or other materials to investigate interactions between plants and the flow field. However, due to the difficulty of conducting scaled tests with real plants in available hydraulic laboratory flumes, only limited work has been done with real plants other than grass. Task 7 of this research addressed this deficiency by conducting well-planned, carefully controlled flume tests in the unique facilities at CSU.

During Task 7, prototype-scale laboratory testing of selected biotechnical engineering treatments was conducted in the large (20 ft wide by 180 ft long) outdoor flume at CSU. Initially, the treatments were installed in large trays and nurtured in CSU's climate-controlled greenhouses, which provide customized light, temperature, and humidity conditions for year-round establishment and growth of many different types of vegetation. When vegetation was established to a predetermined condition, the trays were moved into the large outdoor flume for testing under the desired hydraulic conditions.

3.1.2 Proposed Treatments for Laboratory Testing

Tests focused on two representative biotechnical measures that were constructed with real plants in large planter boxes (6 ft wide by 20 ft long by either 12 or 18 in. deep). Plant materials were given time to establish on the banks of an experimental trapezoidal channel prior to testing. A variety of environmentally sensitive bank-protection measures were considered as potential candidates for testing at prototype scale at CSU. Due to cost considerations, only two treatments could be accommodated under this research project. Therefore, the various treatments presented in *NCHRP Report 544* (McCullah and Gray 2005) were carefully evaluated from the perspective of having wide applicability across the nation, as well as practical issues of:

- Constructability,
- Physical testing requirements/constraints,

Copyright National Academy of Sciences. All rights reserved.

- Quantitative measurements of key hydraulic variables, and
- Condition monitoring of each component before testing and after each test flow event.

The two biotechnical bank-protection treatments suggested to, and approved by, the NCHRP Project 24-39 panel for testing were:

1. Live siltation with live staking and rock toe at a 3H:1V slope (Tray 1).
2. VMSE also referred to as FES lifts in this case at a 2H:1V slope (Tray 2).

Figure 3.1 shows CSU's greenhouse facility and vegetated trays used in the laboratory testing program.

The willow components of these treatments were harvested locally and consisted of *Salix exigua* (also known as sandbar willow, narrowleaf willow or coyote willow), a shrub-type willow that is common to riparian corridors throughout most of the United States. *Salix exigua* has been specifically designated by the NRCS Plant Materials Program as well suited for erosion control:

> Sandbar Willow is used for stream bank and lake shore stabilization and riparian area development or restoration. It is recommended for deep wet lowland, overflow areas, wet meadow sites, stream banks, lake shores, and other areas with a high water table. (USDA 2007)

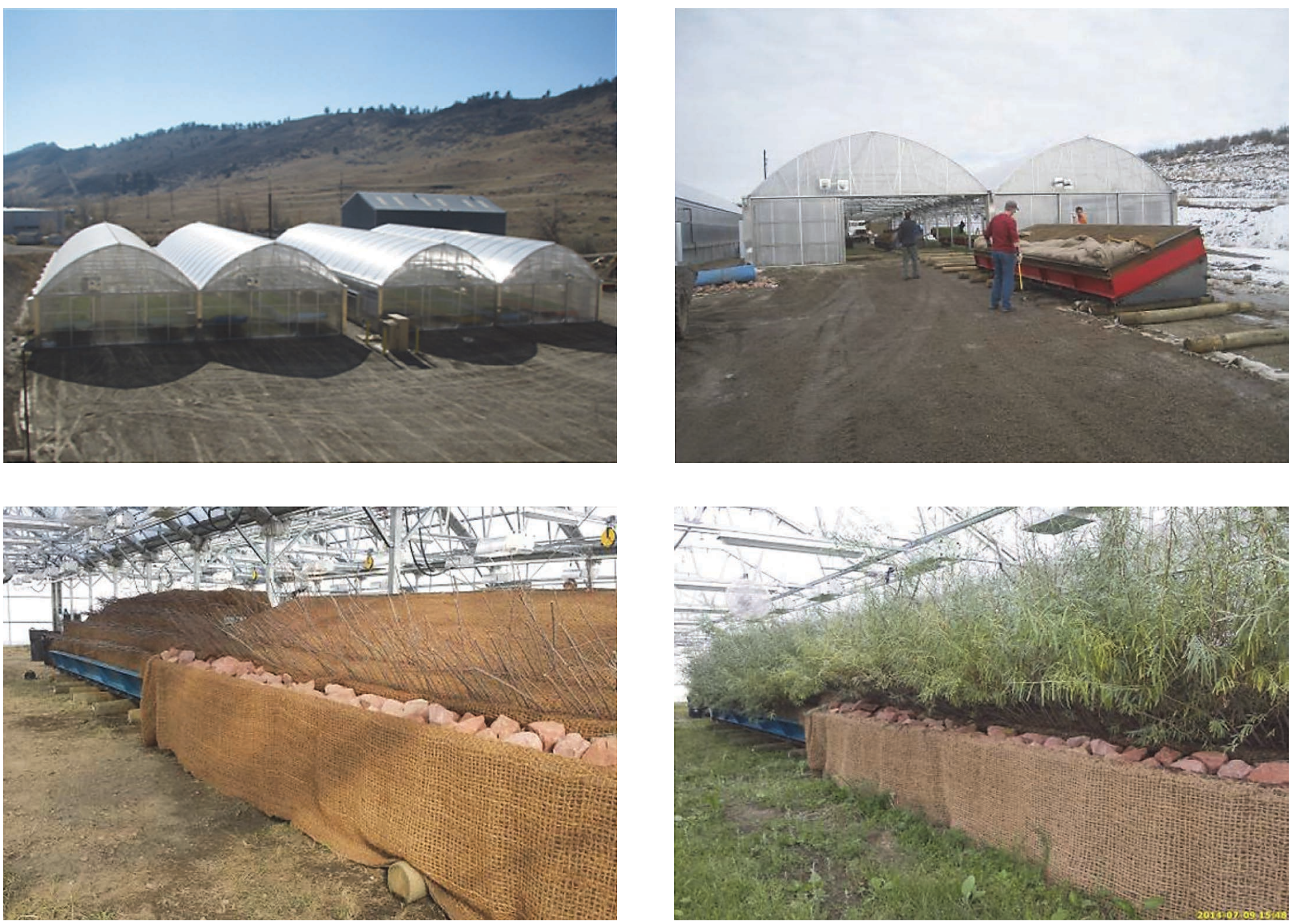


Figure 3.1. (Upper) Climate-controlled greenhouses at CSU's hydraulics laboratory. (Lower) Trays 1 and 2 inside the greenhouse.

Copyright National Academy of Sciences. All rights reserved.

Figure 3.2. **Salix exigua** ***on Fossil Creek, Fort Collins, Colorado.***

Figure 3.2 shows native *Salix exigua* at a local site in Fort Collins, Colorado, from which the cuttings for the test installations were obtained.

The two treatments described above, including planter box (tray) dimensions, are shown in Figures 3.3 and 3.4. The rationale for selecting these two treatments is discussed in detail in the following section. The approach adopted for prototype-scale laboratory testing of the selected bank-protection measures is presented in Section 3.2.

3.1.3 Selection of the Task 7 Testing Treatments

All aspects of the proposed testing program were considered in selecting the two biotechnical treatments recommended, including physical restrictions of the greenhouse facilities where the treatments were to be grown, transport to the outdoor flume for testing, and the physical constraints of the outdoor testing flume. The 44 treatments in *NCHRP Report 544* (McCullah and Gray 2005) were reviewed and initially narrowed to 18 candidates. Based on the objectives of NCHRP Project 24-39, treatments that are intended to address geotechnical processes or that are redirective in nature (e.g., some river training structures) were eliminated from consideration, leaving only continuous techniques that protect the bank against fluvial erosion.

For the Task 2 survey (see Section 2.3) the initial list of 18 *NCHRP Report 544* treatments included live gully repair and joint planting. On closer examination, live gully repair was considered to be somewhat out of the scope of a stream bank protection project, as this treatment represents an application to halt or repair local erosion of the stream bank in a confined area (i.e., a gully) rather than an extended bank-protection treatment. Furthermore, joint planting was considered to be a variation of vegetated riprap, which was on the list for the survey, with the difference being that for joint planting the vegetation would be inserted in the joints of an existing riprap treatment as opposed to be being installed at the time of riprap installation for vegetated riprap. The hydraulic signature of both treatments would be similar once the planted or inserted willows in the stone have reached maturity. Accordingly, vegetated riprap was retained as a candidate but joint planting was eliminated which narrowed the "short list" to 16 treatments.

Details on these 16 treatments for stream bank protection are summarized in Appendix A with reference to the McCullah and Gray (2005) findings regarding availability of hydraulic design data (hydraulic loading), common reasons for failure, and research opportunities/needs

Copyright National Academy of Sciences. All rights reserved.

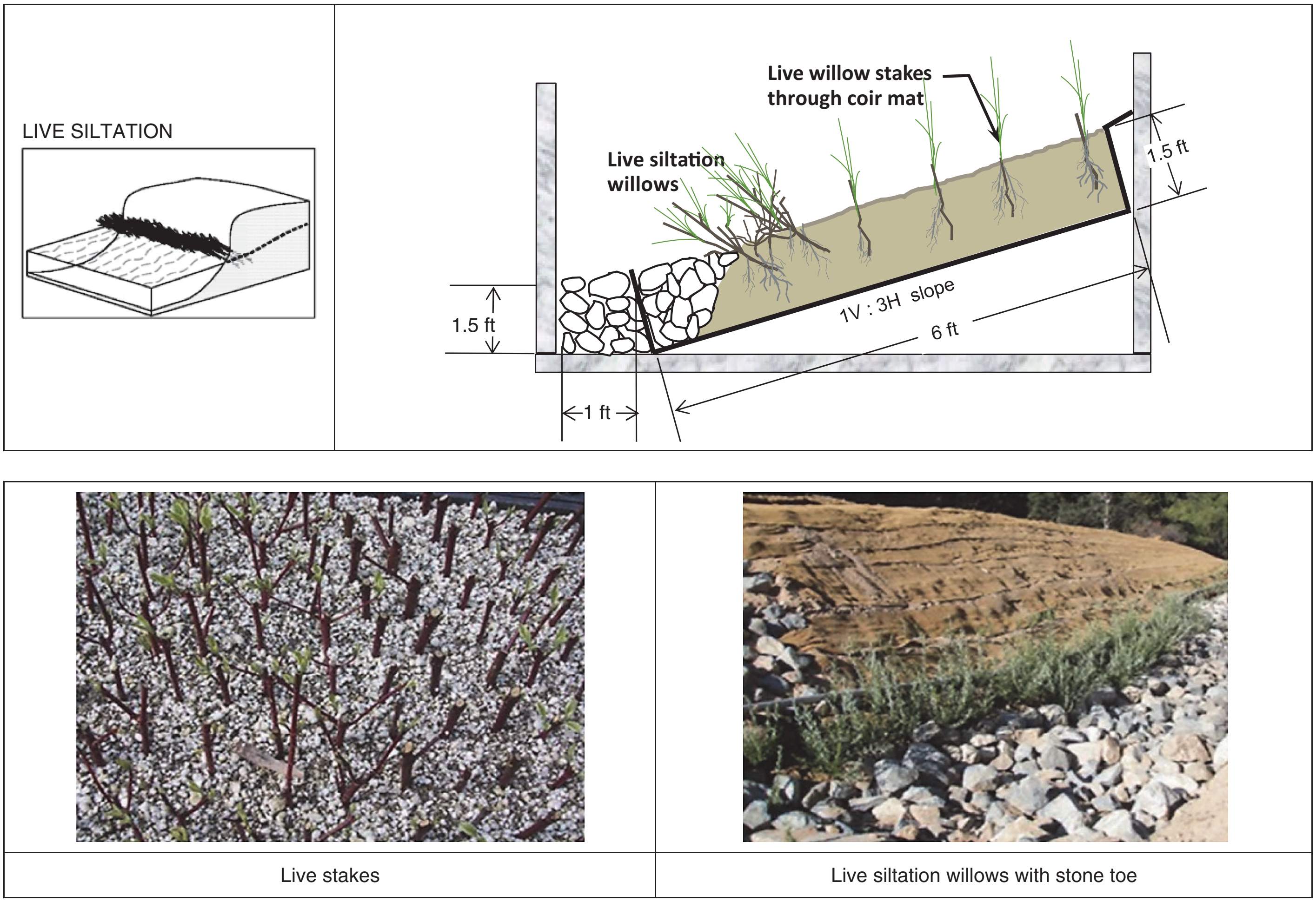


Figure 3.3. Live siltation with live staking and stone toe.

identified in *NCHRP Report 544.* All of these factors as well as the extensive experience of research team members in designing, installing, and monitoring numerous biotechnical treatments in the field, in addition to agricultural engineering and vegetation planting and survivability concerns, were considered in the selection of the two treatments proposed for testing.

The planter trays that have previously been constructed at CSU for the USACE levee overtopping testing are 6-ft wide, 20-ft long, and 12-in. deep. To avoid substantial construction costs it was imperative to keep within these basic dimensions for this project's testing. The requirement to roll the trays out of the greenhouse and move them by crane approximately 250 ft to the outdoor flume also needed to be considered in terms of tray strength, lifting weight, and the 20-ft wide by 180-ft long dimensions of the flume. In developing the testing program, the discharge limit of about 150 ft^3/s for the flume also had to be kept in mind. To this end, a hydraulic calculation spreadsheet was developed to provide discharge, velocity, and shear stress ranges for various configurations of the trays in the flume.

An additional concern was the practicality of growing willows in a live siltation or staking configuration in a 12-in. deep soil lift. To accommodate a concern that the willows may become "root bound" the tray depth for the stone toe/live siltation configuration (Figure 3.3) was increased to 18 in. The increased soil depth increased the weight of the trays and required reinforcing of the USACE's configuration. This also created a challenge for lifting and positioning the trays

Copyright National Academy of Sciences. All rights reserved.

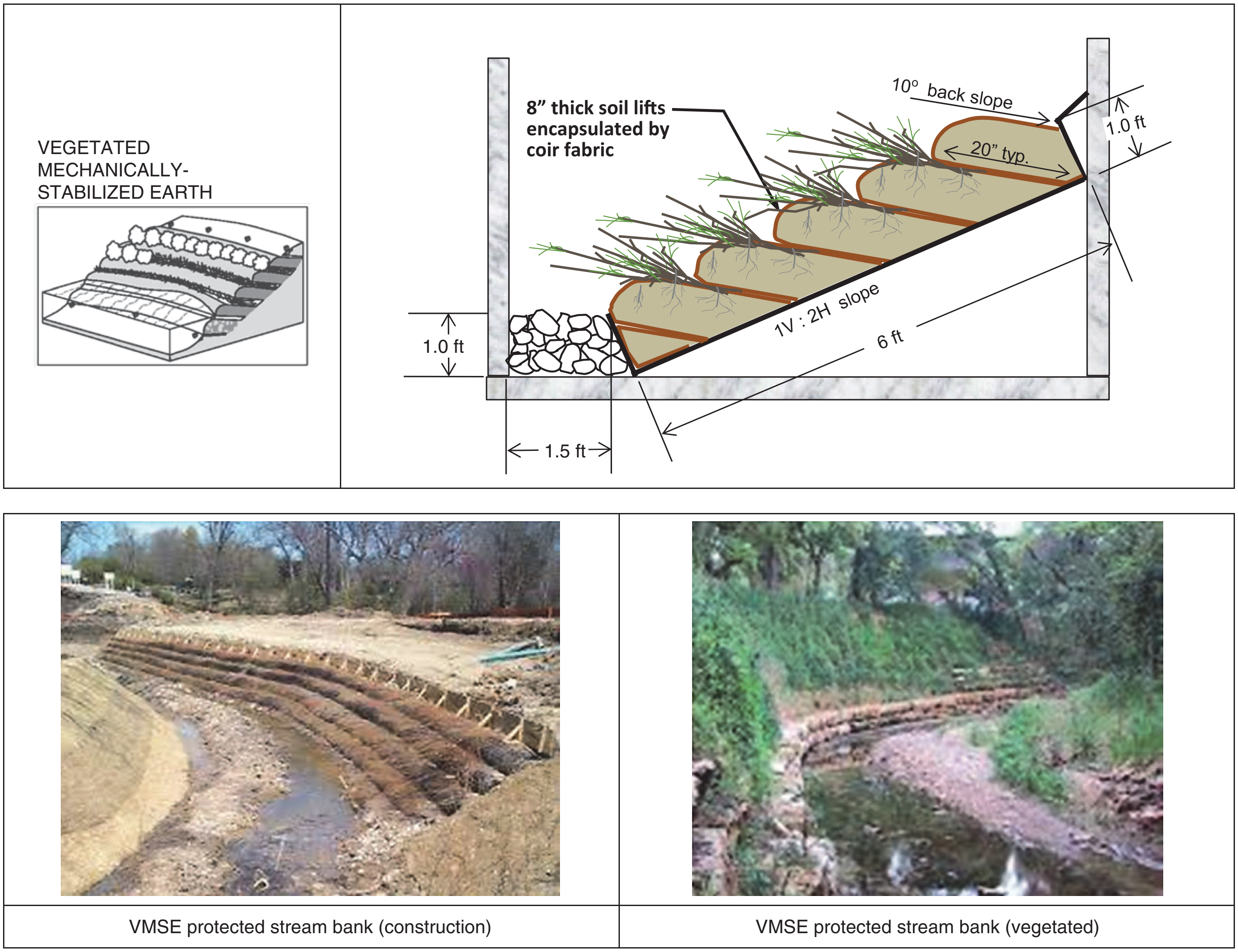


Figure 3.4. VMSE.

in the testing flume. To keep Task 7 testing within the constraints of the planned budget the VMSE treatment was installed in an existing 12-in. deep tray (see Figure 3.4).

In addition, the treatments needed to be grown in the greenhouse with the trays at the same slope as they will have in the flume so that the orientation of the willow plantings as they grow is consistent with the orientation that would be expected if they were planted in a field installation. This required some additional framing in the greenhouse facility, as the USACE's treatments consist of various species of turf grass that are grown with the trays in a horizontal position. Also, the plantings needed to be rooted to a depth of about 2/3 of the height of the plant protruding into the flow to preclude physical pull out of the vegetation by hydraulic forces.

As noted by Gray (2002):

> A conflict appears to exist between engineering requirements to compact soil to a high density to improve its engineering properties—such as increased strength and decreased compressibility—and agronomic needs to maintain soil in a relatively loose condition to improve its ability to support vegetation. This conflict or contradiction, while real, has been misunderstood and overstated. The objectives of compaction from an engineering perspective have frequently been obscured in a manner that makes accommo-

Copyright National Academy of Sciences. All rights reserved.

dation for plant-growth needs more difficult to achieve. Furthermore, vegetation can be grown successfully in compacted soil under less-than-ideal conditions provided certain limits and precautions are observed.

Based on guidance in the article quoted above and Goldsmith et al. (2001), the following criteria for soils in the treatment testing trays were followed:

1. Plants need soils compacted to less than 90% of the standard Proctor maximum dry density, with best conditions in the 80% to 85% range.
2. To retain hydraulic conductivity, soils should be compacted dry of optimum moisture content.
3. Absolute densities that limit plant growth vary by soil texture. Sandy soils can be denser. In general, growth limiting bulk densities are 87 lb/ft^3 for clay soils and 106 lb/ft^3 for sandy soils.

With the physical constraints of the system identified, the treatments were considered from the perspective of having the widest applicability as prototypes or components of treatments that might be installed nationwide. The final considerations for the two recommended treatments involved both a review of the research needs identified in *NCHRP Report 544* (see this report's Appendix A) and the experience of the research team regarding resource agency preferences as they have evolved as well as treatments that are currently being used in the widest variety of applications.

The *Hydraulic Engineering Circular No. 23* design guidelines for FHWA (Lagasse et al. 2009) and the guidance in *NCHRP Report 544* indicate emphatically that, just as with traditional hard engineering treatments, the key to success for any treatment is that the toe must not fail if the treatment is to succeed. Consequently, it was desirable to test at least one treatment with a rock toe. It was also important to have a treatment that was composed of multiple components in an upslope direction. Transitions between components strongly influence the progressive roughness response from the high-velocity flow or splash zone to the less aggressive hydraulic conditions of the upper-bank slope zone. The detailed measurements in the flume provide insight on the hydraulic effects of these transitions, which are applicable to treatments composed of multiple material types.

The initial concept for the stone-toe treatment was to transition from the stone-toe to willows and then to turf grass on the upper slope; however, from a species survivability point of view it was noted that as the willows mature they tend to shade and override the turf grass, making this a less than desirable combination. In addition, willows for live siltation and willow staking are becoming much more frequently used across the country (see Table 2.8). Accordingly, for this configuration it was decided to place the willows above the stone toe in a live siltation orientation and replace the turf grass concept for the upper slope with live willow stakes through a coir mat (see Figure 3.3). The hydraulic data from testing this configuration had broad applicability to either multi-component systems or treatments using just individual components (i.e., simply using live siltation or willow staking alone) for stream bank protection.

The second proposed treatment recognizes that many resource agencies tend to prefer a treatment without any rock component. A treatment without a hard toe incorporating soil lifts and willow plantings is described in *NCHRP Report 544* as VMSE as shown in Figure 3.4. The FES lifts can be tested within the confines of a treatment tray on a 1V:2H slope. A 10-degree back slope on the soil lifts was suggested and, to prevent pull out, the coir fabric would normally extend deeper into the embankment than would be possible with the trays; but, fastening the fabric to the tray base would prevent pull out and will not affect the hydraulic response and data acquired for this treatment. Since the resource agencies tend to discourage rock, and, in some cases, actually prohibit rock, testing the hydraulic limits of this second configuration would have wide potential applicability and interest.

Appendix A contains a summary of both the hydraulic design data available in, and research opportunities recognized by, McCullah and Gray (2005) for the 16 treatments that were considered.

Copyright National Academy of Sciences. All rights reserved.

Several of the research opportunities that were addressed, at least in part, by the two treatments selected for testing under NCHRP Project 24-39 are summarized below:

Live Siltation—Research into velocities that this technique can withstand would be helpful.
Live Staking—Studies would be valuable regarding the effect live staking has on increasing the ability of other measures to withstand higher velocities and shear stresses.
VMSE—Some uncertainty exists at present as to the exact permissible shear stresses and velocities for VMSE interfaces. Additional research would also be helpful on the nature of the interaction between roots and fabric and root architecture and distribution in VMSE structures.

Since Task 7 was restricted by the available budget to testing only two treatments in the laboratory, the two treatments selected had the widest applicability to other treatment approaches and addressed a number of research needs identified in *NCHRP Report 544.* In reviewing the "short list" of 16 treatments from *NCHRP Report 544*, the Task 7 testing provided information relevant to live brush layering, VMSE, live staking, live siltation, live brush mattresses, live fascines, and ECBs. Thus, the treatments selected for Task 7 testing provided currently unavailable hydraulic design data related to seven of the 16 treatments. This maximized the return on the investment in the laboratory testing task of this research.

3.2 Laboratory Testing Plan

The steps involved in installing, testing, and evaluating the bank-protection treatments shown in Figures 3.3 and 3.4 are described in this section.

3.2.1 Installation

1. The soil, rock, and coir fabric required for each specific treatment were installed in large planter trays in the CSU climate-controlled greenhouse (see Figure 3.1).
2. Live (dormant) willow cuttings, ⅜ to ⅝ in. diameter, were delivered to CSU in January, 2014. The cuttings were soaked for 3 weeks in aerated water at 37-degrees Fahrenheit prior to installation in the trays.
3. Soil used for the installation consisted of custom blended 20% compost, 40% sand, and 40% topsoil, measured by volume. A compost sample was delivered to the researchers on December 19, 2013. A compost maturity index of 7 on the Solvita scale was measured on December 26, 2013. Thus, the compost met the requirement of a "maturity index of 6 or greater as measured by the Solvita scale" (Brewer 2001).
4. Sand consisted of fine aggregate as defined by AASHTO standard M6. Grain size distribution (GSD) and Unified Soil Classification System (USCS) classification (SM—silty sand) were determined by an independent geotechnical firm. The median grain size was 0.73 mm.
5. The loamy topsoil component was screened through a 2.3 mm sieve to remove all large particles and deleterious materials. The resulting soil was approximately 68% sand and 32% silt and clay, and was classified as a sandy loam/loamy sand as defined by the USDA soil triangle.
6. Compost, sand, and loamy topsoil were combined at a 1:2:2 ratio by volume in a large container and blended until uniformly mixed. This mixing procedure was repeated until enough soil was obtained. A sample of this material was subjected to washed sieve analysis (ASTM C117 and C136), Atterberg limits (ASTM D4318), and Standard Proctor Density (ASTM D698) tests. The blended soil properties are:
   - D_{50} = 0.43 mm where D_{50} is the median particle size.
   - Liquid Limit = 28%.
   - Plastic Limit = 10%.
   - Plasticity Index = 18%.
   - Maximum Standard Proctor Density = 116 lb/ft^3.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

7. Both Trays 1 and 2 were outfitted with substantial drainage ports in the bottom to allow for proper soil drainage. One inch of pea gravel was placed in the bottom of the box as an underdrain. A permeable geotextile was placed over the gravel layer to prevent migration of soil into the underdrain. The custom blended soil was then placed in 6-in. lifts and compacted to a target density of 83% ± 3% of Standard Proctor Density.
8. The willow cuttings were installed in the trays in early February 2014 and allowed to establish over a 7-month period. The soil in the trays was kept moist (but not saturated) using both drip and mist-type irrigation. The temperature was maintained at 80 to 90-degrees Fahrenheit, 75% or greater relative humidity, under grow lights that remained on approximately 16 hours per day for the first 8 weeks to ensure good establishment.
9. Tray 1: Willow spacing in Tray 1 consisted of two rows of live siltation willows. The first was placed immediately above the rock toe at a 45-degree angle to the plane of the slope, with cuttings spaced 2 in. apart. The second row was placed 1 ft upslope from the first. Live willow stakes were installed by piercing the ECB and hammering a metal stake (approximately 0.5-in. diameter) through the soil to create a pilot hole to the bottom of the box. Willow stakes were then inserted into the pilot holes.

   On the upper part of the slope, cuttings were placed in rows with 2-ft longitudinal spacing and 1-ft spacing up the slope in a staggered pattern. On this part of the slope, 10-in. long soil staples were added to hold the ECB in place. The staples were hand driven throughout the upper area of live staking at the same spacing as the live stakes (2-ft horizontal, rows offset 1-ft vertical) with the staples located midway between the willow cuttings. Cuttings were embedded the full 18-inch depth of Tray 1. Figure 3.5 shows the completed installation in Tray 1.
10. Tray 2: Willow spacing in Tray 2 consisted of rows of cuttings spaced 2 in. apart. Each row was sandwiched between successive lifts of fabric-wrapped soil 8 in. thick, having a back slope of 10 degrees into the slope. No soil staples were used in Tray 2. Cuttings were embedded the full 12-in. depth of Tray 2. No cuttings were placed into the top of the uppermost lift, nor into the vertical face of any lift. Figure 3.6 shows the completed installation in Tray 2.
11. Measurements of plant growth and root establishment for the vegetation were performed after 3 months and again after 7.5 months to ensure that a representative canopy and root system had established prior to testing. Figure 3.7 provides photographs of willow growth

	
Tray 1 willow installation. Note rock toe in tray.	Tray 1 willow installation showing growth after 4 weeks.

Figure 3.5. Tray 1 installation.

Copyright National Academy of Sciences. All rights reserved.

Tray 2 willow installation. Note no rock toe and no planting into top of uppermost lift.

Tray 2 willow installation showing growth after 4 weeks.

Figure 3.6. Tray 2 installation.

determination and Table 3.1 presents the results of oven-dried weights of the biomass of the various above-ground and below-ground components.

12. After full willow establishment, the trays were moved by crane and placed in the outdoor River Engineering Flume at CSU with associated upstream and downstream transition sections, each 20-ft long, which provided artificial roughness elements to condition the flow entering and leaving the test section. The longitudinal slope along the test section and exit transition was 4.0%.
13. Between the toe of the tray and the flume wall, a layer of 6 in. D_{50} riprap was placed and grouted to establish a "stream bed." The riprap was approximately 1 ft wide for the Tray 1 installation, and 1.5 ft wide for the Tray 2 installation.

Growth after 3 months.

Growth after 7.5 months.

Figure 3.7. Willow growth determination.

Copyright National Academy of Sciences. All rights reserved.

Table 3.1. Willow growth after 3 months and after 7-½ months.

Component	Weight After 3 Months of Growth (grams)	Weight After 7.5 Months of Growth (grams)
Total biomass	506.3	1052.4
Above-ground biomass:	252.4	412.3
1. Leaves/shoots (new growth)	123.9	199.1
2. Original cuttings	128.5	213.2
Below-ground biomass	253.9	640.1
1. Roots (new growth)	94.8	277.1
2. Original cuttings	159.1	363.0
Ratio, new growth to original cuttings	0.76	1.28
Ratio, roots to shoots	0.77	1.39

Note: Weights after oven drying at 160 degrees Fahrenheit.

14. Between the top edge of each tray and the opposite flume wall, metal flashing was used to seal the gap between the tray and the wall. The flashing was covered with a strip of coir fabric to give it the same roughness as the rest of the bed surface. Figure 3.8 shows both Trays 1 and 2 installed in the flume, prior to testing.

3.2.2 Testing Protocols and Data Collection

1. Cross-section surveys were performed prior to testing at pre-established transects located 4, 8, 12, and 16 ft downstream from the upstream edge of the test tray.
2. The flume flow and stoplog tailgate were adjusted (when necessary) to achieve the desired flow conditions. Three discharges were examined:
   a) A relatively low "mean annual" discharge of 50 cfs which only partially submerged the stream bank;

Tray 1 (looking upstream).	Tray 2 (looking downstream).

Figure 3.8. Trays 1 and 2 prior to testing.

Copyright National Academy of Sciences. All rights reserved.

b) An intermediate flow rate of 100 cfs which just reached the top of the stream bank; and
c) A "design" discharge of 150 cfs that fully submerged the entire bank slope.

3. During each flow, 1-D point velocity measurements were taken at each transect at 20%, 60%, and 80% of the total flow depth, and also as close to the bed as possible. The measurements were made at approximately 1-ft intervals across each cross section.
4. During each flow, 3-D acoustic Doppler velocimeter measurements were taken near the bed at selected locations where the probe could be positioned within the submerged willow vegetation.
5. After each flow, each treatment was examined for any damage to its various components (e.g., loss of vegetation, movement of rock, or soil loss) and cross-section surveys were repeated at each of the four transects.

3.3 Tray 1 Testing—Live Siltation and Live Staking with Riprap Toe

Testing of the prototype-scale willow treatments was conducted at CSU's hydraulics laboratory during August and September 2014. Tray 1 was craned into place in early August 2014 and tested August 11–13. The water temperature during all tests remained at 45 to 46 degrees Fahrenheit. A summary of the three tests (Test Numbers 1 through 3) is provided below, and Figure 3.9 provides photographs of the tests in progress. Discussion of the data analyses and results is provided in Section 3.5.

Test 1 was conducted on August 11, 2014 with the 3H:1V test section installed in the flume. The test discharge of 50 cfs ran for approximately 4.5 hours. The water surface came just to the top of the test tray but did not reach the flume wall on the upslope side of the test section. The live siltation willows along the lower portion of the slope were inundated and pronated in the flow, but the live staking willows on the upper portion of the slope remained upright for the duration of the test.

Test 2 was conducted on August 12, 2014. Discharge through the test channel was 100 cfs and was sustained for 4 hours. Water reached the flume wall at the top of the slope, which inundated the top of the test tray to a depth of about 0.3 to 0.5 ft. Willows were pronated approximately two-thirds of the way across the flume.

Test 3 was conducted on August 13, 2014, and was run for 4 hours at 150 cfs. Water reached the flume wall at the top of the slope, which inundated the top of the test tray to a depth of about 1.0 to 1.2 feet. Virtually all of the willows were pronated into the water during Test 3 (two stems at the top of the slope near cross section XS16 did not pronate).

Erosion during Tray 1 tests: Overall, very little erosion occurred during Tests 1, 2, and 3 on Tray 1. On average, the elevations measured at the predetermined transects after Test 1 were 0.01-ft higher than the pre-test survey, indicating that overall, little or no soil material was lost from the test section. Some migration and rearrangement of soil beneath the coir/jute ECB was observed after each test, with local areas exhibiting, at most, 0.13 ft of degradation after Test 3; other local areas exhibited as much as 0.18 ft of aggradation. No damage to the coir/jute fabric was observed after completion of the three tests.

3.4 Tray 2 Testing—VMSE Without Hard Toe

After the third and final test on Tray 1, it was removed from the flume and Tray 2 was installed. Tray 2 was tested during the period September 4–11, 2014. The water temperature during all tests remained at 45 to 46 degrees Fahrenheit. A summary of the three tests (Test Numbers 4 through 6)

Copyright National Academy of Sciences. All rights reserved.

Tray 1, Test 1 (50 cfs) looking upstream

Tray 1, Test 2 (100 cfs) looking upstream

Tray 1, Test 3 (150 cfs) looking downstream

Tray 1, post-test inspection after Test 3

Figure 3.9. Tray 1 during testing.

is provided below, and Figure 3.10 provides photographs of the tests in progress. Discussion of the data analyses and results is provided in Section 3.5.

Test 4 was performed on September 4, 2014 for a duration of 4 hours. A free fall occurred at the downstream end of the exit section. The discharge was approximately 50 cfs, with water reaching midway up the vertical face of the uppermost soil lift. The lowermost two rows of willows were pronated, while the uppermost two rows remained upright.

A tear in the coir fabric, along with localized depressions indicating soil loss beneath the fabric at other locations, began forming on the test section during Test 4. The tear occurred in the face of the lowermost soil lift and was located 8 ft downstream of the upstream edge of Tray 2. The tear resulted in a 3-in. by 5-in. hole with 3 in. of soil loss measured back into the face of this lift, but was not apparent on the top surface of the lift.

Copyright National Academy of Sciences. All rights reserved.

Tray 2, Test 4 (50 cfs) looking downstream

Tray 2, Test 5 (100 cfs) looking downstream

Tray 2, Test 6 (150 cfs) looking downstream

Tray 2, post-test inspection after Test 6

Figure 3.10. Tray 2 during testing.

Test 5 was conducted on September 9, 2014 with a discharge of 100 cfs. Duration of the test was 4 hours. After Test 4, stoplogs were installed to a height of 17.5 in. above the flume floor to raise water levels on the exit section and the test section. Water completely inundated the test section and steel flashing, reaching the flume wall at the top of the slope and inundating the uppermost soil lift to a depth of about 0.8 to 1.0 ft. All the willows were pronated during this test except for a small group in the vicinity of cross section XS16 near the downstream end of the test section.

A new, 3-in.-deep hole in the coir fabric formed during Test 5 in the top surface of the fourth soil lift approximately 6.5 ft from the upstream edge of the test section. The hole that was present in the face of the bottom soil lift after Test 4 was enlarged during Test 5, growing to 15 in. in length with a depth of about 4 in. Both large and fine willow roots were exposed in this hole, and the top surface of the soil lift began showing a depression. During Test 5, a significant amount soil within the uppermost soil lift was washed out, although no tears in the fabric were observed.

Copyright National Academy of Sciences. All rights reserved.

Test 6 was conducted on September 11, 2014 at a discharge of 150 cfs for a duration of 4 hours. The stoplogs used in Test 5 were left in place for Test 6. The water surface completely inundated the test section to a depth of 1.2 to 1.4 ft above the uppermost soil lift and all willows were completely pronated during the test. Soil fill within the uppermost tier (Tier 5) was almost completely washed away after Test 6, but no tears in the coir fabric were observed.

On the fourth soil lift, the hole at 6.5 ft from the upstream edge was enlarged from the top surface into the vertical face. Depressions in the coir fabric up to 4 in. deep indicated soil loss at local areas, either on the top surface, the vertical face, or both. Erosion along the bottom soil lift included the major hole at 8 ft, with 6 in. of erosion into the face of the soil lift and further depression of the top surface.

Erosion During Tray 2 Tests. During Test 4 on Tray 2 (50 cfs), little erosion occurred. The average erosion depth when compared with the pre-run survey was 0.02 ft. During the test, willows were pronated up to the second tier. However, it was noted that local tears and holes in the fabric, as well as other areas of soil loss depressions, began forming on the test section during Test 4, the largest of which was a 3-in. by 5-in. hole in the ECB with approximately 3 in. of soil loss. This hole was located on the bottom tier, 8 ft downstream of the upstream edge of the tray.

Holes present after Test 4 were enlarged during Test 5 and grew even larger during Test 6. Both Tests 5 and 6 exhibited significant soil loss, and additional areas of damage to the fabric were observed. The photo in the lower right of Figure 3.10 shows a hole that began forming during Test 5 in the top of the fourth tier approximately 6.5 ft from the upstream edge of the test section. That hole grew to about 3 in. deep during Test 6 (shown in Figure 3.10) and the soil was eroded behind the ECB forming the vertical face of the soil lift.

The hole in the face of the bottom soil lift grew to approximately 15 in. long after Test 6, with a depth of as much as 6 in. in places. This hole was located approximately 6 to 8 ft downstream of the upstream edge of the tray. Both fine and large willow roots were exposed in the hole.

It is important to note that topmost (fifth) soil lift was entirely submerged during Tests 5 and 6. No vegetation was planted into the top surface of this lift, and most of the soil fill within this lift was washed out after Test 6. In Section 3.5, erosion contour maps for each test, created from post-test surveys at predetermined transects, clearly show the overall erosion patterns as well as localized areas of soil loss whether due to tears/holes in the coir fabric or soil washout beneath the fabric.

3.5 Testing and Data Summary

3.5.1 Calibration of Manning n Values

Measured water surface elevations in the vegetated test sections of Trays 1 and 2 were used to calibrate HEC-RAS models of each test. Fixed flume components (flume walls and rock riprap stream bed) were modeled using estimated Manning n values of 0.015 and 0.035, respectively. The artificial roughness of the upstream approach section was modeled assuming a Manning n ranging from 0.055 to 0.08 to match the upstream water surface elevation measured by CSU.

The vegetated slope of the test section was modeled using a Manning n value that was adjusted by trial and error to achieve the best fit to the observed water surface for all of the tests. Figures 3.11 and 3.12 show the results of the calibration efforts for Trays 1 and 2, respectively. The distance between HEC-RAS computational cross sections ranged from 0.5 to 1.0 ft.

In general, the Manning n resistance coefficient was found to be significantly higher for Tray 2 compared to Tray 1. This is presumably due both to the overall density of the cuttings used between

Copyright National Academy of Sciences. All rights reserved.

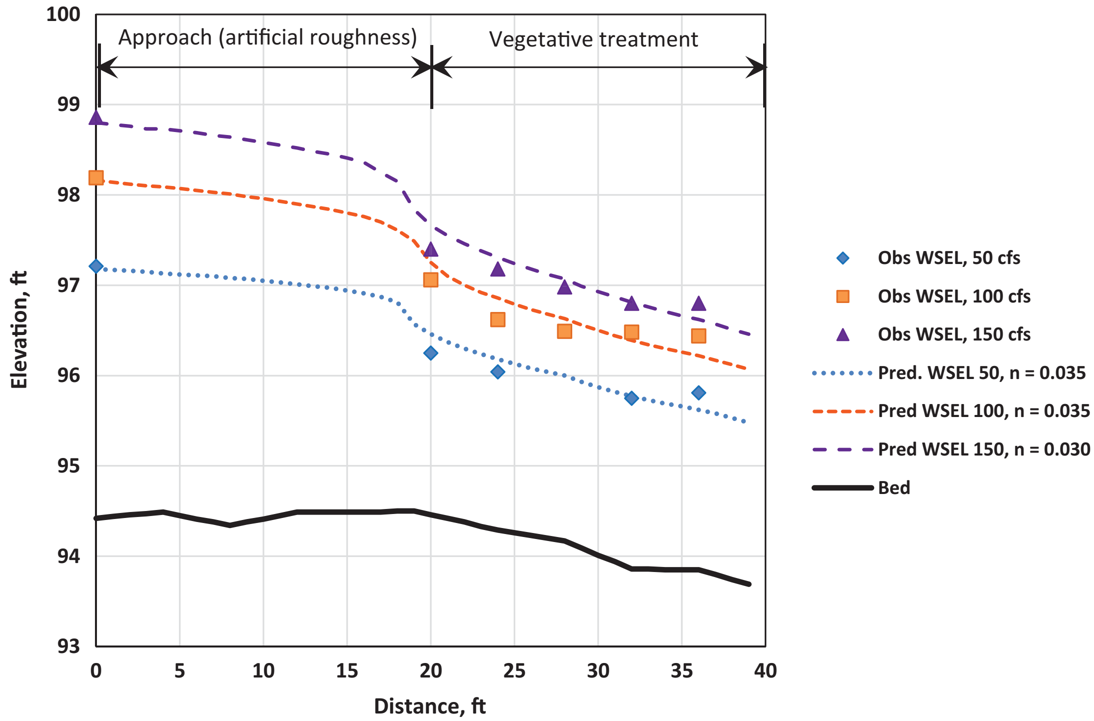


Figure 3.11. HEC-RAS calibration of Manning n values, Tray 1.

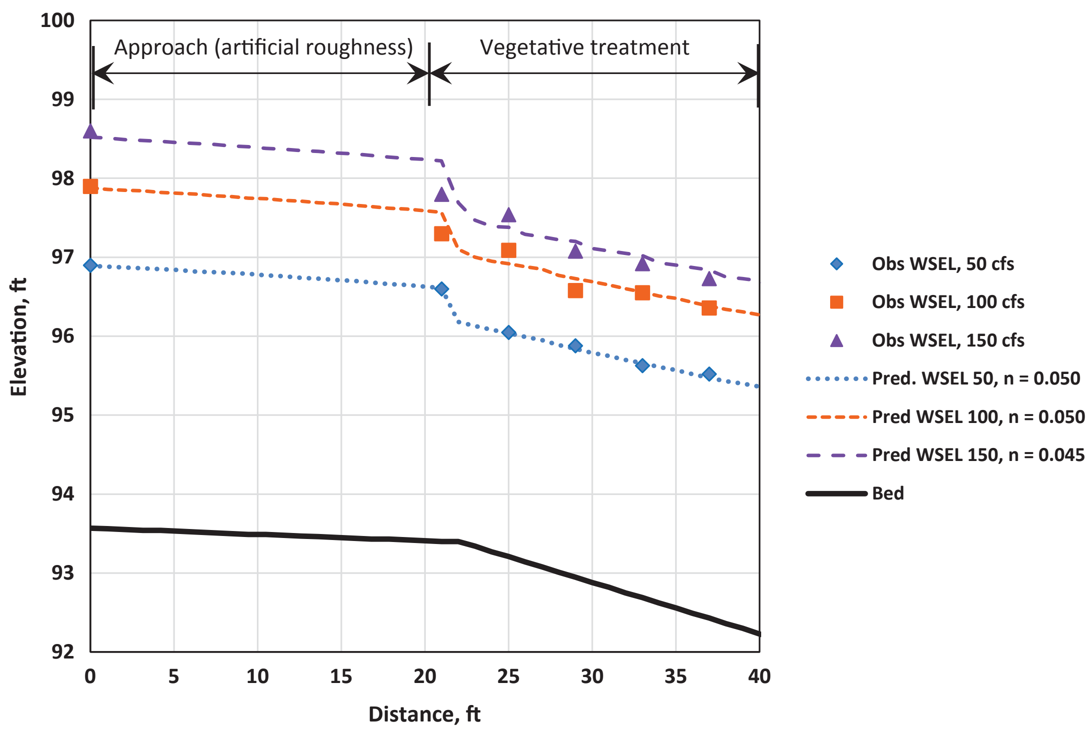


Figure 3.12. HEC-RAS calibration of Manning n values, Tray 2.

Copyright National Academy of Sciences. All rights reserved.

Table 3.2. Results of HEC-RAS calibration runs.

	Discharge, cfs	Manning n of Vegetated Bank	Range of Energy Grade Slope, ft/ft	Range of Velocity[1], ft/s	Range of Froude Number
TRAY 1	50	0.035	0.021 – 0.037	6.6 – 8.0	1.08 – 1.41
	100	0.035	0.017 – 0.032	7.6 – 9.8	1.05 – 1.41
	150	0.030	0.013 – 0.025	9.2 – 11.6	1.06 – 1.47
TRAY 2	50	0.050	0.042 – 0.046	6.1 – 6.3	0.89 – 0.91
	100	0.050	0.041 – 0.044	7.1 – 7.3	0.92 – 0.94
	150	0.045	0.037 – 0.041	8.6 – 8.8	0.99 – 1.03

[1]Cross-sectional average velocity from HEC-RAS (V = Q/A).

the soil lifts in Tray 2, as well as the irregular slope geometry due to the stair-step configuration of the lifts. Table 3.2 provides a summary of the HEC-RAS calibration runs on the vegetative treatments in Trays 1 and 2.

The Froude numbers in Table 3.2 indicate that all three tests of Tray 1 were conducted with supercritical flow conditions, whereas the Tray 2 tests were conducted at subcritical to near-critical conditions. The range of cross-section average velocities in Tray 1 is much greater than that in Tray 2 because of the continued acceleration of flow in the downstream direction in Tray 1. The slopes of the energy grade lines in the table also indicate that the Tray 2 tests resulted in near-uniform flow because the energy slopes are very near the nominal bed slope of 0.04 ft/ft.

The highest discharge (150 cfs, Tests 3 and 6) resulted in lower energy slopes compared to the smaller flows, and therefore lower Manning n values, which presumably is due to the total pronation of the willow stems. Note that the longitudinal bed profile in Figure 3.11 reflects the riprap "stream bed" surface because it was the lowest component in the surveyed elevations, whereas the lowest component in Figure 3.12 was the edge of the test tray.

3.5.2 Point Velocity Measurements and Velocity Distributions

During each test, three streamwise point velocity measurements were taken (20%, 60%, and 80% of the total depth of flow) with a Marsh-McBirney 1-D electromagnetic flowmeter. In addition, at most locations it was possible to obtain a fourth point velocity reading within about 2 in. above the bed surface. The meter was mounted on a point gage and suspended from a data collection cart which traversed the length of the test section on rails mounted on top of the horizontal flume walls.

The velocity data were collected at predetermined cross sections located approximately 4, 8, 12, and 16 ft downstream of the leading (upstream) edge of each test tray. Typically, a set of data was taken above the rock riprap "stream bed," and proceeded at about 1-ft intervals up the vegetated slope at each cross section, adjusted as necessary based on vegetation clusters.

The following series of figures provides the contours showing velocity distributions corresponding to cross sections 4, 8, 12, and 16, respectively, as Figures 3.13 through 3.16. In these figures, the velocity distributions for each flow (50, 100, and 150 cfs) are shown, with Tray 1 results presented in the left-hand column, and the corresponding plots for Tray 2 shown in the right-hand column.

During the low-flow tests (50 cfs, Tests 1 and 4) on both Trays 1 and 2, the velocity contour plots show the effectiveness of the willows in pushing the higher velocity flow away from the bed, particularly near the toe of the slopes. This effect is somewhat less pronounced at the higher

Copyright National Academy of Sciences. All rights reserved.

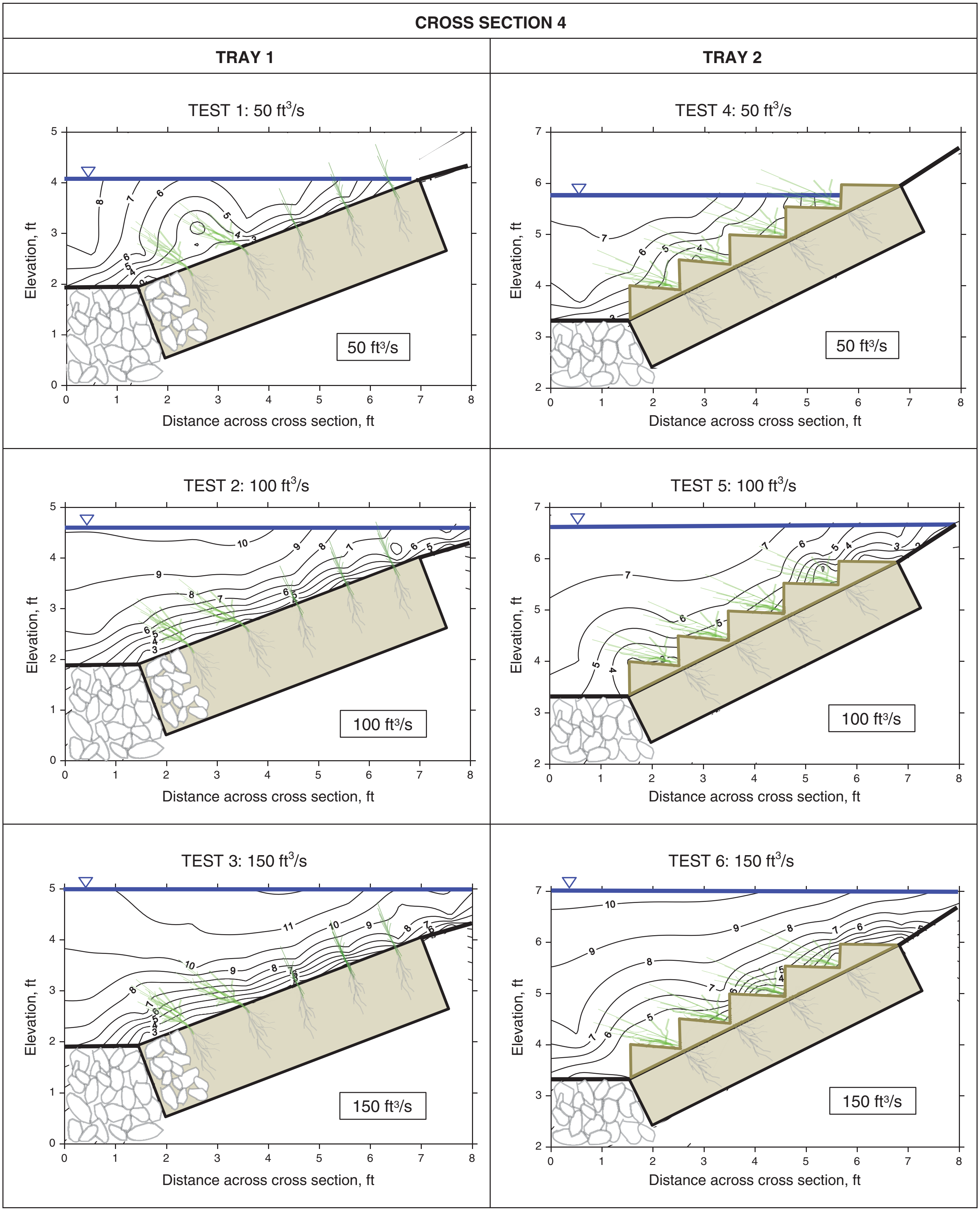


Figure 3.13. Velocity contours at Cross Section 4, Trays 1 and 2.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

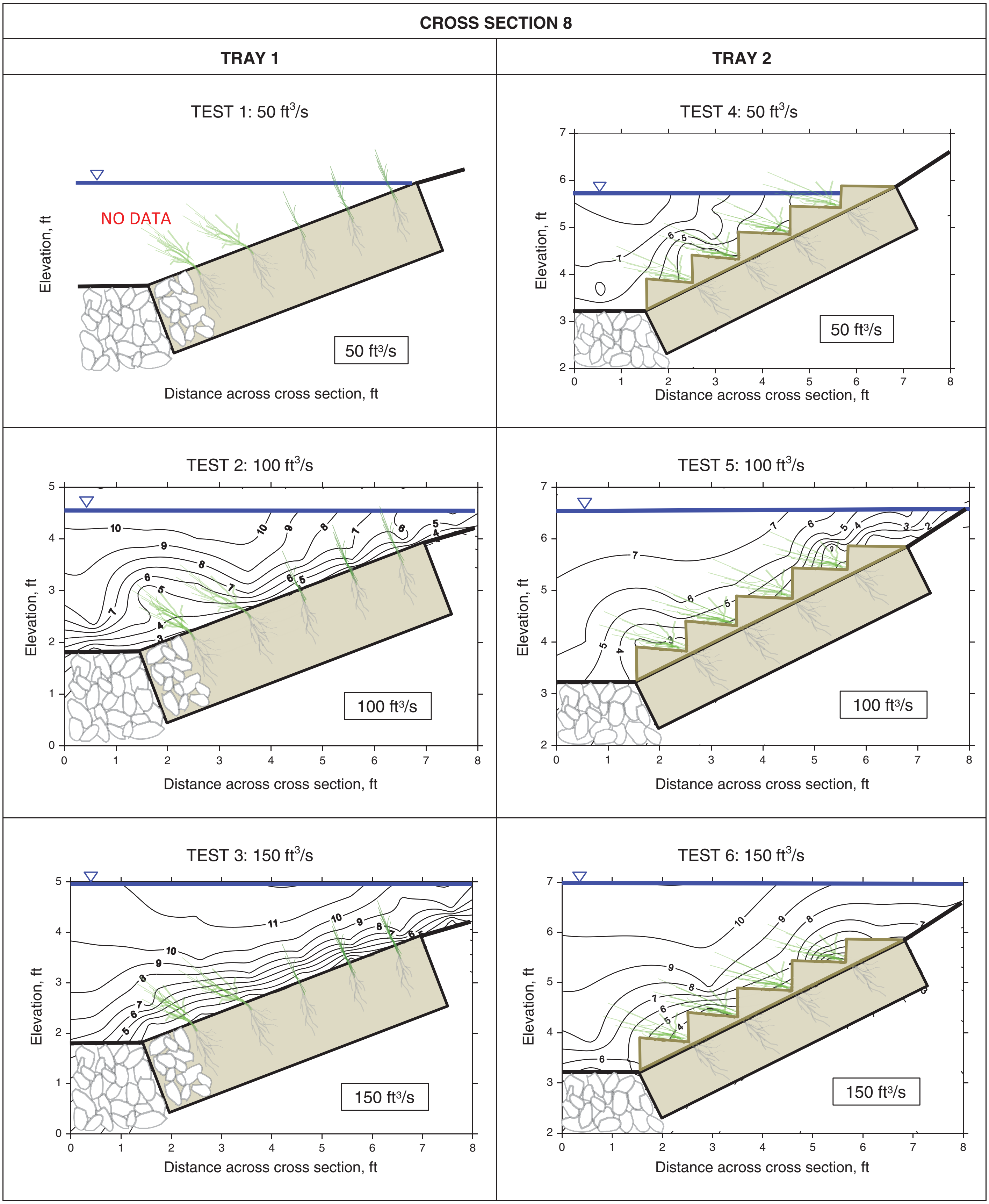


Figure 3.14. Velocity contours at Cross Section 8, Trays 1 and 2.

Copyright National Academy of Sciences. All rights reserved.

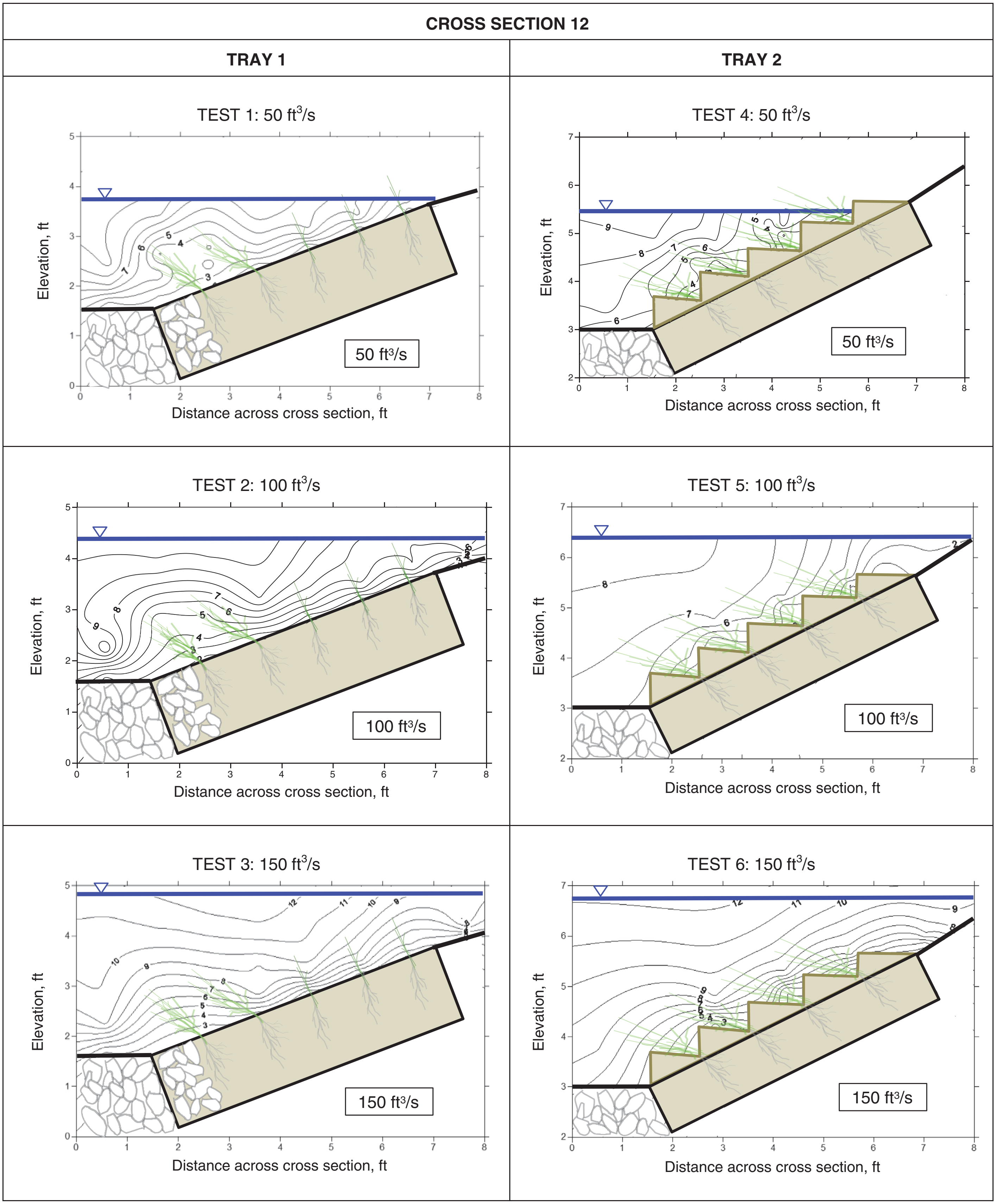


Figure 3.15. Velocity contours at Cross Section 12, Trays 1 and 2.

Copyright National Academy of Sciences. All rights reserved.

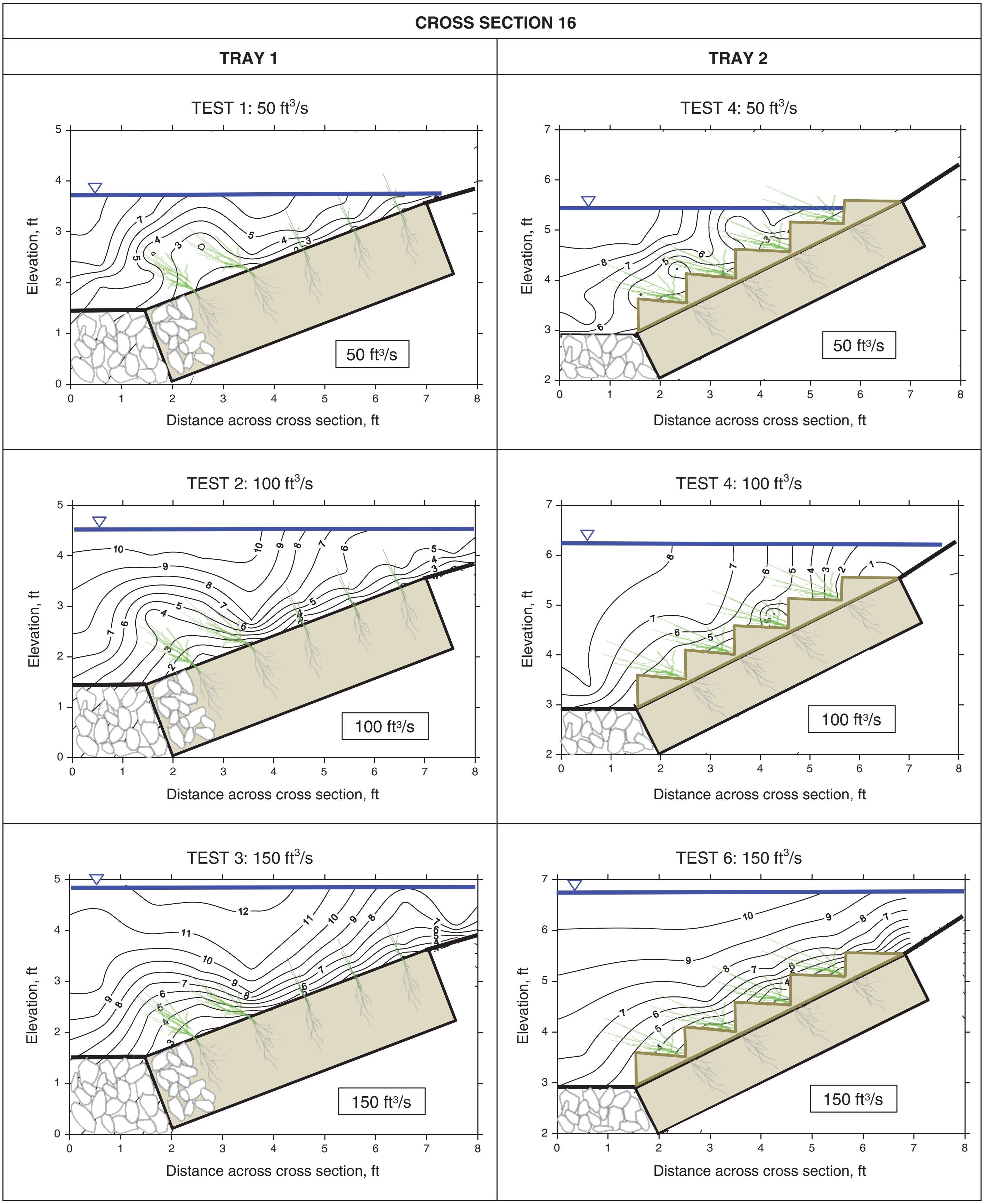


Figure 3.16. Velocity contours at Cross Section 16, Trays 1 and 2.

Copyright National Academy of Sciences. All rights reserved.

flows (100 and 150 cfs), although the live siltation willows near the toe of the slope in Tray 1 were more effective at producing this condition. This can be seen by comparing the velocity contour pattern in Tray 1 at Cross Section 4 vs. the patterns at Cross Sections 8, 12, and 16. This appears to be a result of the flow transitioning further downstream into the vegetative treatment.

The point velocity at 60% depth (V_{60}) is generally considered to represent of the depth-average velocity in the water column at that location. The measured V_{60} values from the Tray 1 and Tray 2 datasets were used with the Manning equation to estimate bed shear stress at each of the measurement locations for all tests, as described in Section 3.5.3.

3.5.3 Bed Shear Stress

Local shear stress at the bed was estimated at all point velocity measurement locations for all tests by using a rearranged form of the Manning equation:

$$\tau_0 = \left(\frac{nV_{60}}{1.486} \right)^2 \frac{\gamma}{y^{1/3}} \quad (3.1)$$

where:

τ_0 = Bed shear stress, lb/ft²
n = Manning n resistance coefficient
V_{60} = Depth-averaged velocity, taken as the point velocity at 60% depth
γ = Unit weight of water, 62.4 lb/ft³
y = Depth of flow above bed, ft

Using the point velocities at 60% depth, the bed shear was calculated using Equation 3.1 and the corresponding values were contoured as a function of the X-Y location within the vegetated test section, where X is the longitudinal (streamwise) direction and Y is the lateral direction across the flume.

Figures 3.17 through 3.19 provide the contours showing bed shear stress distributions corresponding to each of the test flows; they present the shear stress contour plots for each flow (50, 100, and 150 ft^3/s). In each figure, Tray 1 results are presented as the upper portion of the figure and Tray 2 results are shown as the lower portion of the figure. The riprap area(s) near the toe/streambed are indicated by dashed lines, as are the areas of metal flashing at the top of the slope. The flow direction is from left to right.

As seen in Figures 3.17 through 3.19, the calculated bed shear stress is significantly different between Tray 1 and Tray 2 for the three flow rates. The color intensity is consistent for all of the contour plots shown in these figures. Table 3.3 provides a comparison of typical shear stress ranges on the vegetated portions of the test sections in Trays 1 and 2.

3.5.4 Erosion

Using the measured bed elevations at each of the four predetermined transects after each flow, the cumulative erosion was calculated and the corresponding values were contoured as a function of the X-Y location within the vegetated test section, where X is the longitudinal (streamwise) direction and Y is the lateral direction across the flume.

Figures 3.20 through 3.22 provide the contours showing measured erosion corresponding to each of the test flows; they present the erosion contour plots for each flow (50, 100, and 150 ft^3/s). In each figure, Tray 1 results are presented as the upper figure and Tray 2 results shown as the lower figure. The riprap area(s) near the toe/streambed are indicated by stippled regions,

Copyright National Academy of Sciences. All rights reserved.

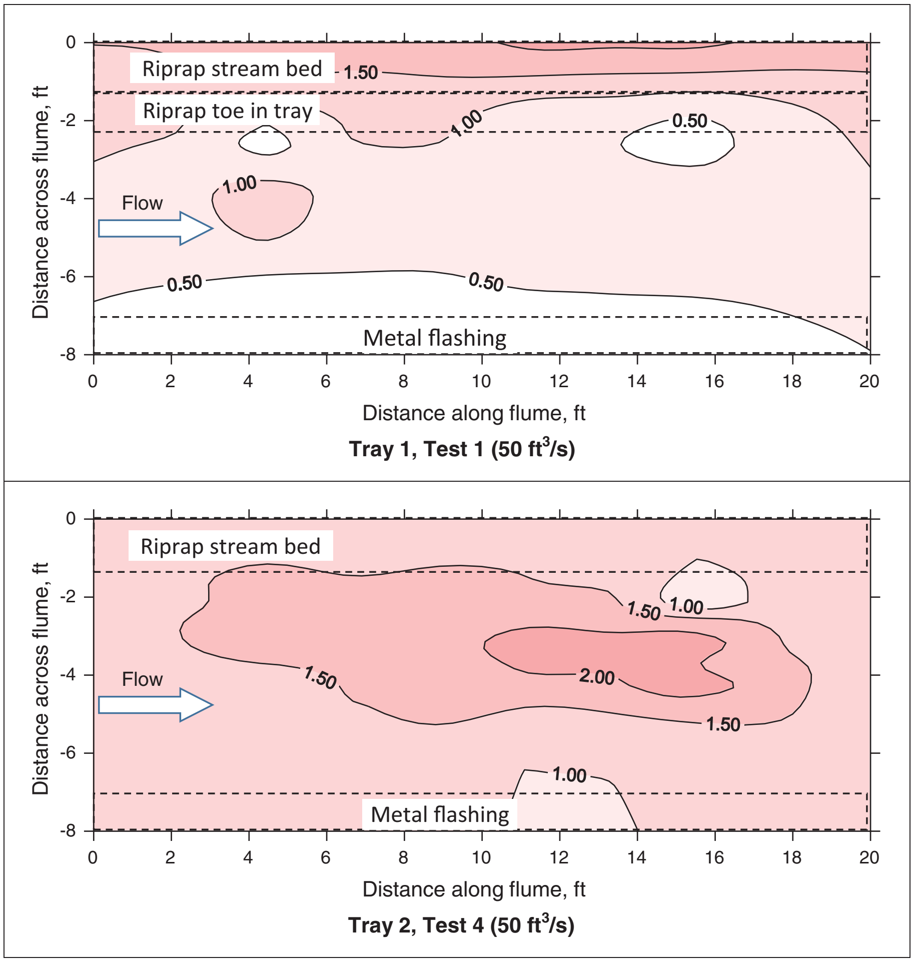


Figure 3.17. Shear stress contours, Trays 1 and 2 at 50 ft³/s.

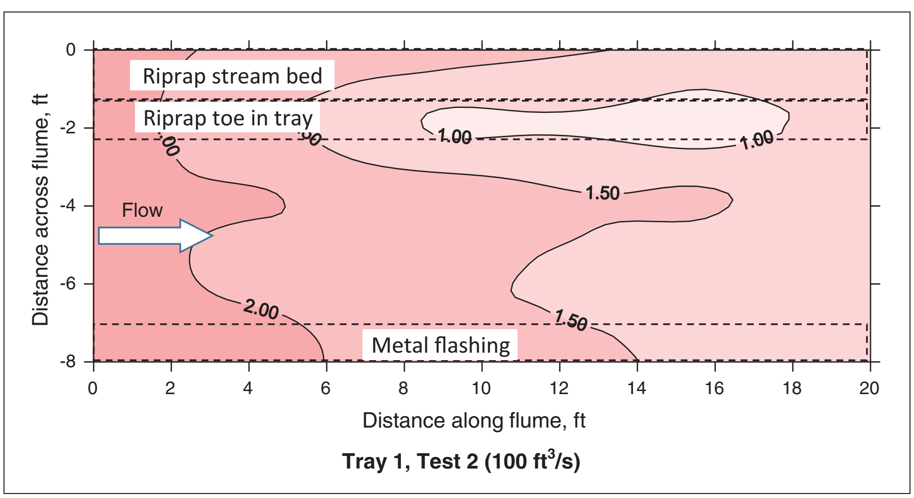


Figure 3.18. Shear stress contours, Trays 1 and 2 at 100 ft³/s.

Copyright National Academy of Sciences. All rights reserved.

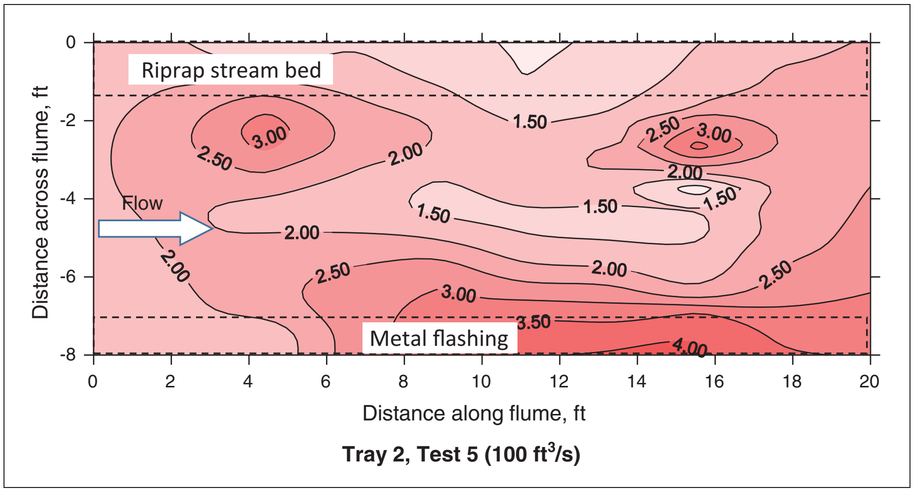


Figure 3.18. *(Continued).*

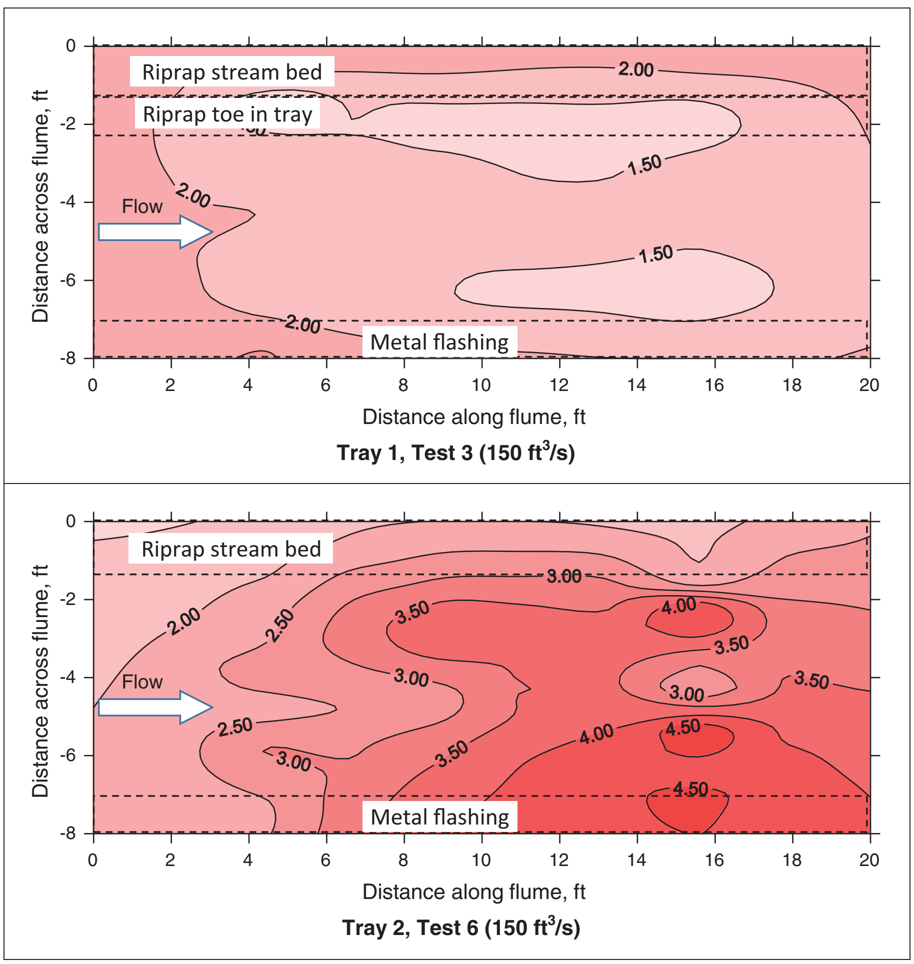


Figure 3.19. ***Shear stress contours, Trays 1 and 2 at 150 ft³/s.***

Copyright National Academy of Sciences. All rights reserved.

Table 3.3. Results of bed shear stress analyses.

	Discharge, ft^3/s	Typical Range of Bed Shear Stress, lb/ft^2	Minimum Bed Shear Stress, lb/ft^2	Maximum Bed Shear Stress, lb/ft^2
TRAY 1	50	0.50 to 0.75	~ 0.25	~ 1.00
	100	1.50 to 2.00	~ 1.00	~ 2.25
	150	1.50 to 2.00	~ 1.25	~ 2.25
TRAY 2	50	1.25 to 2.00	~ 1.00	~ 2.25
	100	1.75 to 3.00	~ 1.00	~ 3.50
	150	2.50 to 4.00	~ 1.75	~ 4.50

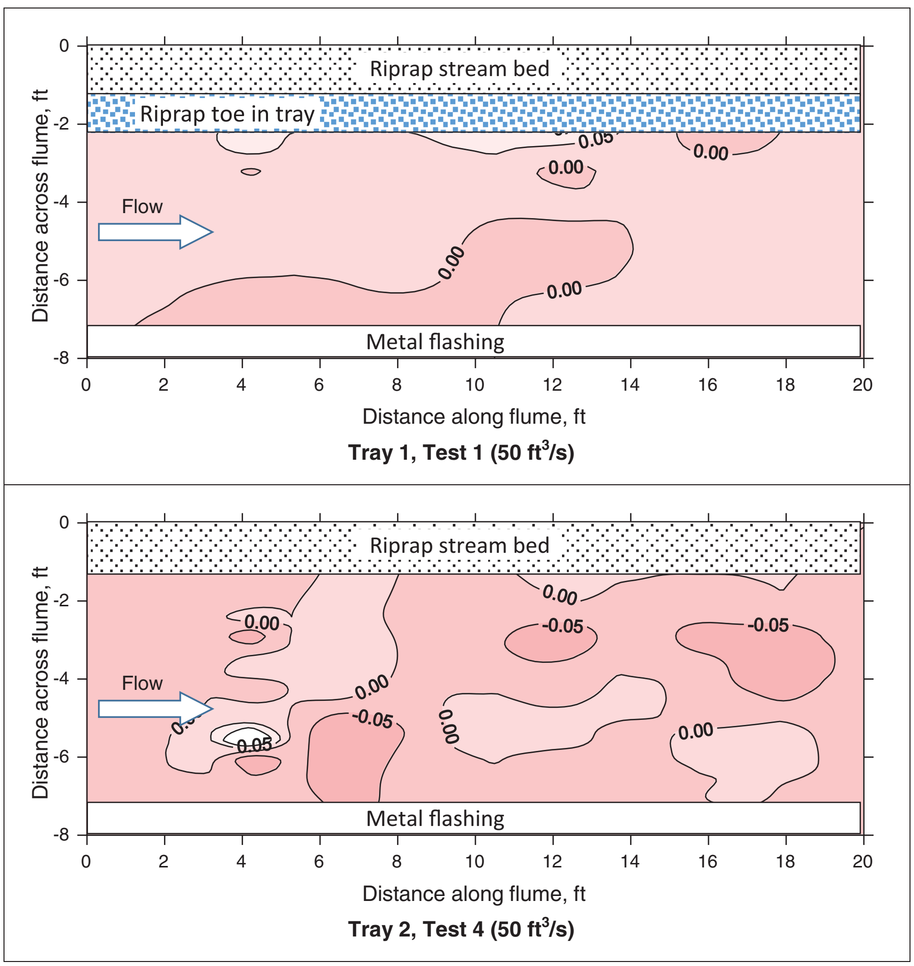


Figure 3.20. Erosion contours, Trays 1 and 2 at 50 ft^3/s.

Copyright National Academy of Sciences. All rights reserved.

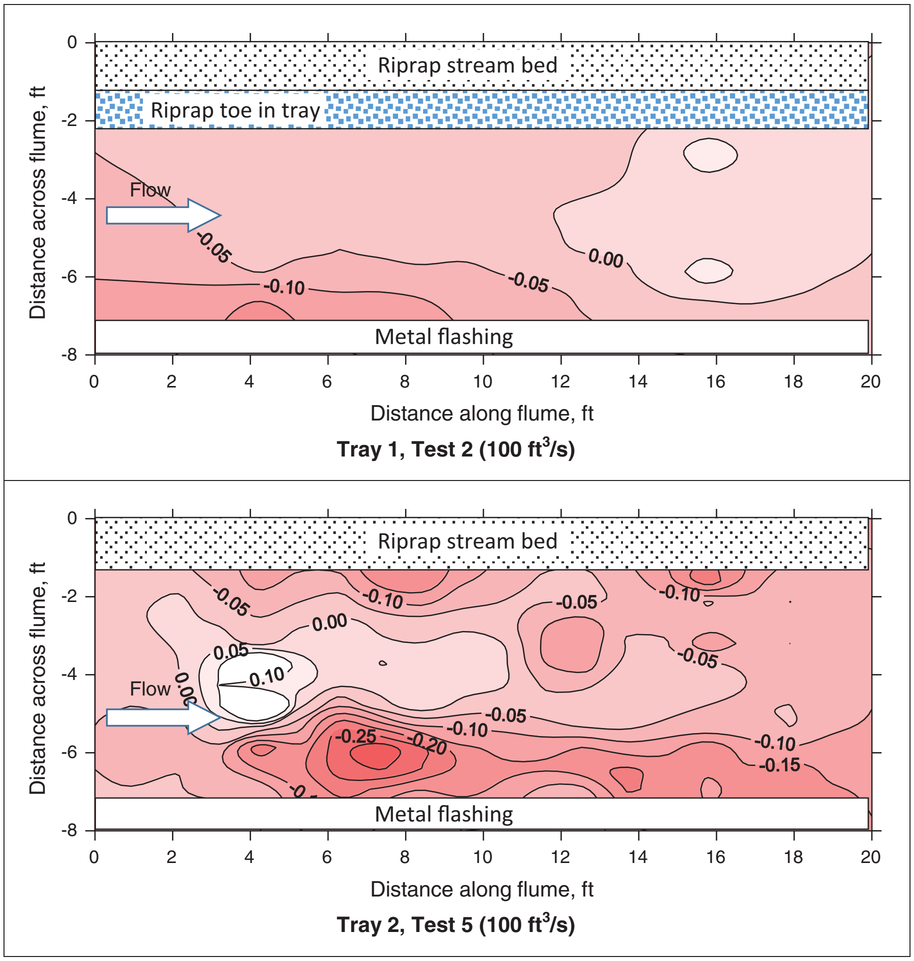


Figure 3.21. Erosion contours, Trays 1 and 2 at 100 ft³/s.

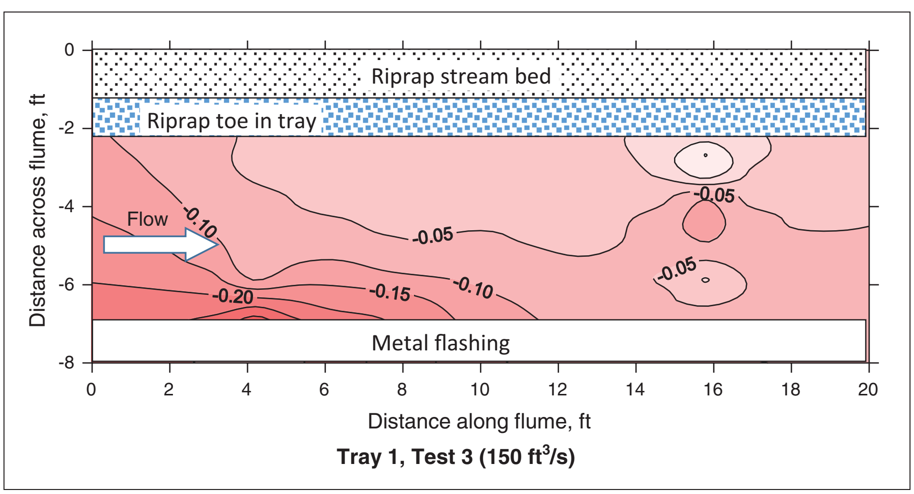


Figure 3.22. Erosion contours, Trays 1 and 2 at 150 ft³/s.

(continued on next page)

Copyright National Academy of Sciences. All rights reserved.

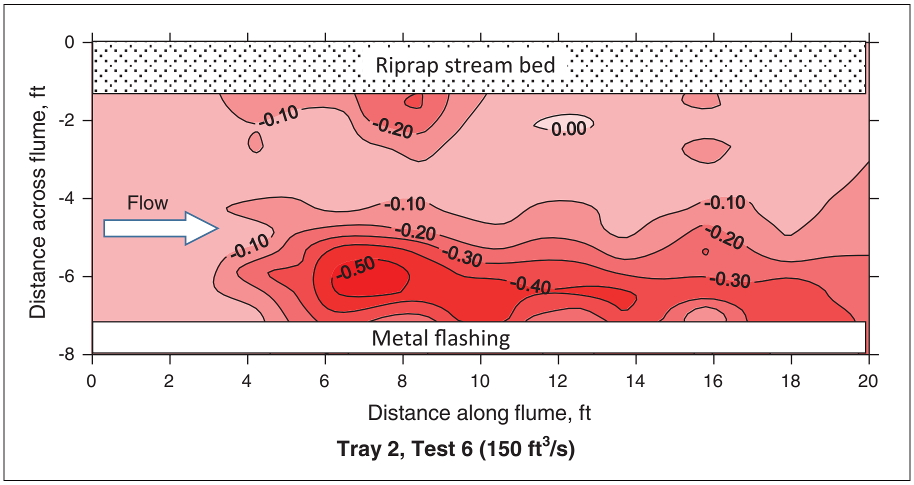


Figure 3.22. (Continued).

as are the areas of metal flashing at the top of the slope. Because no erosion occurred on areas of riprap or metal flashing, the contoured portion of the figure is blanked out in these areas. Negative values on the contour lines indicate erosion, while positive values indicate aggradation due to rearrangement of soil beneath the coir/jute fabric. The flow direction is from left to right.

In Figures 3.20 through 3.22, the change in bed elevation is significantly different between Tray 1 and Tray 2 for the three flow rates. The color intensity is consistent for all of the contour plots shown in these figures. Table 3.4 provides a comparison of measured erosion depths in Trays 1 and 2 corresponding to the different discharges.

The contour maps in Figures 3.21 and 3.22 clearly indicate the severe washout of soil from within the uppermost soil lift of Tray 2 during the 100 and 150 ft^3/s flows. The soil loss in the uppermost lift was evident along nearly the entire length of the test tray, as described previously in Section 3.4. A photo of the uppermost soil lift after Test 6 (150 ft^3/s) is shown in Figure 3.23. Note that no willow staking was done in the top surface of this lift.

Figures 3.21 and 3.22 also indicate the development and growth of the tear in the coir/jute fabric forming the face of the lowermost soil lift in Tray 2. The tear was initiated during Test 4 and began sagging the top surface of this lift due to soil loss during Tests 5 and 6.

Table 3.4. Results of bed erosion analyses.

	Discharge, ft^3/s	Typical Range of Bed Erosion, ft	Minimum Bed Erosion, ft	Maximum Bed Erosion, ft
TRAY 1	50	-0.025 to +0.025	~ +0.050	~ -0.025
	100	-0.050 to -0.000	~ +0.050	~ -0.150
	150	-0.150 to -0.025	~ +0.075	~ -0.300
TRAY 2	50	-0.050 to -0.000	~ +0.100	~ -0.075
	100	-0.150 to -0.000	~ +0.100	~ -0.300
	150	-0.400 to -0.100	~ 0.000	~ -0.550

Note: Positive values indicate aggradation (deposition) beneath fabric; negative values indicate erosion.

Copyright National Academy of Sciences. All rights reserved.

Figure 3.23. Tray 2 at the end of Test 6 (150 ft³/s). Note soil washout and collapse of the uppermost soil lift.

3.6 Appraisal of Testing Results

The quantitative analyses of velocity, shear stress, and erosion data presented in the previous sections support the qualitative observations made during the course of the testing. Tray 1 (3H:1V bank slope with live staking, live siltation willows, and riprap toe within the testing tray) exhibited significantly less erosion, lower bed shear stress, and lower Manning n values compared to Tray 2 (VMSE soil lifts with no hard toe).

3.6.1 Erosion vs. Shear Stress

Although the calculated bed shear stress and the measured erosion data were highly variable over the vegetated treatment areas of both trays as evidenced by the contour plots presented previously, trends are apparent in the datasets. The average erosion depths and corresponding shear stresses for Trays 1 and 2 after each test are presented in Table 3.5 and Figure 3.24. The average values of these variables are computed from all V_{60} point velocity and bed surface measurements taken over the entire test section.

Figure 3.24 suggests that a threshold shear stress of about 0.9 lb/ft^2 is required to initiate erosion. Once erosion begins, the erosion depth appears to be a linear function of shear stress.

Further trend analysis was conducted by collating the shear stress and erosion data at all of the measurement points by partitioning each cross section into four separate stream tubes (measured from left flume wall looking downstream, adjacent to the "stream bed"), as follows:

- Stream Tube 1: 0.0 to 2.0 ft
- Stream Tube 2: 2.0 to 4.0 ft

Copyright National Academy of Sciences. All rights reserved.

Table 3.5. Average values of shear stress and erosion, all tests.

	Test No.	Discharge, ft^3/s	Average Shear Stress, lb/ft^2	Average Erosion Depth, ft
Tray 1	1	50	0.75	0.01
	2	100	1.50	0.06
	3	150	1.70	0.10
Tray 2	4	50	1.61	0.03
	5	100	2.43	0.13
	6	150	3.24	0.24

- Stream Tube 3: 4.0 to 6.0 ft
- Stream Tube 4: 6.0 to 8.0 ft

This partitioning is necessary because the velocity data at a particular cross section were not collected at the same lateral distance (y-coordinate) as the erosion measurements. In most cases, the number of velocity measurements in any given stream tube was not the same as the number of erosion measurements. Thus, in order to pair the data, the maximum erosion rate within each stream tube was paired with the maximum shear stress in the same stream tube.

Erosion rate in inches per hour was determined by taking the erosion depth and dividing by the duration of each test (4 hours, with the exception of Test 1 which was run for 4.5 hours). The results of this partitioning approach are shown in Figures 3.25 and 3.26 for Trays 1 and 2, respectively. In these figures, the x- and y-axes scales are consistent to facilitate comparison. The partitioning better shows the variability of erosion rate and shear stress and more clearly shows the clustering of data for the different discharges used in the full-scale laboratory testing program.

Comparing Figures 3.25 and 3.26, it can be seen that the stream-tube maximum shear stress in Tray 1 did not exceed a value of 2.6 lb/ft^2 for any of the tests, whereas it reached a maximum of about 5.4 lb/ft^2 in Tray 2.

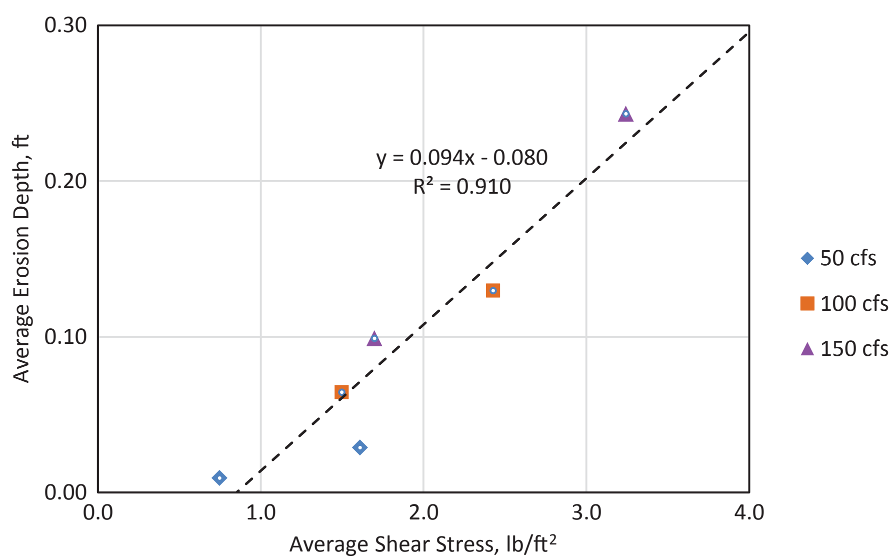


Figure 3.24. Average erosion depth vs. average shear stress, all tests.

Copyright National Academy of Sciences. All rights reserved.

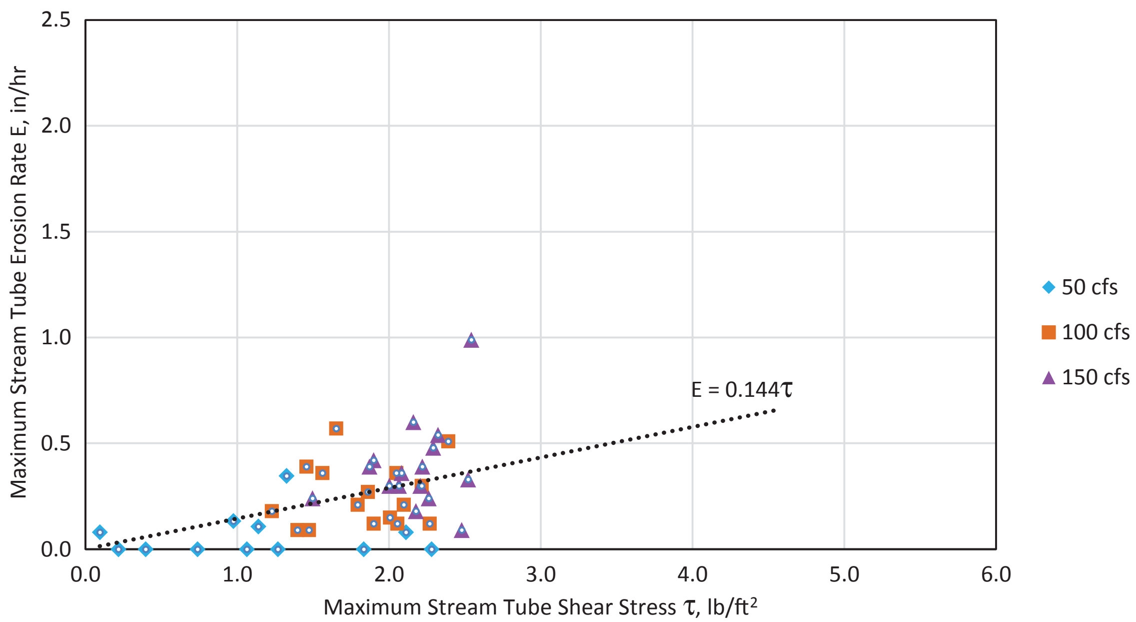


Figure 3.25. Erosion rate vs. shear stress, Tray 1.

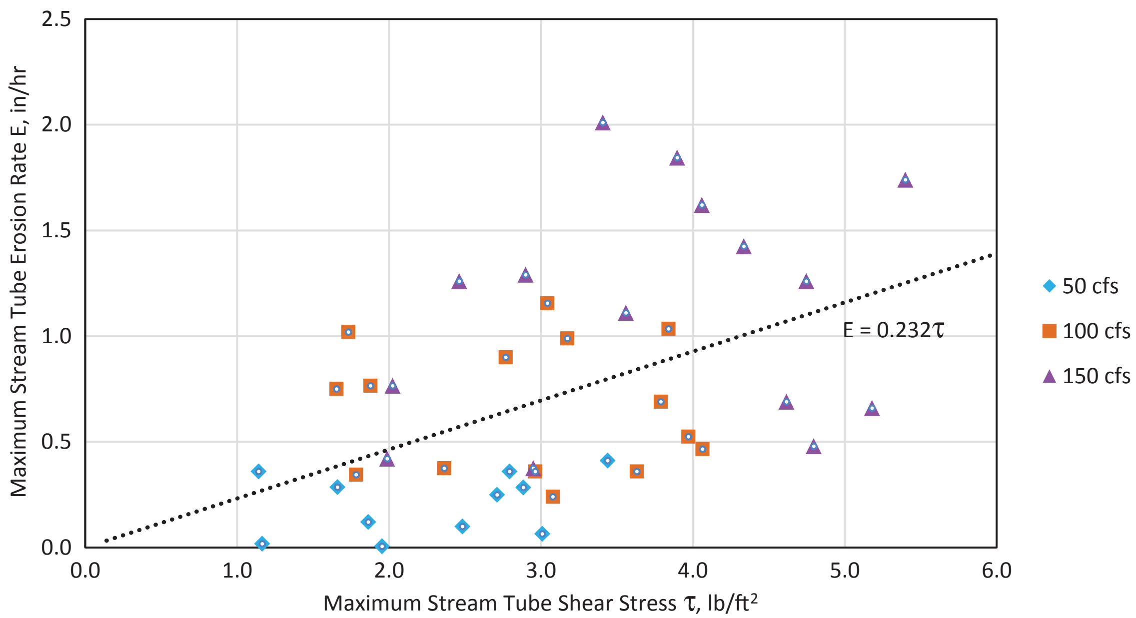


Figure 3.26. Erosion rate vs. shear stress, Tray 2.

Copyright National Academy of Sciences. All rights reserved.

86 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Likewise, the maximum erosion rate in any stream tube in Tray 1 was 1.0 in. per hour, while in Tray 2 the maximum erosion rate was 2.0 in. per hour. Therefore, in general, doubling the shear stress results in a doubling of erosion rate. This again suggests a linear relationship between erosion and shear stress.

While correlation between maximum stream tube erosion rates and shear stresses is poor, trends are apparent in both Trays 1 and 2. The data indicate that erosion begins to occur when a threshold shear stress of about 1.0 lb/ft^2 is exceeded. This is very similar to the averaged data of Figure 3.24; however, no predictive relationship is implied by presenting the data in this fashion.

Shear stresses and erosion were least at the lowest flow rate (50 ft^3/s) in both trays. In Tray 1, the cluster of erosion vs. shear stress points is similar for the 100 and 150 ft^3/s flows. However, in Tray 2, the data clusters are different for the two higher flows. A possible explanation for this may be that the construction of the vertical lifts of the VMSE in Tray 2 created preferential pathways for higher velocity flow to occur against the face of each lift. Figure 3.27 shows a close-up of preferential flow pathways along the faces of soil lifts in Tray 2 before, during, and after testing.

3.6.2 Pronation of Willows

As discussed in Sections 3.3 and 3.4, willow stems were bent in the direction of flow during the tests to different degrees based on depth of inundation as well as local velocity impinging on the vegetation. During each test, the lateral distance from the left flume wall to the point where the willows remained upright was noted (at the highest flow, 150 ft^3/s, all the vegetation was pronated and lying beneath the water surface in both trays).

The data from all tests were segregated into two groups: willows standing upright and willows laid over. The depth was then plotted vs. velocity at 60% depth (V_{60}) for every data point as shown in Figure 3.28. The product of depth and velocity is unit discharge, and is often used as a measure of flood hazard to humans in inundated areas. A unit discharge of 5.3 ft^3/s/ft was found to distinguish between pronation (solid symbols) and non-pronation (open symbols) of the *Salix exigua* (sandbar willow) used in this testing program.

Sandbar willow is extremely resilient and pliable, and resisted damage at all ranges of flow conditions tested. Characteristics of the willows at the time of testing included the biomass measurements presented in Table 3.1, typical stem diameters of ⅜ to ⅝ in., and typical aboveground stem heights of 3 to 5 feet. Figure 3.29 is a close-up photograph of the only stem that actually broke during the testing program (Test 6 at 150 ft^3/s, near the toe of the slope at Cross Section 16 in Tray 2). The point velocity V_{60} and shear stress at this location during Test 6 were 11.4 ft/s and 3.5 lb/ft^2, respectively.

3.6.3 Summary of Laboratory Testing Program

From the observations, data collected, and subsequent data analyses of the full-scale tests, the following observations are made:

1. The vegetative treatment of Tray 1 (live siltation willow and live staking with stone toe) exhibited significantly lower Manning n resistance coefficients, bed shear stresses, and erosion compared to Tray 2 (VMSE soil lifts with soft toe) at the same discharge.
2. A higher density of willows per square yard of surface area does not necessarily result in better performance. Rather, the overall geometry of the bank slope and planting configuration appears to be the more important factor in the overall performance of the vegetative component. For example, the stair-step configuration of the VMSE creates preferential pathways for high-velocity flow, which results in the potential for damage to the fabric of the soil lifts.

Copyright National Academy of Sciences. All rights reserved.

a. Prior to testing (photo taken in greenhouse).

b. During Test 6. Note pronation of willows and exposed faces of soil lifts.

c. After Test 6. Note exposed faces of soil lifts.

d. After Test 6. Note deformed face of soil lift (originally vertical).

Figure 3.27. Preferential flow pathways (yellow arrows) along the faces of soil lifts in Tray 2.

Copyright National Academy of Sciences. All rights reserved.

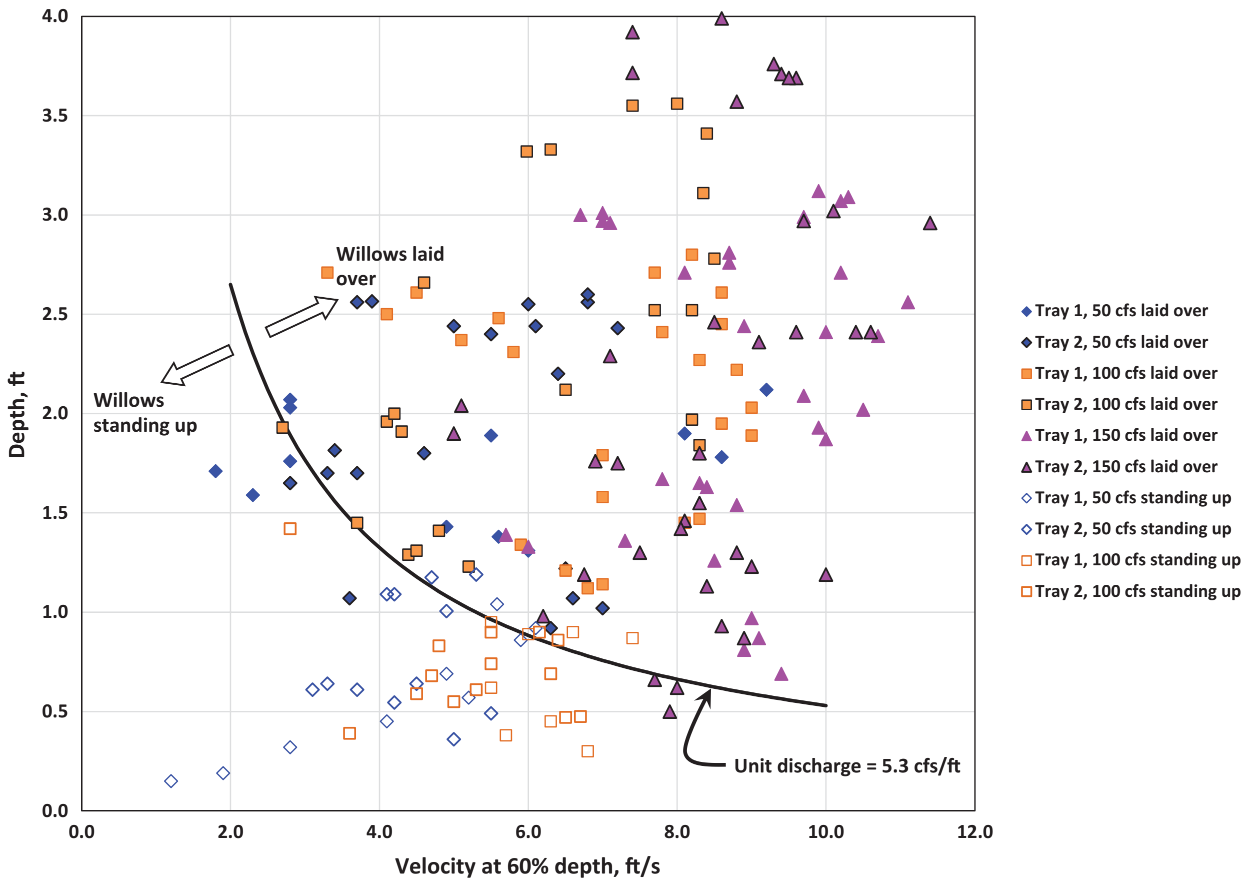


Figure 3.28. Depth vs. velocity curve distinguishing pronated vs. non-pronated willow stems.

Figure 3.29. Photograph showing broken stem at the end of Test 6 (150 ft³/s).

Copyright National Academy of Sciences. All rights reserved.

3. The live siltation willows at the toe of the bank slope in Tray 1 were significantly more effective at shifting the region of high-velocity flow away from the stream bank and toward the main channel compared to the stair-step configuration of soil lifts and vegetation of the VMSE treatment in Tray 2.
4. Vulnerable areas of the VMSE treatment are the faces of the individual soil lifts. In particular, the lowermost lift at the toe of the bank slope is subject to damage if left unprotected by other means, such as a stone (i.e., riprap), toe armor, or other "hard" engineered treatment. Qualitative observations suggest that preferential pathways for high-velocity flow along the faces of the soil lifts appear to be a shortcoming of this bank-protection treatment.
5. The uppermost soil lift of VMSE is also vulnerable to soil loss if it becomes fully submerged and is not vegetated on its top surface. In contrast, the top surfaces of soil lifts that are lower down on the slope were seen to be protected by the pronated willows of the lift above, which provided a "shielding" effect.
6. For both bank-protection treatments, the threshold shear stress at which erosion begins is approximately 1.0 lb/ft^2.
7. The shear stress corresponding to local areas of significant soil loss (up to 0.25 ft) was approximately 2.5 lb/ft^2 in both trays. This threshold was reached in Tray 1 during Test 3 (150 ft^3/s) and in Tray 2 during Test 5 (100 ft^3/s).
8. Areas of excessive soil loss ranging from 0.3 to 0.5 ft were observed in Tray 2 during Test 6 (150 ft^3/s). The corresponding shear stresses for this condition were 3 to 4.5 lb/ft^2.
9. Because of the difference in Manning n roughness between the two treatments, limiting values of permissible velocity were found to be 7 to 9 ft/s for Tray 1, and 5 to 7 ft/s in Tray 2.
10. For both treatments tested, there is a large amount of variability in bed shear stress and erosion from point to point along the bank slope. This was seen in both the longitudinal (downstream) flow direction as well as the lateral (upslope) direction.

Copyright National Academy of Sciences. All rights reserved.

CHAPTER 4

Design Guidelines and Appraisal of Research Results

4.1 Overview

This chapter contains both general and site-specific guidance for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank protection measures. From a macro-scale perspective, selection and design of an environmentally sensitive stream bank treatment must consider the watershed and river system processes that drive river channel response, including climatic, hydrologic, hydraulic, and geomorphic considerations. Ultimately, however, the success or failure of a selected treatment will depend on its ability to adapt to site-specific micro-scale processes in a given stream reach, including hydraulic, geomorphic, and geotechnical considerations. Conformance to design and construction guidance as well as a rigorous monitoring and maintenance effort will help ensure the success of the treatment.

Monitoring and maintenance of, in particular, the vegetative component of an environmentally sensitive treatment is often the key to a successful installation (see Section 4.2.5). Equally important are issues involving potential impacts to the aquatic habitat (both positive and negative) at the treatment site (Section 4.2.6). In addition, for the engineer involved in the multidisciplinary design of a treatment, guidance from FHWA on bioengineered treatments should be considered (Section 4.2.7). The engineer on the design team must also consider potential professional liability issues related to "stamping" an environmentally sensitive design. Some thoughts on these issues are provided in Section 4.2.8.

The focus of the chapter is on detailed standalone design guidelines for the two environmentally sensitive treatments subjected to hydraulic laboratory testing under Task 7 of this project (as described in Chapter 3). Detailed design guidelines updated by the results of hydraulic laboratory testing are presented in Section 4.3.1 (Live Siltation and Live Staking with Rock Toe) and Section 4.3.2 (VMSE Without Hard Toe). An overview of design guidelines for a related treatment (vegetated riprap) provides value-added guidance on a third treatment in Section 4.3.3. Section 4.4 features two detailed examples of the application of environmentally sensitive stream bank protection measures employed in conjunction with stream channel restoration projects. Recognizing that dryland landscapes are quite different from those of more humid regions, one example involves a detailed engineering analysis underpinning the application of environmentally sensitive techniques on an arid region perennial stream—the Rio Grande near Bernalillo, NM (Section 4.4.2). The second example deals with a smaller stream in a humid region with significant infrastructure issues—Malletts Creek near Ann Arbor, MI (Section 4.4.3).

The chapter concludes with an appraisal of results from this research project (Section 4.5). Key observations derived from various research activities (survey and site visits) are provided together with a summary of advances in the state of practice.

Copyright National Academy of Sciences. All rights reserved.

4.2 General Considerations

4.2.1 Introduction

Factors that affect stream stability at highway infrastructure can be classified as hydrologic, hydraulic, and geomorphic. Rapid and unexpected changes can occur in streams in response to human activities in the watershed and/or natural disturbances of the fluvial system, making it important to anticipate changes in channel geomorphology, location and behavior. Geomorphic characteristics of particular interest are the alignment, geometry, and form of the stream channel. The behavior of a stream depends not only on the apparent stability of the stream at a specific reach of interest, but also on the behavior of the stream system of which it is a part. Upstream and downstream changes may affect future stability at the treatment site. Natural disturbances such as floods, drought, earthquakes, landslides, forest fires, etc., may result in large changes in sediment load in a stream and major changes in the stream channel. These changes can be reflected in aggradation, degradation, or lateral migration of the stream channel. The following section provides an overview of general considerations relevant to implementing the guidelines for specific treatments that follow. For more detailed coverage of these important topics, reference to FHWA's Hydraulic Design Series (HDS) 6 (Richardson et al. 2001) or Hydraulic Engineering Circular- (HEC)-20 (Lagasse et al. 2012), and the American Society of Civil Engineers' (ASCE's) sedimentation engineering handbook (ASCE 2008) is suggested.

4.2.2 Hydrologic, Hydraulic, and Geomorphic Considerations

Hydrologic Factors

Magnitude and Frequency of Floods. The hydrologic analysis for a stream reach consists of establishing peak-flow frequency relationships and such flow-duration hydrographs as may be necessary. Flood-frequency relationships are generally defined on the basis of a regional analysis of flood records, a gaging station analysis, or both. Regional analyses have been completed for all states by the USGS. Flood-frequency relationships at gaged sites can be established from station records that are of sufficient length to be representative of the total population of flood events on that particular stream. The Pearson Type III distribution with log transformation of flood data is recommended by the Water Resources Council (1981) for station flood data analysis. Where flood estimates by regional analysis vary from estimates by station analysis, factors such as gaging station record length and the applicability of the regional analysis to that specific site should be considered, as well as high-water information, flood data, and information on flood levels at existing structures on the stream. FHWA's HDS 2 should be referred to for more detailed information and guidelines on hydrologic analysis (McCuen et al. 2002).

Flood History and Rainfall-Runoff Relations. Consideration of flood history is an integral step in attempting to characterize watershed response and morphologic evolution. Although the occurrence of single large storms can often be directly related to system change in any region of the country, this is not always the case. In particular, the succession of morphologic change may be linked to the concept of geomorphic thresholds. Under this concept, although a single major storm may trigger an erosional event in a system, the occurrence of such an event may be the result of a cumulative process leading to an unstable geomorphic condition.

Where available, the study of flood records and corresponding system responses, as indicated by time-sequenced aerial photography or other physical information, may help determine the relationship between morphological change and flood magnitude and frequency. Evaluation of wet-dry cycles can also be beneficial to an understanding of historical system response. Observable historic change may be found to be better correlated with the occurrence of a sequence of events

Copyright National Academy of Sciences. All rights reserved.

during a period of above average rainfall and runoff than with a single large event. The study of historical wet-dry trends may explain certain complex aspects of system response. For example, a large storm preceded by a period of above-average precipitation may result in less erosion, due to better vegetative cover, than a comparable storm occurring under dry antecedent conditions; however, runoff volumes might be greater due to saturated soil conditions.

A good method to evaluate wet-dry cycles is to plot annual rainfall amounts, runoff volumes, and maximum annual mean daily discharge for the period of record. A comparison of these graphs will provide insight into wet-dry cycles and flood occurrences. Additionally, a plot of the ratio of rainfall to runoff is a good indicator of watershed characteristics and historical changes in watershed condition (Lagasse et al. 2012).

Special Considerations in Arid Regions. Since dryland landscapes are quite different from those of more humid regions, analysis of flood history is of particular importance to understanding arid region stream characteristics. In an arid region, the topography and landforms are more abrupt, the soils are thinner, the bedrock exposures are usually more pronounced, and the streams are smaller and are likely to be dry for at least part of the year. Overall, the physical environment reflects the lack of water and mechanical weathering and erosion predominate over chemical weathering and solution, as compared to a humid environment. In a humid environment, high precipitation produces vegetation and soils that are well developed and stabilized. Under these conditions, natural streams generally carry small suspended sediment loads, reflecting this stability in the upland watersheds. Additionally, high precipitation produces a dilution effect on the sediments that are eroded (Simons, Li & Associates 1982).

In contrast, dryland streams normally carry large sediment loads from erosion by both wind and water. The precipitation generating the erosion in a dryland environment usually results from small storm cells that may be limited in areal extent, but can produce high-intensity rain and rainfall energy. This type of storm produces "flashy" runoff with pronounced capacity for sediment removal and transportation. Only rarely does a single storm produce runoff in all parts of a dryland stream basin and extended periods may pass with no streamflow at all. Many dryland streams flow only during the spring runoff and immediately after major storms. For example, Leopold et al. (1966) found that arroyos near Santa Fe, New Mexico, flow only about three times a year. As a consequence, dryland stream response can be considered to be more hydrologically dependent than streams located in a humid environment.

Whereas the simple passage of time may be sufficient to cause change in a stream located in a humid environment, time alone, at least in the short term, may not necessarily cause change in a dryland system due to the infrequency of hydrologically significant events. Thus, the absence of significant morphological changes in a dryland stream or river, even over a period of years, should not necessarily be construed as an indication of system stability. The unique hydrologic and morphologic characteristics of a dryland stream can have a significant impact on the utility or survivability of the vegetative component(s) of environmentally sensitive treatments (see Section 4.4. for an example of an arid region application).

Hydraulic and Geomorphic Factors

Mechanics of Channel Response. Because of the number of interrelated variables that can react simultaneously to natural or imposed changes in a river system, river response to both natural and human-induced forces is complex and varied in nature, but trends are generally predictable. However, Richardson et al. (2001) details the variables affecting alluvial channel geometry and bed roughness and concludes that the nature of these variables is such that, unlike rigid boundary hydraulics problems, it is difficult to isolate and study the role of an individual variable. For example, evaluation of the effects of increasing channel depth on average velocity is

Copyright National Academy of Sciences. All rights reserved.

hampered because related variables such as flow resistance, the form of bed roughness, channel cross-section shape, and sediment discharge also respond to the changing depth. Position and shape of alternate, middle, and point bars can also be expected to change.

Geomorphic and geotechnical factors that can influence stream stability include stream size, flow habit (i.e., ephemeral or perennial), and the characteristics of channel boundaries. The bed material of a stream can be a cohesive material, sand, gravel, cobbles, boulders, or bedrock. Bank material is also composed of these materials but may be dissimilar in composition from the bed material. The stability and rate of change in a stream are dependent on material in the bed and banks. Other natural factors such as the stream's relationship to its valley, floodplain and planform characteristics, and features such as natural levees, incision, and riparian vegetation are important indicators of stream stability (or instability).

Hydraulic factors that affect stream channel stability are numerous and include bed forms and their effects on sediment transport, resistance to flow, flow velocities, and flow depths. They also include the magnitude and frequency of floods; characteristics of floods (i.e., duration, time to peak, and time of recession); flow classification (e.g., unsteady, nonuniform, turbulent, supercritical, or subcritical); ice and other floating debris in the flow; and flow constrictions. Other factors include the effects of natural and human-induced changes that affect the hydrology and hydraulic flow conditions of the stream.

Human-induced changes in the drainage basin and the stream channel, such as alteration of vegetative cover and changes in a pervious (or impervious) area can alter the hydrology of a stream, sediment yield, and channel geometry. Channelization, stream channel straightening, stream-side levees and dikes, bridges and culverts, reservoirs, gravel mining, and changes in land use can have major effects on streamflow, sediment transport, and channel geometry and location.

Water discharge is the key factor that affects channel shape and sediment transport. Related hydraulic variables, such as velocity, depth, and flow area, are important in the analysis of channel response. Coinciding with these are channel shape, channel slope, and flow resistance from grain roughness and bed forms. Geology and soils of the channel bottom and banks help determine the relative erodibility of the system, and therefore its response to other changes or alterations. Local variations in geology, soils, vegetation, and flow rate play important roles in determining bank stability in channels.

Consequently, an alluvial river will generally change its position and shape as a result of hydraulic forces acting on its bed and banks. These changes may be slow or rapid and may result from natural environmental changes or from changes by human activities in the watershed or river channel itself. When a river channel is modified locally, this local change frequently causes modification of channel characteristics both up and down the stream. The response of a river to human-induced changes often occurs in spite of attempts to keep the anticipated response under control. Such changes can have a significant effect on the success or failure of an environmentally sensitive stream bank treatment intended to correct a localized problem.

Sediment Transport. The movement of sediment is described by the sediment continuity concept. This concept, like water continuity, describes the input, output, and storage change of sediment in the watershed or stream channel.

Sediment transport is usually considered in three parts:

1. Bed load—sediment movement primarily along the stream bed.
2. Suspended load—sediment transport primarily in the flow with some contact and interchange with the stream bed, and
3. Wash load—fine particles suspended in the flow that are not found in appreciable quantities in the bed material.

Copyright National Academy of Sciences. All rights reserved.

Bed load and suspended load can be described by transport equations as they are usually related to transport capacity. Wash load, however, is dependent primarily on supply conditions. In upland (low order) watersheds, the concept of supply and capacity is crucial, as it determines the sediment yield. Typically, transport capacity for small sizes (e.g., wash load) is in excess of the supply. Therefore, the yield is related to the supply. Conversely, for large sizes, the capacity is much less than the supply (e.g., large cobbles in a mountain stream), and therefore capacity controls. The relationship between sediment supply and sediment transport capacity influences long-term processes in the stream system such as aggradation and degradation which, in turn, influence the selection, design, and performance of environmentally sensitive stream bank protection measures (see Section 4.2.3).

4.2.3 Site-Specific Physical Processes Affecting Environmentally Sensitive Treatments

Introduction

In spite of their complexity, all rivers are governed by the same basic factors discussed in Section 4.2.2. In the design of environmentally sensitive treatments, one must understand and work with these natural factors:

- Geologic factors, including soil conditions;
- Hydrologic factors, including possible changes in flows, runoff, and the hydrologic effects of changes in land use;
- Hydraulic characteristics such as depths, slopes, and velocity of streams and what changes may be expected in these characteristics in space and time; and
- Geomorphic characteristics of the stream, including the probable geometric alterations that will be activated by the changes a treatment project and future projects will impose on the channel.

The following subsections present several site-specific concepts important to the design of environmentally sensitive stream bank protection measures.

Bankfull Discharge. *NCHRP Report 544* (McCullah and Gray 2005) contains detailed coverage on a series of special topics relevant to the design of environmentally sensitive stream bank treatments (see also Section 2.1). McCullah and Gray (2005) note that dynamically stable stream channels formed in fully alluvial materials (sediments that can be eroded and deposited by the stream) tend to have widths, depths, and slopes that reflect a balance among the geologic and hydrologic variables that interact to create the fluvial system. Many engineers and resource managers have found the concept of channel-forming discharge to be a useful tool in understanding and managing streams. This concept is based on the idea that even though channel width, depth, and slope vary along a stream and through time, average values of width, depth, and slope tend to be constant for a reach with a given drainage area if:

1. The stream bed and banks are alluvial;
2. There have not been any extreme floods, droughts, earthquakes, forest fires, or other catastrophic events in the recent past;
3. The watershed is largely free of human-caused disturbances, such as land-use changes, grazing, mining, road building, dams, or channelization; and furthermore
4. The channel geometry is such that the greatest discharge the channel will carry without overflowing is not a rare flood (which moves tremendous amounts of sediment, but occurs only rarely) or a low flow (which occurs frequently, but has relatively little erosive power), but is an intermediate magnitude, such as the one- or two-year flood.

This characteristic discharge is referred to as the “channel-forming” or “dominant” discharge, Q_{cf}. This discharge therefore dominates channel form and process, at least for streams in humid

Copyright National Academy of Sciences. All rights reserved.

regions and for perennial streams in semi-arid environments (Soar and Thorne 2001 and Biedenharn et al. 2001).

Clearly, very few stream reaches meet the four criteria outlined above, and few can be described as "dynamically stable" or "fully alluvial" without qualification. Therefore, channel geometries often vary considerably from sizes needed to convey Q_{cf}. Many workers ignore departures from ideal conditions, and determine bankfull stage based on field indicators like permanent vegetation or terraces, but this approach can lead to errors.

One of the principal reasons for estimating "channel-forming discharge" (or dominant discharge) is to ensure that any planned modification to channel cross section (as a result of proposed bank or channel protection measures along a reach of stream) will be compatible with this discharge. There are several approaches that can be employed to estimate this channel-forming discharge. Under the right conditions, other types of flows, including "bankfull discharge," can be used as surrogates.

At least three approaches are available for determining Q_{cf}: effective discharge (Q_{eff}), bankfull discharge (Q_{bf}), or the discharge that corresponds to a given return interval, Q_{ri} (Table 4.1).

The expression, "bankfull discharge," Q_{bf}, should be used to refer to the maximum discharge that the channel can convey without overflow onto the floodplain. Although this definition, proposed by Copeland et al. (2001) differs from that used by others (e.g., Rosgen 1996), it eliminates confusion. As noted above, theoretically Q_{bf} and Q_{eff} are generally equivalent in channels that have remained stable for a period of time, thus allowing the channel morphology to adjust to the current hydrologic and sediment regime of the watershed allowing Q_{bf} to be used as a surrogate for Q_{eff}. In such a channel, the bankfull discharge generally corresponds to a sharp change in the slope of the rating curve. It must be noted, however, that in an unstable channel that is adjusting its morphology to changes in the hydrologic or sediment regime, Q_{bf} can vary markedly from Q_{eff}.

Finally, the quantities Q_{eff}, Q_{bf}, and Q_{ri} are estimates of Q_{cf}, and thus more than one of these should be considered (Biedenharn et al. 2001). Computed effective and bankfull discharges outside the range between the 1- and 3-year recurrence intervals should be questioned. The computed effective and recurrence interval discharges should be compared with field evidence to ascertain if these discharges have geomorphic significance. Channel performance should be

Table 4.1. Comparison of approaches for finding the channel-forming discharge (Q_{cf}) (McCullah and Gray 2005).

Quantitative Estimate of Q_{cf}	Data Requirements	Recommended For	Limitations
Effective Discharge (Q_{eff})	Historical hydrology for flow-duration curve (10 years or more recommended) or synthetic flow-duration curve; channel survey; hydraulic analysis; sediment gradation; sediment transport analysis and model calibration (if possible)	Channel design	Requires large dataset and training in hydraulic engineering or fluvial geomorphology
Bankfull Discharge (Q_{bf})	Channel survey; hydraulic analysis and model calibration using observed stage-discharge relation (if possible). Identification of field indicators in a stable, alluvial reach	Stability assessment; estimation of Q_{eff} in stable channels	Can be very dynamic in unstable channels/watersheds; field indicators can be misleading
Return Interval Discharge (Q_{ri})	Historical hydrology for flood frequency analysis, regional regression equations, or hydrologic model	First approximation of Q_{eff} and/or Q_{bf} in stable channels	No physical basis; relations to Q_{eff} and Q_{bf} inconsistent in literature

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

examined for a range of discharges that represent key levels for aquatic habitat, riparian vegetation, channel stability, or flow conveyance (Copeland et al. 2001).

The bankfull discharge special topic in *NCHRP Report 544* includes detailed guidance for determining effective discharge, bankfull discharge, and discharge for a specific return period for use in design of environmentally sensitive stream bank treatments at both gaged and ungaged sites.

An ongoing project (NCHRP Project 24-40) at CSU will address issues related to "Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings." This project (Bledsoe et al. in process) is scheduled for completion in early 2016. The objectives of NCHRP Project 24-40 are to develop a scientifically supported method for defining the design hydrology for DOT stream restoration projects along with an understanding of how that design hydrology might change with land-use changes. Steps to produce that methodology include the following:

- Investigate flow metrics other than peak annual flood frequency curves for more consistent correlation with channel-forming processes (such as distribution of daily mean discharge, flow duration, key points on a flow-duration curve, etc.).
- Develop quantitative methods for estimating the impact of land-use change on the design metric that is appropriate for design.
- Investigate the connection between these changes and changes in channel-forming discharge, and consequently bankfull channel hydraulic geometry.

These methods should include changes due to urbanization, surface mining, agriculture, and forestry practices. When available, the results of NCHRP Project 24-40 could change, update, or expand bankfull discharge concepts related to design of environmentally sensitive stream bank protection measures.

In relation to the vegetative component of environmentally sensitive treatments, McCullah and Gray (2005) also note that establishing the annual high water (AHW) serves as a guide to identify where vegetative techniques should be positioned on a given stream bank (in some stable streams systems, AHW may be equivalent to bankfull discharge). The AHW may or may not represent the average annual peak discharge or the elevation for the 1-year event, but it does represent the lower limit suitable for establishing permanent woody vegetation. This is important because vegetation usually should not be planted below the AHW elevation. Generally the channel boundary below the AHW elevation is subjected to higher velocities and boundary shear stresses than regions above, therefore AHW roughly delineates the upper boundary of the zone in which structural support should be applied to the toe of the bank. The annual low water (ALW) indicates the general elevation the roots must be able to penetrate down to in order to have access to water during the dry season. ALW approximates the depth of the vadose zone in a stream bank soil profile. The elevation of the vadose zone is increasingly dictated by soil type as distance from the stream lengthens (McCullah and Gray 2005).

Design high water (DHW), as calculated and specified by the designer, defines the upper elevation extent of a structure or technique, not including the required level of freeboard. The DHW elevation simply depicts the extent to which a technique may be inundated during a rare (design) hydrologic event. The designer must select techniques and materials suitable for hydraulic forces (i.e., waves, currents, seepage) or gravitational loading anticipated under design conditions. Design hydraulic loading may or may not coincide with the highest water levels. The relationship between river stage and hydraulic loading is site-specific due to differences in energy slope, channel roughness, and channel geometry. Figure 4.1 provides a visual representation of DHW, AHW, ALW, and examples of techniques suitable for particular elevations (McCullah and Gray 2005). For more details, reference to *NCHRP Report 544* is suggested.

Copyright National Academy of Sciences. All rights reserved.

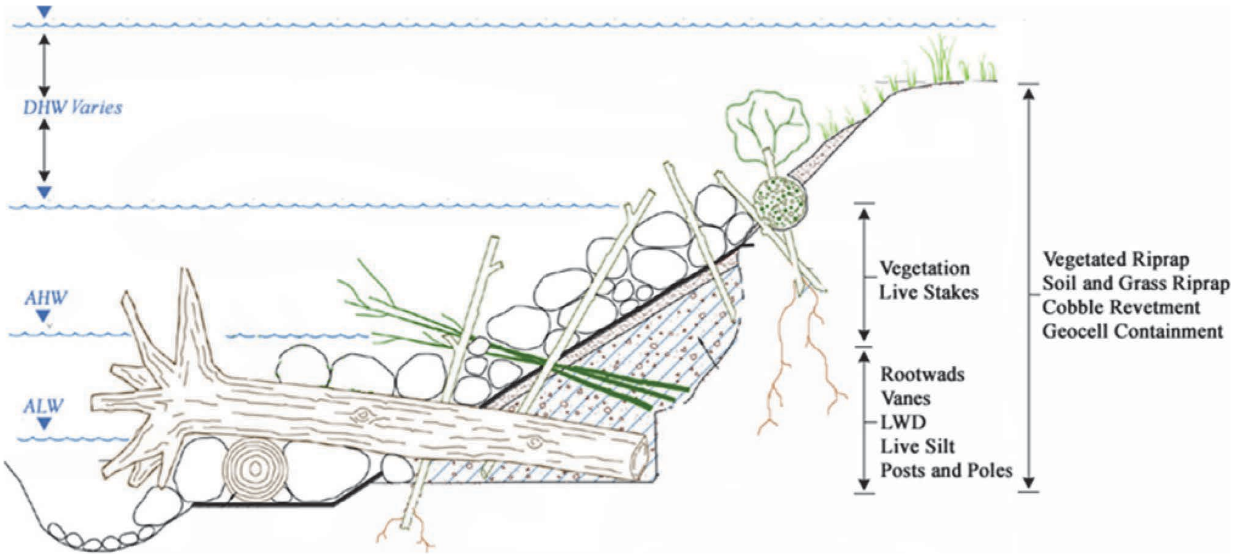


Figure 4.1. Elevation diagram of DHW, AHW, and ALW (McCullah and Gray 2005).

Conveyance. *NCHRP Report 544* also contains a special topic on management of conveyance in relation to design of environmentally sensitive stream bank treatments. Here the term conveyance refers to the amount of flow a channel can carry with a given energy slope (i.e., it represents the frictional controls imposed on discharge rate by channel cross-sectional shape and roughness). Bed and bank stabilization treatments can modify cross-sectional shape, influence roughness, and otherwise influence channel conveyance. The incorporation of vegetation and large wood into channel and bank stabilization measures frequently results in rougher channel boundaries than more traditional measures. For example, plantings of woody vegetation may provide more flow resistance than riprap revetment. Changes in conveyance properties of a channel can have both engineering and ecological implications. If flooding or upstream drainage is an issue at the site in question, the designer may have to estimate the impact of proposed measures on flood stages. During low-flow periods conveyance properties affect both depth and velocity, which have important implications for fish and other stream dwelling organisms (see Section 4.2.6). In either case, an environmentally sensitive approach to channel protection implies a thoughtful review of the consequences of any large alteration in existing channel conveyance properties (McCullah and Gray 2005).

This special topic in *NCHRP Report 544* includes guidance on such stream-related hydraulic concepts as:

- Uniform flow equations,
- Estimating Manning n values for simple and complex boundaries, and
- Selecting Manning n values for vegetated boundaries.

For uniform flow conditions *NCHRP Report 544* notes that the oldest and perhaps simplest approach for computing channel conveyance for steady flow conditions involves the use of a uniform flow equation like the Manning or Chezy equations that contain a coefficient that represents the combined effect of all of the channel characteristics that contribute to flow resistance. For example, the coefficient n in the Manning equation:

$$Q = \frac{1.486}{n} AR^{2/3}S^{1/2} \qquad (4.1)$$

reflects channel bed material, bank conditions, planform, and cross-section shape for an entire reach, while Q is the discharge in ft^3/s, A is the cross-sectional area of the flow in ft^2, R is the

Copyright National Academy of Sciences. All rights reserved.

hydraulic radius in ft, and S is the energy slope. R is equal to A/P, where P is the wetted perimeter in ft, and S is equal to the bed slope when flow is uniform. If SI units are used, the conversion factor in the numerator is simply 1.0 instead of 1.486.

Experienced designers often select n values based on experience or calibrate their n values based on stage-discharge curves from nearby gaging stations. Typically the Manning equation as expressed above is applied to an entire reach only for preliminary estimates or as a first step in design. More detailed analyses are typically based on computer models that represent the channel as a series of cross sections, for example, the USACE 1-dimensional HEC-RAS model (USACE 2010).

When trying to simulate flow effects of vegetation, the user must decide if seasonal factors should be considered. Case studies show that flow resistance due to deciduous vegetation in full leaf is much greater than for dormant (winter) conditions. HEC-RAS allows input of constant factors for adjusting n values by month. Finally, over the long term, vegetation may impact conveyance by inducing sediment deposition. Inclusion of sedimentation in the hydraulic analysis for a project will increase the cost and complexity of the analysis several times (McCullah and Gray 2005).

Again, referring to *NCHRP Report 544* for more detailed guidance is suggested. HEC-20 (Lagasse et al. 2012) and HDS 6 (Richardson et al. 2001) also provide guidance on applications of the Manning and Chezy equations and detailed guidance for estimating the roughness coefficient. References cited in Section 2.2.5 under "Fluid Mechanics" provide additional detail on recent findings regarding the effect of woody vegetation on flow resistance.

Analyzing Aggradation and Degradation. For the successful performance of any stream bank protection it is essential to determine, and, if necessary, control the vertical stability of the stream bed in the reach of concern. If progressive long-term degradation problems in particular exist, most hard engineering and environmentally sensitive treatments will ultimately fail unless this process is controlled by a countermeasure to correct and hold the vertical position of the stream bed.

The typical effects associated with bed elevation changes at highway infrastructure are the exposure and undermining of foundations from degradation or a reduction in flow area from aggradation (resulting in more frequent overbank flow). Bank caving associated with degradation poses the same problems at structures as lateral erosion from bend migration, but the problems may be more severe because of the lower elevation of the stream bed. Aggrading stream channels also tend to become wider as aggradation progresses, eroding floodplain areas and highway embankments on the floodplain (Lagasse et al. 2012).

It has been reported that there are serious problems at about three degradation sites for every aggradation site (Brown et al. 1980). This is a reflection of the fact that degradation is more common than aggradation, and also the fact that aggradation does not directly endanger the infrastructure foundation. It is not, however, an indication that aggradation is not a serious problem in some channel reaches.

Problems commonly associated with degrading channels include the undermining of cutoff walls, other flow-control structures, and bank protection. Bank sloughing because of degradation often greatly increases the amount of debris carried by the stream and increases the potential for blocked waterway openings, reduced conveyance, and increased scour at bridges (Lagasse et al. 2010). The hazard of local scour becomes greater in a degrading stream because of the lower stream bed elevation.

Aggradation in a stream channel increases the frequency of higher stages that can cause damage. In the case of highway infrastructure, bridge decks and approach roadways become inundated more frequently, disrupting traffic, subjecting the superstructure of the bridge to hydraulic forces that can cause failure, and subjecting approach roadways to overflow that can erode and cause

Copyright National Academy of Sciences. All rights reserved.

failure of the embankment. Where lateral erosion or increased flood stages accompanying aggradation increase the debris load in a stream, the hazards of clogged bridge waterway, reduced conveyance, and hydraulic forces on bridge superstructures are increased.

Data records for at least several years are usually needed to detect bed elevation problems. This is due to the fact that the channel bottom often is not visible and changes in flow depth may indicate changes in channel width, flow rate, local scour, or obstructions rather than bed elevation changes. Reach-scale bed elevation changes typically develop over long periods of time even though rapid change can occur during an extreme flood event. The data needed to assess bed elevation changes include historic stream bed profiles and long-term trends in stage-discharge relationships. Occasionally, information on bed elevation changes can be gained from a series of maps prepared at different times. Bed elevations at railroad, highway, and pipeline crossings monitored over time may also be useful. On many large streams, the long-term trends have been analyzed and documented by agencies such as the USGS and the USACE.

As noted in Section 4.2.2, long-term bed elevation changes may be the natural trend of the stream or may be the result of some modification to the stream or watershed. The stream bed may be aggrading, degrading, or in relative equilibrium in the vicinity of a planned bank-protection project. Long-term aggradation and degradation do not include the cutting and filling of the stream bed at a stream crossing that might occur during a runoff event (contraction and local scour). A stream may cut and fill at specific locations during a runoff event and also have a long-term trend of an increase or decrease in bed elevation over a longer reach of a stream. The problem for design of stream bank protection measures is to estimate the long-term bed elevation changes that will occur during the life of the planned treatment.

A long-term trend may change during the life of a project as a result of modifications to the stream or watershed (see Section 4.2.2). Such changes may be the result of natural processes or human activities. The designer must assess the present state of the stream and watershed and then evaluate potential future changes in the river system. From this assessment, the long-term stream bed changes must be estimated.

Factors that affect long-term bed elevation changes are dams and reservoirs (up- or downstream of a study reach), changes in watershed land-use (urbanization, deforestation, etc.), channelization, cutoffs of meander bends (natural or of human origin), changes in the downstream channel base level (control), gravel mining from the stream bed, diversion of water into or out of the stream, natural lowering of the fluvial system, and movement of a bend with respect to stream planform. Tidal ebb and flood may degrade a coastal stream; whereas, littoral drift may result in aggradation. The elevation of the bed under stream crossings on streams tributary to a larger stream will follow the trend of the larger stream unless there are controls. Controls could be bed rock, dams, culverts, check dams, or other structures.

Data from the USACE, USGS, and other federal and state agencies should be considered when evaluating long-term stream bed variations. If no data exist or if such data require further evaluation, an assessment of long-term stream bed elevation changes for riverine streams should be made using the principles of river mechanics [see HDS 6 (Richardson et al. 2001)]. Such an assessment requires the consideration of all influences upon the study reach, i.e., runoff from the watershed to a stream (hydrology), sediment delivery to the channel (watershed erosion), sediment transport capacity of a stream (hydraulics), and response of a stream to these factors (geomorphology and river mechanics).

To organize an assessment of long-term aggradation and degradation, a three-level fluvial system approach can be used. The three-level approach consists of (1) a qualitative determination based on general geomorphic and river mechanics relationships, (2) an engineering geomorphic analysis using established qualitative and quantitative relationships to estimate the probable behavior of the

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

stream system to various scenarios or future conditions, and (3) physical models or physical process computer modeling using mathematical models such as the USACE HEC-RAS (USACE 2010) to make predictions of quantitative changes in stream bed elevation due to changes in the stream and watershed. Methods to be used in Levels 1 and 2 are presented in HEC-20 (Lagasse et al. 2012) and HDS 6 (Richardson et al. 2001). Another source for guidance on qualitative and engineering geomorphic analyses is the USACE manual *Channel Stability Assessment for Flood Control Projects* (1994).

The biennial bridge inspection reports for bridges on the stream reach under study are an excellent source of data on long-term aggradation or degradation trends. Also, inspection reports for bridges crossing streams in the same area or region should be studied. In most states the biennial inspection includes taking the elevation and/or cross section of the stream bed under the bridge. These elevations are usually referenced to the bridge, but these relative bed elevations will show trends and can be referenced to sea level elevations. Successive cross sections from a series of bridges in a stream reach can be used to construct longitudinal stream bed profiles through the reach.

The USGS and many state water resource and environmental agencies maintain gaging stations to measure stream flow. In the process, they maintain records from which the aggradation or degradation of the stream bed can be determined. Where an extended historical record is available, one approach to using gaging station records to determine long-term bed elevation change is to plot the change in stage through time for a selected discharge. This approach is often referred to as establishing a "specific gage" record.

Figure 4.2 shows a plot of specific gage data for a discharge of 500 cfs (14 m^3/sec) from about 1910 to 1980 for Cache Creek in California. During that period, Cache Creek experienced significant gravel mining with records of gravel extraction quantities available since about 1940. When the historical record of cumulative gravel mining is compared to the specific gage plot, the potential impacts are apparent. The specific gage record shows more than 10 ft (3 m) of long-term degradation in a 70-year period.

In addition, the geology and geomorphology of the site need to be studied to determine the potential for long-term bed elevation changes at the project site. Quantitative techniques for stream bed aggradation and degradation analyses are covered in detail in HEC-20 (Lagasse et al. 2012). These techniques include:

- Incipient motion analysis,
- Analysis of armoring potential,
- Equilibrium slope analysis, and
- Sediment continuity analysis.

Sediment transport concepts and equations are discussed in detail in HDS 6 (Richardson et al. 2001), HDS 7 (Zevenbergen et al. 2012), and HEC-20 (Lagasse et al. 2012).

Sediment transport computer models can be used to determine long-term aggradation or degradation trends. These computer models route sediment down a channel and adjust the channel geometry to reflect imbalances in sediment supply and transport capacity. The USACE HEC-RAS (USACE 2010) model is an example of a sediment transport model that can be used for single-event or long-term estimates of changes in bed elevation.

Sediment routing is essentially an application of the sediment continuity concept. Here, sediment inflow and outflow for a specific reach are analyzed and the sediment transport capacity is used to update cross-section geometry, which is then used to update the hydraulic calculations. The geometry is updated for individual cross sections, though the hydraulic variables can be weighted with up- and downstream cross sections. A flood hydrograph or long-term

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

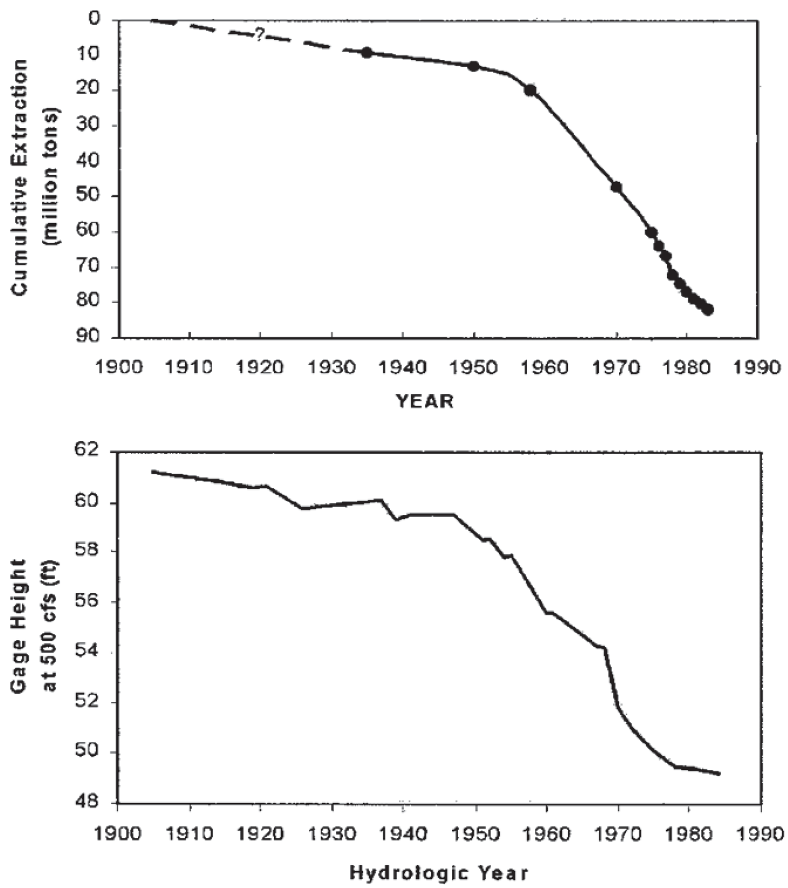


Figure 4.2. Specific gage data for Cache Creek, California.

flow hydrograph is entered as a series of constant flows. Within each flow time step, many sediment transport and cross-section updating time steps are often required. The model does not assume that transport capacity is reached at every cross section, but limits erosion based on potential entrainment rates and limits deposition based on fall velocity, flow velocity, and water depth. Sediment layer depths, as well as lateral limits for erosion and deposition are also input. Sediment transport modeling generally requires greater model extent upstream and downstream than a hydraulic flow model, as well as careful consideration of all boundary conditions (hydraulic and sediment).

The Channel Evolution Model. Earth scientists (geomorphologists) have historically concerned themselves with documenting and explaining the changing morphology of the landscape through time and have documented the changing character of a landscape during long periods of geologic time. Initially, this type of evolution of landforms would appear to be of no interest to the highway engineer, but it serves as an alert that change can be expected at the scale of individual landforms (hillslopes, channels), and that the change can be sufficiently rapid to cause problems with the design and maintenance of environmentally sensitive stream bank protection measures (Lagasse et al. 2012).

In the case of incised channels (gullies, arroyos) rapid incision can be followed by channel adjustment (deepening, widening) to a new condition of relative stability (on an engineering time scale) as erosion decreases, sediment storage increases, and a floodplain develops (Figure 4.3). Simon (1989) obtained data on the sediment loads transported through incised channels in Tennessee (Figure 4.4). The stages of channel evolution shown in Figure 4.3 are reflected in the changing

Copyright National Academy of Sciences. All rights reserved.

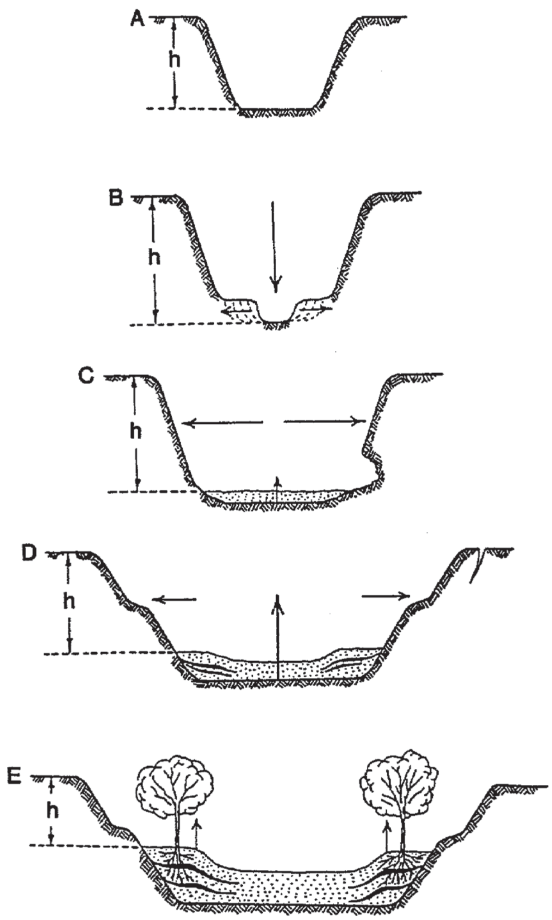


Figure 4.3. Evolution of incised channel from initial incision (A, B) and widening (C, D) to aggradation (D, E) and eventual relative stability; h is bank height (Schumm et al. 1984).

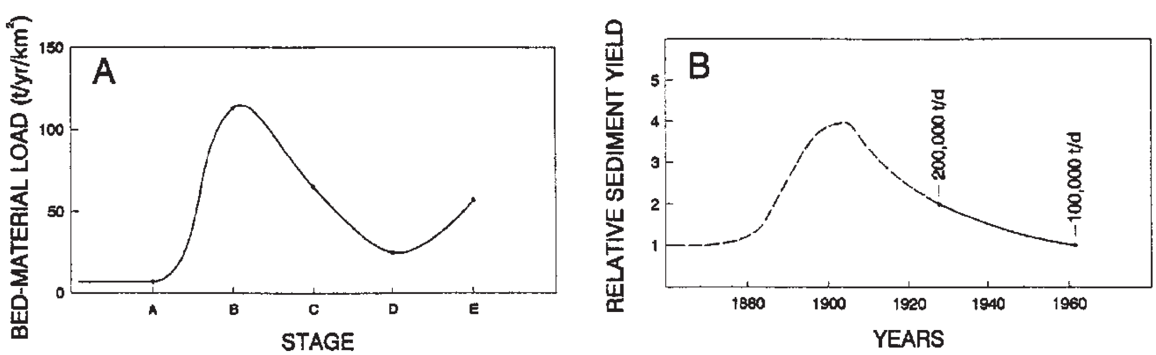


Figure 4.4. Sediment loads following channel incision: (A) bed-material load transported by incised Tennessee streams for each stage of incised-channel evolution (Figure 4.3), (B) hypothetical (dashed line) and measured (solid line) sediment volumes transported through Grand Canyon (Gellis et al. 1991).

Copyright National Academy of Sciences. All rights reserved.

sediment loads of Figure 4.4. Note that there is an apparent increase of sediment load at stage E (Figure 4.4A) as some stored sediment is remobilized.

Although applicable only to incised channels, this and similar evolution models (Harvey and Watson 1986) have been of value in developing an understanding of watershed channel dynamics and in characterizing whether or not a reach is stable (ASCE 2008). This model (Figure 4.3) was originally based on observations of Oaklimiter Creek, a channelized (straightened) stream with sandy bed and cohesive banks in northern Mississippi (Schumm et al. 1984). The sequence described a systematic response of a channel to base level lowering and encompasses conditions that range from disequilibrium (Figure 4.3E) to a new state of dynamic equilibrium (Figure 4.3B and 4.3E). Stages C and D in Figure 4.3 illustrate the widening that can accompany incision. These stages are only conceptual and variations may be encountered in the field; however, the sequence enables the evolutionary state of the channel to be determined from field observations that record the characteristic channel forms associated with each stage of evolution. The morphometric characteristics of the channel reach types can also be correlated with hydraulic, geotechnical, and sediment transport characteristics (ASCE 2008).

Field investigations in the upper Colorado River basin have also revealed that the large arroyos formed by incision of valley-floor alluvium in the latter part of the nineteenth century are at present storing sediment in newly developed floodplains (Gellis et al. 1991). Daily sediment-load data downstream from these arroyos for 1930–1963 were examined, with later data excluded to avoid confounding effects of reservoirs. These incised channels are also behaving as illustrated in Figure 4.3. At the later stages of adjustment they are eroding less sediment and storing larger amounts of sediment. As a result, sediment loads at the Grand Canyon gaging station have decreased during the period of record, prior to closure of Glen Canyon Dam and other upstream dams in 1963 (Figure 4.4B). In addition, sediment deposition in Lake Powell between 1963 and 1986 is only 43 percent of that estimated prior to dam construction (Ferrari 1988), which indicates that the channel adjustment process is occurring throughout the upper Colorado River basin in a manner similar to that in the incised channels of Tennessee (Figure 4.4A). Because of climatic differences, the evolutionary changes involved in the complex response of Figures 4.3 and 4.4 require about 100 years in the Southwest but only about 40 years in the Southeast.

As noted in Section 4.2.4, mature trees on a graded bank slope are convincing evidence of bank stability. A detailed study of bank erosion on streams in southern British Columbia provides a quantitative assessment of the role of riparian vegetation in limiting channel width adjustments in bends during major flood events (Beeson and Doyle 1995). A total of 748 bends in four stream reaches were assessed by comparing pre- and post-flood aerial photography. Bends without riparian vegetation were found to be nearly five times as likely as vegetated bends to have undergone detectable erosion during the flood events. The likelihood of erosion on semi-vegetated bends was between that of the vegetated and non-vegetated category of bends. Most of the non-vegetated bends experienced major erosion (widening) in excess of 150 ft (45 m). Similar findings have been reported for streams in other regions, but the effect of riparian vegetation diminishes as bank heights and angles increase so that root reinforcement does not extend deeply enough to intersect failure planes. Also, large rivers deeply inundate the lower bank so that vegetation does not grow in that critical zone.

Although the landscape as a whole may appear unchanging except over long periods of time, components of the landscape can evolve or adjust to human activities and hydrologic variations (Figures 4.3 and 4.4) during relative short periods of time and can pose serious problems for the design and successful implementation of environmentally sensitive stream bank protection treatments as successive waves of aggradation and degradation sweep through the system on an engineering time scale.

Copyright National Academy of Sciences. All rights reserved.

Consequently, one of the key factors recommended for evaluation during a field site visit of an existing environmentally sensitive treatment or during the reconnaissance phase for the selection and design of a new treatment is to establish whether or not the channel is vertically stable and, if it is not, what the channel evolution stage for the reach of interest is (see Appendix C, Field Data Forms, Part 2).

The Key to Stability. Both *NCHRP Report 544* and FHWA's HEC-23 (Lagasse et al. 2009) note that a common cause of failure for both "hard" and "soft" stream bank protection measures is erosion at the upstream and downstream "flanks" on the bank and/or erosion at the toe on the stream bed. McCullah and Gray (2005) address the issue of bank or flank keys in a special topic "The Key to Stability is the Key." They observe that many stream bank protection projects fail at the upstream or downstream end. One of the important lessons derived from the Section 32 Program (see Table 2.1) is that the most common mistake in designing protection for an eroding bank is to extend bank protection too far upstream and not far enough downstream.

Local flow acceleration or "expansion" at the downstream end of a protected bank often leads to local scour that progressively undercuts the protection and eats its way upstream. At the upstream end, erosion associated with impinging flow sometimes results in flow above or behind the protective measures and eventual failure. Keys consist of rock riprap or other heavy granular material buried in deep trenches dug at 30 degree angles (not perpendicular) to the flow (see Figure 4.5) (McCullah and Gray 2005).

Design considerations include:

- Soil types.
- Flow velocities.
- Flood crests, durations, and recurrence intervals.
- Active failure areas.

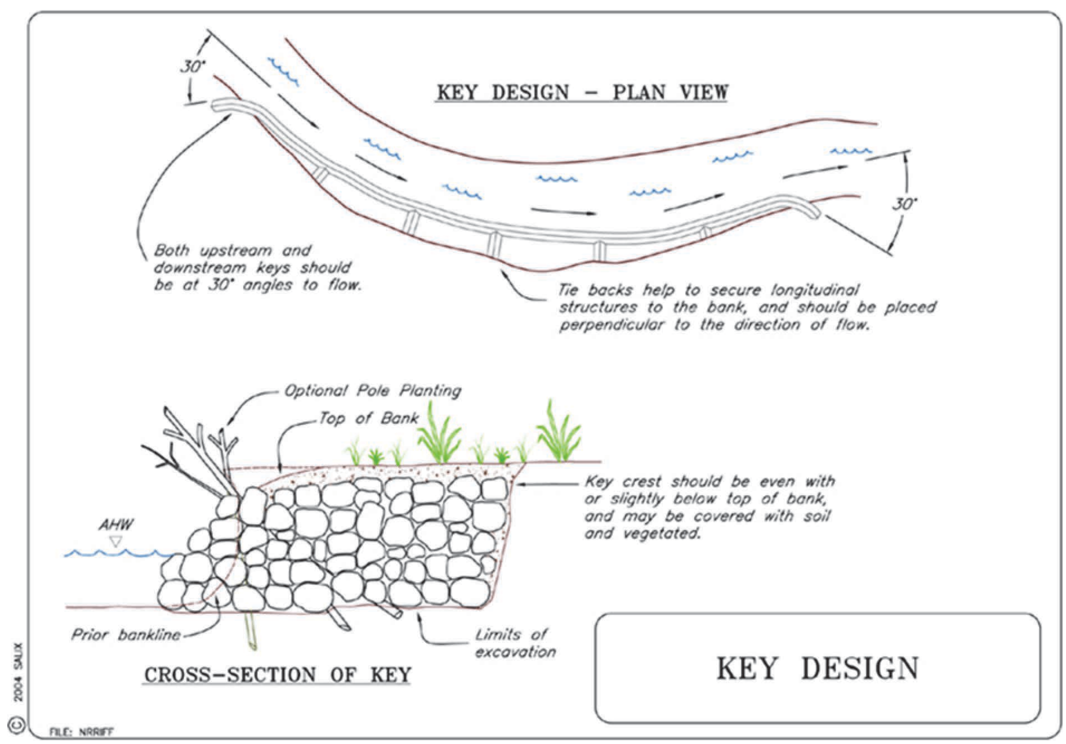


Figure 4.5. Plan and cross-section views of keys (McCullah and Gray 2005).

Copyright National Academy of Sciences. All rights reserved.

- Vegetation.
- Height of bank.
- Exposed key rocks in banks that can be angled to help redirect flow.
- Crests of keys should be flush (even) with the bank, as this will decrease turbulence and chance of scour (see Figure 4.5). If key rock is exposed on the surface of the bank, it can be angled to help redirect flow on the bank back toward the stream.
- Keys at the upstream and downstream ends of continuous longitudinal features should not be at a 90 degree angle to the feature, but at a 30 degree angle.

HEC-23 "Bridge Scour and Stream Instability Countermeasures: Experience, Selection and Design Guidance" (Lagasse et al. 2009) provides guidance for the toe scour issue for stream bank protection measures. The recommendations for riprap revetment regarding toe scour are typical (see HEC-23 Design Guideline 4) where the depth of maximum scour for countermeasure "toe down" into the stream bed includes the sum of long-term degradation, contraction scour, and toe scour. As noted, FHWA's HEC-20 (Lagasse et al. 2012) provides guidance for estimating long-term degradation in a stream reach and HEC-18 (Arneson et al. 2012) provides equations for calculating contraction scour. HEC-23 includes design guidance for estimating scour in a protected bendway (toe scour) based on work by Maynord (1996). While these techniques were developed for armoring countermeasures such as riprap or articulating concrete block systems, they are applicable to estimating "toe down" requirements for any environmentally sensitive treatment that includes a "hard" toe (e.g., longitudinal stone toe).

HEC-23 notes that deep regions along the toe of the outer bank of a bendway are the result of scour. High velocity along the outer bank is caused by secondary currents and greater outer-bank depths, and together with the resultant shear stress, produce scour and cause a difference between the sediment load entering and exiting the outer-bank zone (see Figure 4.9). Since secondary currents transport sediment supplied, in large part, from outer-bank erosion toward the inner bank of a bend, hardening of the outer bank by longitudinal bank-protection structures may cause the channel cross section to narrow and deepen by preventing the recruitment of eroded outer-bank sediments.

Experience is usually the most reliable means of estimating scour depth when designing a bank-protection project for a particular stream. Lacking experience on a particular stream, scour depths may be estimated using physically based analytical models or empirical methods. Although scour depth can be estimated empirically or analytically, empirical methods are generally found to provide better agreement with observed data.

Maynord (1996) provides an empirical method for determining scour depths on a typical bendway bank-protection project. Although his studies are restricted to sand-bed streams, the Maynord method agrees reasonably well with the limited number of gravel-bed data points obtained by Thorne and Abt (1993). Nonetheless, the techniques presented by Maynord are restricted to meandering channels having naturally developed widths and depths, and cannot be applied to channels that have been confined to widths significantly less than would occur naturally.

Maynord's method of estimating scour depth is based on a regression analysis of 215 data points. The scour data used in developing his equation were measured at high discharges that were within the channel banks and had return intervals of 1–5 years. Maximum depth as defined in his best-fit equation for scour depth estimation is a function of R_c/W, width-to-depth ratio, and mean depth as follows:

$$\frac{D_{mxb}}{D_{mnc}} = 1.8 - 0.051\left(\frac{R_c}{W}\right) + 0.0084\left(\frac{W}{D_{mnc}}\right) \quad (4.2)$$

Copyright National Academy of Sciences. All rights reserved.

where:

R_c = Centerline radius of the bend, ft (m)
W = Width of the bend, ft (m)
D_{mxb} = Maximum water depth in the bend, ft (m)
D_{mnc} = Average water depth in the crossing upstream of the bend, ft (m)

The terms D_{mxb} and D_{mnc} are defined in Figure 4.6.

The applicability of Maynord's equation is limited to streams with R_c/W from 1.5 to 10 and W/D_{mnc} from 20 to 125 because of the lack of data outside these ranges. He recommends that for channels with $R_c/W < 1.5$ or width-to-depth ratios less than 20, the scour depth for $R_c/W = 1.5$ and $W/D_{mnc} = 20$, respectively, be used.

In addition, Thorne and Abt (1993) suggest these methods are valid unless there is significant interaction between the main channel flow and overbank flow. Therefore, Maynord (1996) recommends that application of these empirical methods to overbank flow conditions should be limited to overbank depths less than 20% of the main channel depth.

Lateral Channel Stability. From a bank-protection standpoint, ideally a stable channel is one that does not change in size, form, or position over time. However, all alluvial channels change to some degree and, therefore, have some degree of inherent instability. For purposes of this document, an unstable channel is defined as one with a rate or magnitude of change that is sufficiently large to be a significant factor in the design and maintenance of engineered structures and countermeasures within the river environment (Lagasse et al. 2012).

Although a stream or river may appear unstable, this does not necessarily indicate that it is not an equilibrium or regime channel. Based on the relationship of channel width, depth, and slope to discharge, most natural alluvial channels have probably attained or approached a state of equilibrium at one time or another. Yet, these channels migrate laterally at rates ranging from imperceptible to very rapidly. Thus, equilibrium or regime channels may not necessarily be stable in the practical engineering sense. An actively migrating channel may maintain its equilibrium

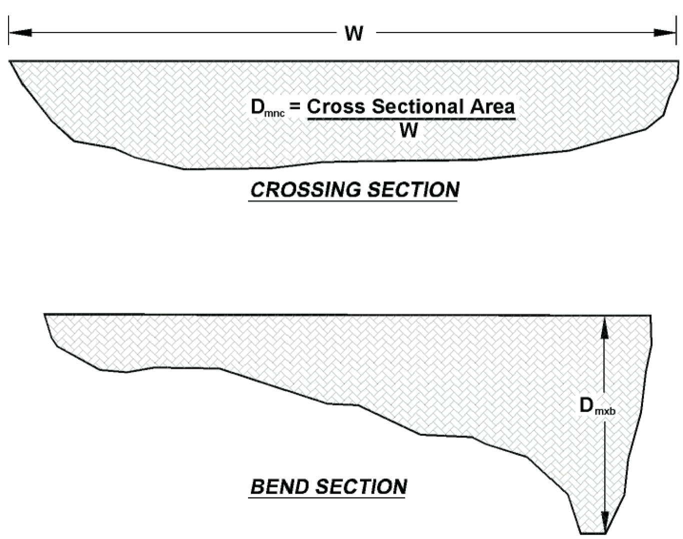


Figure 4.6. Definition sketch of width (W) and mean water depth at the crossing upstream (D_{mnc}) of the bend and maximum water depth in the bend (D_{mxb}).

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

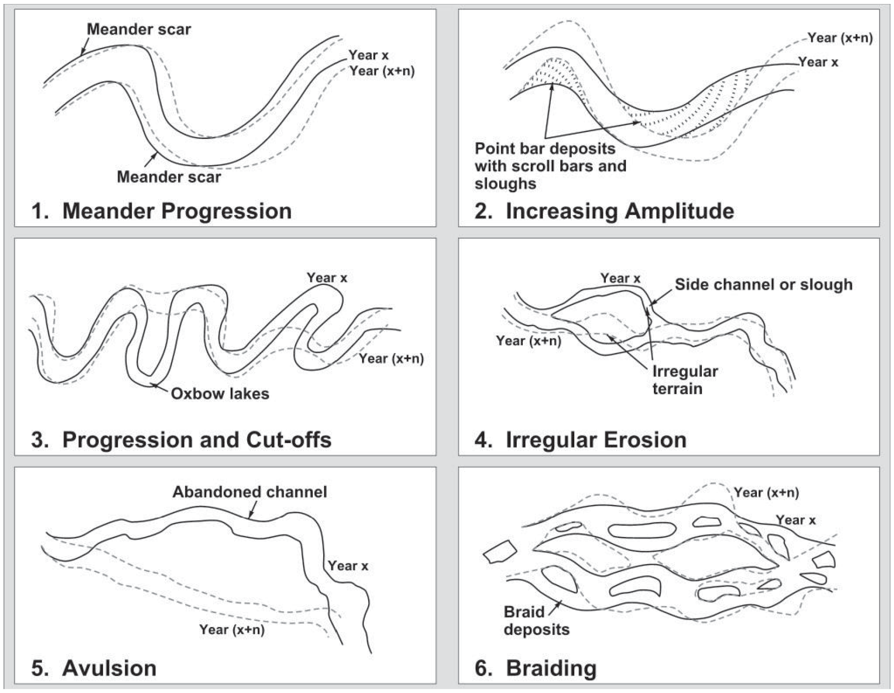


Figure 4.7. Types of lateral activity and typical associated floodplain features (Thorne 1998).

slope and cross section while posing a threat or hazard to engineered structures and both "hard" and "soft" countermeasures. Some types of lateral instability are shown in Figure 4.7.

Meandering streams (Sketches 1, 2, and 3 in Figure 4.7) are classified as either actively or passively meandering. An actively meandering stream has sufficient stream power to deform its channel boundaries through active bed scour, bank erosion, and point bar growth. Conversely, while a passively meandering stream is sinuous, it does not migrate or erode its banks. Such channels are sometimes termed, "ideally stable," or "moribund."

Although there is no completely satisfactory explanation of how or why meanders develop (Knighton 1998), it is known that meanders are initiated in straight channels by localized bank retreat which alternates from one side of the channel to the other in a more or less regular pattern. In addition, deformation of the channel bed may be an important prerequisite that modifies the pattern of flow prior to meandering. It is believed that secondary helicoidal flow develops spontaneously in straight channels as a result of vortices generated at the boundary walls (Figure 4.8) (Einstein and Shen 1964, Shen and Komura 1968). A pair of surface-convergent helical cells will form if vortices develop along both banks. Inequalities in bank roughness may induce asymmetry in these cells and periodic reversal of the dominant cell. This periodically reversing helicoidal flow has an important influence on the pattern of erosion and deposition through meanders, and more specifically by forming a meandering thalweg and alternating bars (Einstein and Shen 1964). In addition, macroturbulent flow and the bursting process (i.e., streamwise fluctuations in the velocity field) are also important components in bank deformation (Yalin 1971 and 1992).

The primary features of the flow pattern through meander bends are:

- Superelevation of the water surface against the outside (convex) bank (Figure 4.9)
- Transverse current directed toward the outer bank at the surface and toward the inner bank at the bed producing a secondary circulation additional to the main downstream flow

Copyright National Academy of Sciences. All rights reserved.

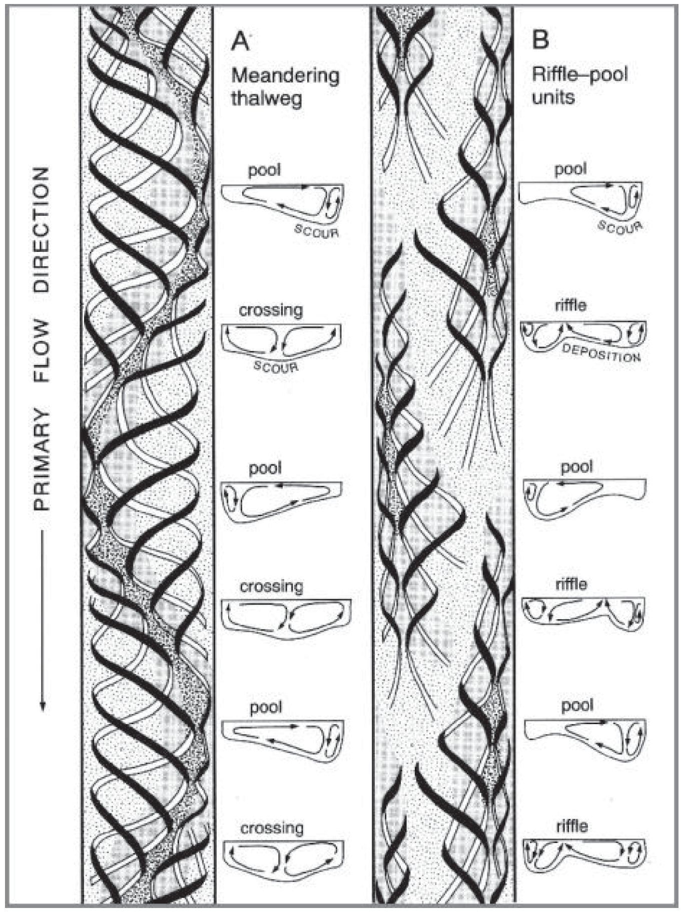


Figure 4.8. Models of flow structure and associated bed forms in straight alluvial channels: (A) Einstein and Shen's (1964) model of twin periodically reversing, surface-convergent helical cells (the dark stippled line shows the trace of the thalweg) and (B) Thompson's (1986) model of surface-convergent flow produced by interactions between the flow and a mobile bed, creating riffle-pool units of alternate asymmetry. Black lines indicate surface currents, and white lines represent near-bed currents (Knighton 1998).

- Maximum-velocity current which moves from near the inner bank at the bend entrance to near the outer bank at the bend exit, crossing the channel at the zone of maximum bend curvature

The interaction between centrifugal force acting outwardly on the water as it flows around the bend and an inward-acting pressure gradient force driven by the cross-stream tilting of the water surface is reflected in the above characteristics. The transverse current and the primary downstream flow component combine to produce the helicoidal motion to the flow. The superelevation of the water surface against the outer bank of a bend produces a locally steep downstream energy gradient and, in turn, a zone of maximum boundary shear stress in close proximity to the outer bank just downstream of the bend apex (Figure 4.9). The maximum shear stress zone shifts outward further upstream as a result of the bar-pool topography and cross-sectional asymmetry characteristic of meander bends.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

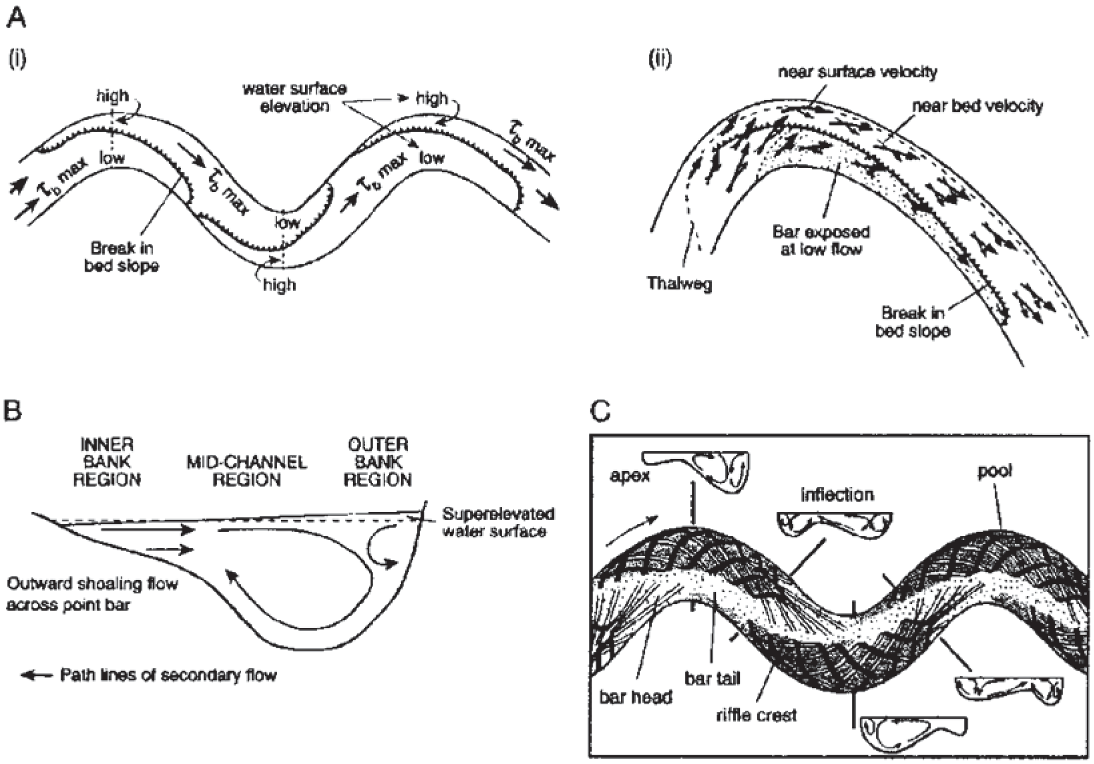


Figure 4.9. Flow patterns in meanders: (A) (i) location of maximum boundary shear stress (τ_o), and (ii) flow field in a bend with a well-developed point bar (after Dietrich 1987); (B) secondary flow at a bend apex showing the outer-bank cell and the shoaling-induced outward flow over the point bar (after Markham and Thorne 1992); and (C) model of the flow structure in meandering channels (after Thompson 1986). Black lines indicate surface currents and white lines represent near-bed currents (Knighton 1998).

Secondary currents, which are usually weaker than primary ones, influence the distribution of velocity and boundary shear stress. Markham and Thorne (1992) divided the bend cross section into three regions relative to the pattern of secondary flow (Figure 4.9):

- Mid-channel region, helicoidal flow is well established passing nearly 90 percent of the flow;
- Cell of opposite circulation develops in the outer-bank region: the strength of this cell increases with discharge, the steepness of the bar, and the acuteness of the bend; and
- Inner bank region where shoaling over the point bar induces a net outward flow, forcing the core of maximum velocity more rapidly toward the outer bank (Dietrich and Smith 1983, Dietrich 1987); increasing stage tends to reduce the shoaling, allowing an inward component of near-bed flow over the bar top.

Understanding the role of secondary currents is particularly important in the design of "redirective techniques" that disrupt the secondary circulation, particularly in larger, deeper channels. For more detail on the utility of redirective techniques in stream bank protection see McCullah and Gray (2005).

In summary, the pattern of primary and secondary currents influences the distribution of erosion and deposition in meanders. In general, erosion in the bend is concentrated along the outer bank downstream of the bend apex where the currents are strongest, while point bar building predominates in a parallel position along the opposite bank, with material supplied

Copyright National Academy of Sciences. All rights reserved.

by longitudinal and transverse currents. This produces a largely down-valley component to meander migration. The next section introduces and references a relatively simple technique for predicting the rate and direction of meander bend movement that could be applied in the design, installation, and monitoring of environmentally sensitive stream bank treatments.

Predicting Meander Migration. In general, most streams are sinuous to some degree and the majority of bank retreat and lateral migration occurs along meander bends. As such, the following discussion on evaluating and predicting lateral migration will focus on meander bends. A relatively accurate method of determining migration rates and direction is through the comparison of sequential historical aerial photography (photos), maps, and surveys. In the 1970s Brice introduced a methodology for conducting a stream stability and meander migration assessment using a comparative analysis of aerial photos, maps, and channel surveys for both the Army Research Office (ARO) and FHWA (Brice 1975, 1982). Today, historical aerial photos and maps can be obtained from a number of federal, state, and local agencies (see HEC-20 Section 6.3 for a detailed listing of sources).

Developing a practical methodology to predict the rate and extent of channel migration (i.e., lateral channel shift and down-valley migration) in proximity to transportation facilities was the objective of NCHRP Project 24-16 (Lagasse et al. 2004). This research produced *NCHRP Report 533: Handbook for Predicting Stream Meander Migration* using aerial photographs and maps. The handbook deals specifically with the problem of incremental channel shift and provides a relatively simple methodology for predicting the rate and extent of lateral channel shifting and down-valley migration of meanders. The methodology is based, primarily, on the analysis of bend movement using map and aerial photo comparison (overlay) techniques. For additional details and a demonstration of the procedure refer to *NCHRP Report 533* (Lagasse et al. 2004) and/or HEC-20 (Lagasse et al. 2012).

As with any analytical technique, aerial photograph comparison technologies have limitations. The accuracy of photo comparison is greatly dependent on the period over which migration is evaluated, the magnitude of internal and external perturbations forced on the system over time, and the number and quality of sequential aerial photos and maps. The analysis will be much more accurate for a channel that has coverage consisting of multiple datasets (aerial photos, maps, and surveys) covering a long period of time (several decades to more than 100 years) versus an analysis consisting of only two or three datasets covering a short time period (several years to a decade). Predictions of migration for channels that have been extensively modified or have undergone major adjustments attributable to extensive land-use changes will be much less reliable than those made for channels in relatively stable watersheds. Since the scale of aerial photography is often approximate, contemporary maps are usually needed to accurately determine the scale of air photos without the use of sophisticated photogrammetric instruments.

In addition to scale adjustment and distortion problems that are inherent in the use of aerial photography for comparative purposes, there are a number of physical characteristics of the river environment that can complicate the prediction of meander migration impacts on transportation facilities. Countermeasures to halt bank erosion or protect a physical feature within the floodplain can have an impact on the usefulness of the overlays and these features should be identified prior to developing the overlays. Anomalous changes in the bend or bankline configuration or a major reduction in migration rates may suggest that bank protection is present, especially in areas where the bankline is not completely visible or on images with poor resolution.

Geologic features such as clay plugs or rock outcrops in the floodplain can also limit the usefulness of the overlays because they can have a significant influence on migration patterns. Bends can become distorted as they impinge on these features and localized bankline erosion rates may decrease significantly as these erosion resistant features become exposed in the bank.

Copyright National Academy of Sciences. All rights reserved.

In reaches where geologic controls are exposed predominantly in the bed of the channel, migration rates may dramatically increase because the channel bed is not adjustable.

A fundamental assumption of overlay techniques based on aerial photo or map comparison is that a time period sufficient to "average out" such anomalies will be available, making the historic meander rates a reasonable key to the future. Even with these limitations, however, determining the rate and direction of movement of a specific bend can provide insight and specificity to the design, installation, and monitoring of environmentally sensitive stream bank protection measures.

Hydraulic Stress on a Bendway. As an indicator of the potential for success with a specific treatment for erosion of the stream bank in a meander bend, the ratio of bend radius of curvature to flow width can provide insight into the force on the meander bend margin. This parameter does not include discharge. A quantitative technique that considers a single-event discharge and an estimate of the radial stress on a meander bend margin was developed to evaluate the performance of alternative stream bank erosion protection techniques for the USACE, Vicksburg District [Water, Engineering & Technology (WET) 1990]. This technique could also be used to evaluate alternative channel instability countermeasures for an erosion site located in a meander bend (Lagasse et al. 2009).

For this technique, Begin (1981) defines radial stress as the centripetal force divided by the outer-bank area. The centripetal force is responsible for deflecting the flow around the bend and is equal to the apparent reactive force of the flow on the bend. Thus, the radial stress is defined as a force per unit area (lbs/ft^2 or N/m^2). Although it is not suggested that the radial stress is directly responsible for meander bend migration or failure of bank-protection countermeasures, Begin did show that the radial stress is related to meander migration. It is assumed that shear stress is related to radial stress because of water surface superelevation and increased near-bank velocity gradients (see Figure 4.9).

Field investigations and computation of radial stress on banklines for channels in the Yazoo River basin in Mississippi clearly showed that rudimentary countermeasures (such as used-tire revetment) were generally unsuccessful even in bends with low to moderate radial stress (WET 1990). The study also showed that stone structures including longitudinal stone dikes and stone spurs performed well in reaches of high radial stress. Isolated failures of stone structures did occur at locations with the highest radial stress. The 2-year storm discharge was used in the computations for radial stress at these sites.

As an alternative, the increased shear force on the outside of bends can be calculated by multiplying the bed shear stress, τ_0, by a dimensionless bend coefficient, K_b. The sharper the bend, the greater the shear stress imposed on the outer bank. The bend coefficient, K_b, is related to the ratio of the bend radius of curvature, R_c, divided by the top width of the channel, T, as shown in Figure 4.10.

While the simplistic techniques presented in this section can provide a "quick estimate" of relative stress on a bendway, design practice is rapidly moving toward the use of 2-D hydrodynamic models that provide shear stress and velocity values for each grid cell at each time step.

4.2.4 Geotechnical Considerations

Overview

As discussed in Sections 4.2.2 and 4.2.3, geomorphic factors that influence the success or failure of an environmentally sensitive stream bank protection measure include aggradation or degradation of the stream bed, the evolution of incised channels, meander migration, channel width adjustments, and radial stress on meander bendways. There is an obvious interplay between

Copyright National Academy of Sciences. All rights reserved.

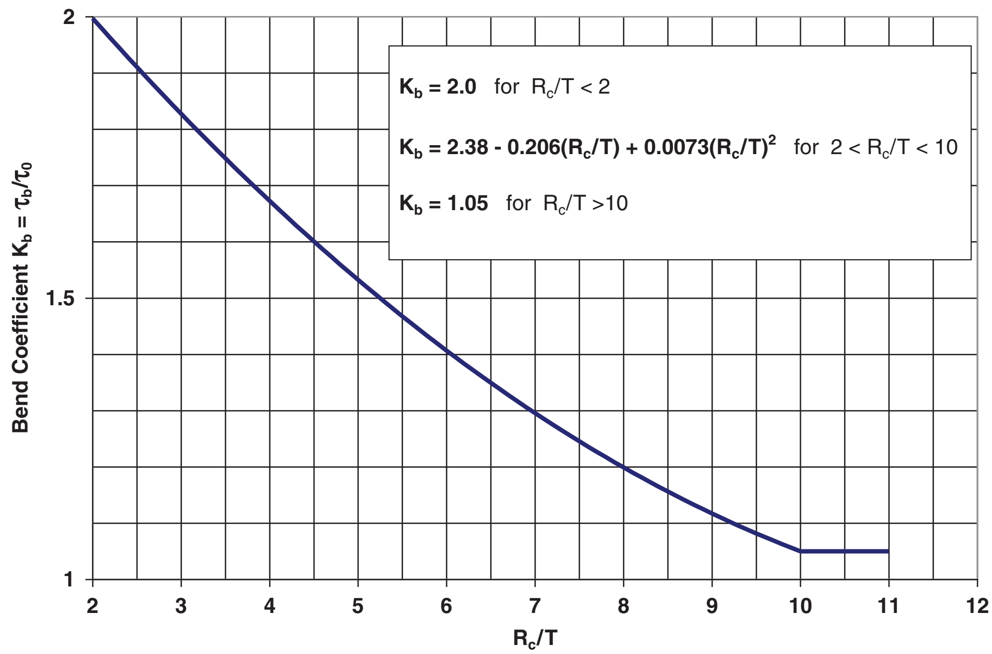


Figure 4.10. Shear stress multiplier, K_b, for bends (Kilgore and Cotton 2005).

these geomorphic factors and the geotechnical considerations that affect the stability of the channel banks on which the erosion protection measures are to be placed. The vertical stability of the channel directly affects the stability of the channel banks, and the lateral stability of the channel is a function of the hydraulic stresses to which the channel banks are subjected. In this section the general processes affecting channel bank geotechnical stability are discussed, followed by consideration of several site-specific factors that influence the success or failure of stream bank erosion control measures.

The appearance of the stream bank is generally a good indication of relative stability. A field inspection of a channel will help to identify characteristics that are associated with erosion rates:

- Unstable banks with moderate to high erosion rates usually have slopes that exceed 30 percent, and a cover of woody vegetation is rarely present. At a bend, the point bar opposite an unstable cut bank is likely to be bare at normal stage, but it may be covered with annual vegetation and low woody vegetation, especially willows. Where very rapid erosion is occurring, the bank may have irregular indentations. Fissures, which represent the boundaries of actual or potential slump blocks along the bankline, indicate the potential for very rapid bank erosion.
- Unstable banks with slow to moderate erosion rates may be partly reshaped to a stable slope. The degree of instability is difficult to assess, and reliance is placed mainly on vegetation. The reshaping of a bank typically begins with the accumulation of slumped material at the base such that a slope is formed and progresses by smoothing of the slope and the establishment of vegetation.
- Eroding banks are a source of debris when trees fall as they are undermined. Therefore, debris can be a strong indicator of unstable bank conditions.
- Stable banks with very slow erosion rates tend to be graded to a smooth slope of less than about 30 percent. Mature trees on a graded bank slope are convincing evidence of bank stability. In most regions of the United States, the upper parts of stable banks are vegetated, but the lower part may be bare at normal stage, depending on bank height and flow regime of the stream. Where banks are low, dense vegetation may extend to the water's edge at normal stage. Where banks are high, occasional slumps may occur on even the most stable graded banks.

Copyright National Academy of Sciences. All rights reserved.

Figure 4.11. Active bank erosion illustrated by vertical cut banks, slump blocks, and falling vegetation.

Active bank erosion can be recognized by falling or fallen vegetation along the bankline, cracks along the bank surface, slump blocks, deflected flow patterns adjacent to the bankline, live vegetation in the flow, increased turbidity, fresh vertical faces, newly formed bars immediately downstream of the eroding area, and, in some locations, a deep scour pool adjacent to the toe of the bank. These indications of active bank erosion can be noted in the field and on stereoscopic pairs of aerial photographs. Color infrared photography is particularly useful in detecting most of the indicators listed above, especially differences in turbidity (Shen et al. 1981). Figure 4.11 illustrates some of the features that indicate that a bankline is actively eroding.

Physical Processes Controlling Bank Failure

Bank Materials. Resistance of a stream bank to erosion is closely related to several characteristics of the bank material. Bank material deposited in the stream can be broadly classified as cohesive, noncohesive, and composite. Typical bank failure surfaces of various materials are shown in Figure 4.12 and are described as follows (Brown 1985):

- Noncohesive bank material tends to be removed grain by grain from the bank. The rate of particle removal and, hence, the rate of bank erosion is affected by factors such as particle size, bank slope, the direction and magnitude of the velocity adjacent to the bank, turbulent velocity fluctuations, the magnitude of and fluctuations in the shear stress exerted on the banks, seepage force, piping, and wave forces. Figure 4.12(a) illustrates failure of banks of noncohesive material from flow slides resulting from a loss of shear strength because of saturation and failure from sloughing resulting from the removal of materials in the lower portion of the bank.
- Cohesive material is more resistant to surface erosion and has low permeability, which reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. However, when undercut and/or saturated, such banks are more likely to fail due to mass-wasting processes. Failure mechanisms for cohesive banks are illustrated in Figure 4.12(b).
- Composite or stratified banks consist of layers of materials of various sizes, permeability, and cohesion. The layers of noncohesive material are subject to surface erosion, but may be partly protected by adjacent layers of cohesive material. This type of bank is also vulnerable to erosion and sliding as a consequence of subsurface flows and piping. Typical failure modes are illustrated in Figure 4.12(c).

Copyright National Academy of Sciences. All rights reserved.

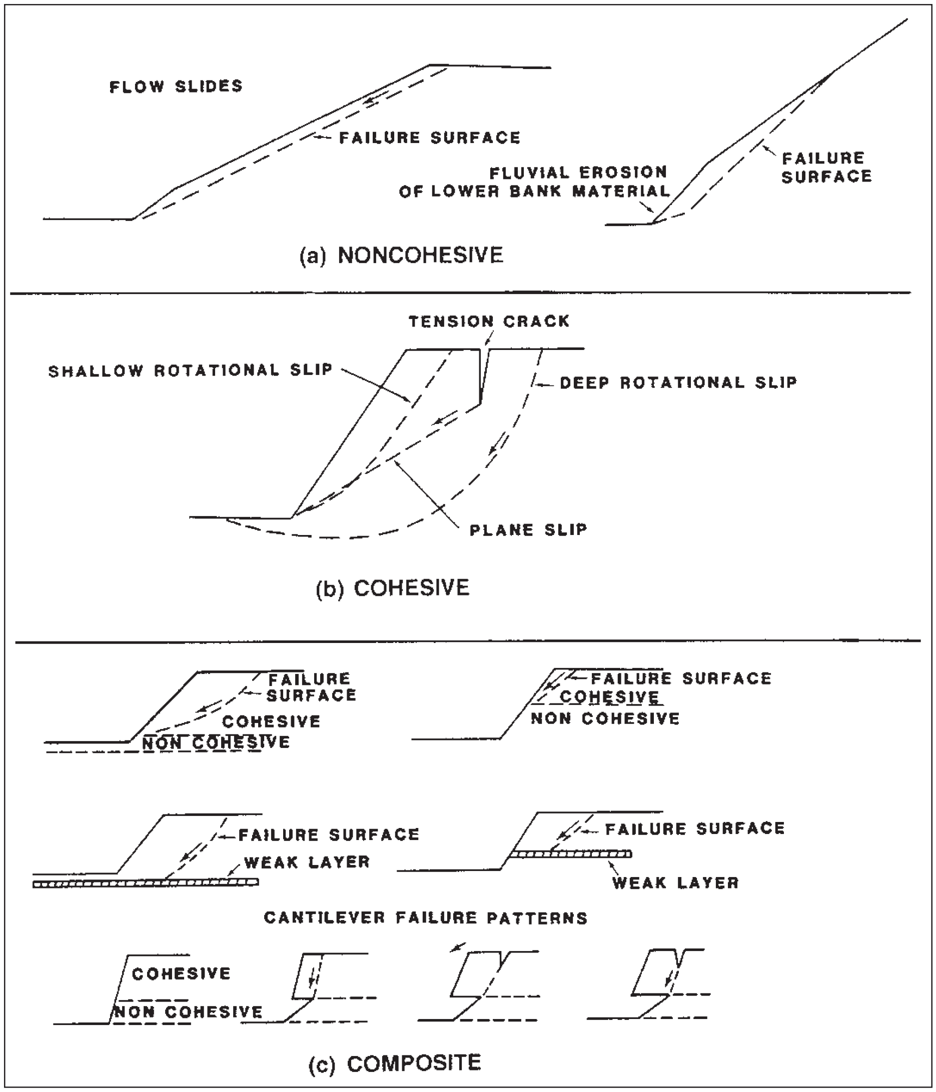


Figure 4.12. Typical bank failure surfaces: (a) noncohesive, (b) cohesive, and (c) composite (after Brown 1985).

Piping. Piping is a phenomenon common to alluvial stream banks. With stratified banks, flow is induced in more permeable layers by changes in stream stage and by waves. If flow through the permeable lenses is capable of dislodging and transporting particles, the material is slowly removed, forming "pipes" that undermine portions of the bank. Without this foundation material to support the overlying layers, a block of bank material drops down and results in the development of tension cracks as sketched in Figure 4.12(c). These cracks allow surface flows to enter, further reducing the stability of the affected block of bank material. Bank erosion may continue on a grain-by-grain basis or the block of bank material may ultimately slide downward and outward into the channel, with bank failure resulting from a combination of seepage forces, piping, and mass wasting.

Mass Wasting. Local mass wasting is another form of bank failure. If a bank becomes saturated and possibly undercut by flowing water, blocks of the bank may slump or slide into the channel. Mass wasting may be caused or aggravated by the construction of homes on river banks, operation of equipment adjacent to the banks, added gravitational force resulting from tree

Copyright National Academy of Sciences. All rights reserved.

growth, location of roads that cause unfavorable drainage conditions, agricultural uses on adjacent floodplain, saturation of banks by leach fields from septic tanks, and increased infiltration of water into the floodplain as a result of changing land-use practices.

Various forces are involved in mass wasting. Landslides, the downslope movement of earth and organic materials, result from an imbalance of forces. These forces are associated with the downslope gravity component of the slope mass. Resisting these downslope forces are the shear strength of the materials and any contribution from vegetation via root strength or engineered slope reinforcement. When the toe of a slope is removed, as by a stream, the slope materials may move downward into the void in order to establish a new equilibrium. Often, this equilibrium is a slope configuration with less than original surface gradient. The toe of the failed mass then provides a new buttress against further movements. Erosion of the toe of the slope then begins the process over again (see discussion of basal endpoint control, below). General mass wasting often accompanies channel incision as bank heights increase.

Bank Erosion and Failure. The erosion, instability, and/or retreat of a stream bank are dependent on the processes responsible for the erosion of material from the bank and the mechanisms of failure resulting from the instability created by those processes. Bank retreat is often a combination of these processes and mechanisms operating at various timescales. While the detailed analysis of bank stability is, primarily, a geotechnical problem, insight on the relationship between stream channel degradation and bank failure, for example, can be important to the designer concerned with the influence of bank instability on environmentally sensitive bank-protection measures. For a detailed discussion of the processes responsible for bank erosion and bank failure mechanisms, refer to HEC-20, Appendix B (Lagasse et al. 2012).

Site-Specific Considerations

Basal Endpoint Control. Material is delivered to the basal area of a bank by mechanical bank failures and erosion. The removal of this material from the basal area depends almost entirely on fluvial entrainment and downstream transport (Figure 4.13). The amount of basal accumulation of bank material depends on the relative rates of supply by bank failures and erosion and removal by fluvial entrainment. Where the flow is able to remove all the sediment supplied to the basal area and scour of the basal area continues, bank erosion will also continue. In contrast, where the rate of supply exceeds the rate of removal, bank stability will be increased with respect to gravity failures because loading and buttressing the base of the slope effectively reduces the bank angle and height. Neill (1984) has argued that the bedload transport rate must set an upper limit to local erosion rates over a period of time, and Nanson and Hickin (1986) support this view. However, if the failed material is cohesive, the failure blocks will gradually break apart and most of it will be transported as wash load.

Carson and Kirkby (1972) characterize the balance between basal supply and removal in terms of three states of basal endpoint control, as follows:

1. Impeded Removal. If bank failures supply material to the base at a higher rate than it is removed, then basal accumulation results, thus decreasing the bank angle and vertical height and increasing bank stability.
2. Unimpeded Removal. Bank failures and erosion supply material to the base at the same rate that it is removed resulting in bank recession by parallel retreat, the rate being controlled by the degree of fluvial activity at the base of the bank. Slope angle and basal elevation remain relatively unchanged.
3. Excess Basal Capacity. Basal scour is greater than the rate of supply of material. This causes bed scour and basal lowering, which increases the bank height and angle and promotes bank failure.

Copyright National Academy of Sciences. All rights reserved.

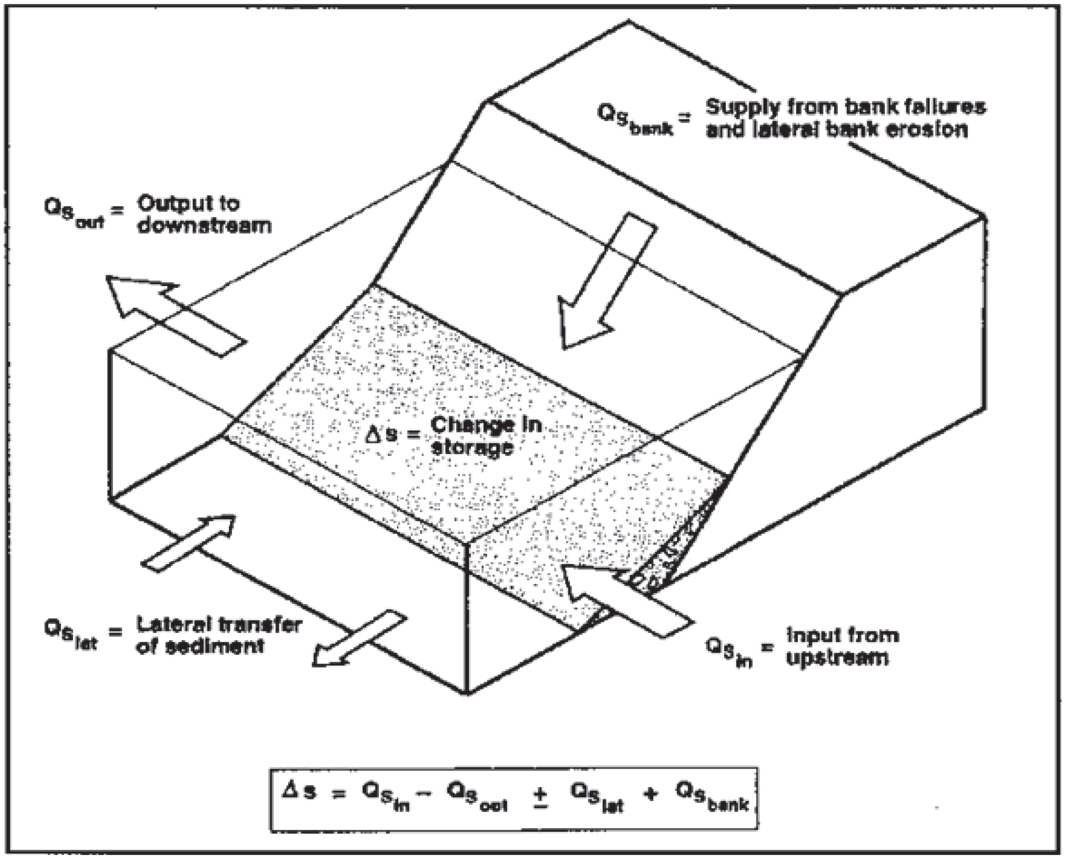


Figure 4.13. Schematic representation of sediment fluxes to and from river bank basal zones (Thorne and Osman 1988).

Estimating Critical Bank Height. The stability of the bank with respect to mass failure is dependent on soil properties and bank geometry. Bed lowering and lateral erosion are the two most common processes that act to steepen the bank and cause bank instability. For estimating critical bank height for steep, cohesive banks, a simple slope stability analysis can be developed. Refer to the analysis approach derived by Osman and Thorne (1988) to predict bank stability response to lateral erosion and bed degradation.

Thorne and Osman (1988) also developed a modeling technique to study the effects of channel widening and bank-sediment contribution on flow energy, stream power, and the rate and extent of bed lowering during degradation and outer-bank stability using a critical shear stress concept to account for lateral erosion and a slope stability criterion for mass failure. Again, a review by the designer is recommended prior to evaluating lateral erosion and bank instability problems in detail for a given site where environmentally sensitive treatments are being considered.

Deterministic Modeling. Currently there are a number of deterministic tools available to the designer of environmentally sensitive stream bank treatments to evaluate geotechnical factors that could influence the choice of treatment or support developing design of treatment components. An example of a deterministic approach is the bank stability and toe erosion model (BSTEM) developed at the USDA-ARS National Sedimentation Laboratory. BSTEM is a spreadsheet tool used to simulate stream bank stability. The user supplies bank geometry, soil properties, vegetation cover and bank water-table levels, and the model outputs factors of safety. If banks fail or erode, new bank geometry is generated. Fluvial erosion of material at the bank toe is simulated using a simple excess-shear stress approach (Simon et al. 2011).

Copyright National Academy of Sciences. All rights reserved.

Many river management situations require information on the stability of the channel banks. These may include assessing the stability of existing channel banks, predicting the effect that changes in riparian land use will have, or designing new channels. The BSTEM is a spreadsheet model that calculates bank Factor of Safety (Fs) for new or existing banks. BSTEM features include:

- Limit equilibrium analysis of planar shear failures with and without tension cracks;
- User-defined and automatically-generated bank geometries: compound and undercut banks allowed;
- Up to five distinct bank material layers;
- Simulated saturated and unsaturated soil strength;
- User-definable positive and negative pore-water pressures or pressures calculated from water table position;
- Optional fiber-bundle root-reinforcement model with data from 22 vegetation species, including willows, grasses and large trees, or the users may enter their own data;
- Hybrid random-walk and random-leap search algorithm for the minimum Fs;
- Clear-water scour hydraulic erosion model;
- Simulated potential options to protect the bank and/or bank toe against hydraulic erosion.

As noted in the BSTEM Users Manual, the model is a physically based model. It represents two distinct processes: the failure by shearing of a soil block of variable geometry and the erosion by flow of bank and bank-toe material. The effect of toe erosion, vegetative treatments, or other bank and bank-toe protection measures can be illustrated by calculating the actual Fs of the bank (Bankhead et al. 2013).

The BSTEM combines three limit equilibrium-method models that calculate Fs for multi-layer stream banks. The methods simulated are horizontal layers, vertical slices with tension crack, and cantilever failures. The model can be adapted to incorporate the effects of geotextiles or other bank stabilization measures that affect soil strength. The model accounts for the strength of up to five soil layers, the effect of pore-water pressure [both positive and negative (matric suction)], confining pressure due to streamflow, and soil reinforcement and surcharge due to vegetation.

BSTEM can be used as a tool for making reasonably informed estimates of hydraulic erosion of the bank and bank toe by hydraulic shear stress. The model is primarily intended for use in studies where bank-toe erosion threatens bank stability. The effects of erosion protection on the bank and toe can be incorporated to show the effects of erosion control measures. The model estimates boundary shear stress from channel geometry and considers the critical shear stress and erodibility of two separate zones with potentially different materials: the bank and bank toe. The bed elevation is assumed to be fixed.

To evaluate stream bank stability, the shear strength of saturated soil can be described by the Mohr-Coulomb criterion (Simon et al. 2011). Driving forces for stream bank instability are controlled by bank height and slope, the unit weight of the soil and the mass of water within it, and the surcharge imposed by any objects on the bank top. The ratio of resisting to driving forces is commonly expressed as the Fs, where values greater than one indicate stability and those less than one, instability.

Figure 4.14 provides a flow chart illustrating the bank stability model inner workings to output an Fs and erosion from both hydraulic and mass failure processes. Both beneficial and detrimental effects of vegetation on bank stability have been observed: plant roots reinforce soils and remove moisture by evapotranspiration, increasing matric suction, but very large trees impose weight loading on banks and woody vegetation may also enhance infiltration of precipitation (Simon and Collison 2002, Gray and Barker 2004, Pollen et al. 2004). Earlier models of root reinforcement of soils ignored the effects of soil type and moisture on root-soil bonds; root tensile strength was simply added to soil strength and roots were assumed to be oriented

Copyright National Academy of Sciences. All rights reserved.

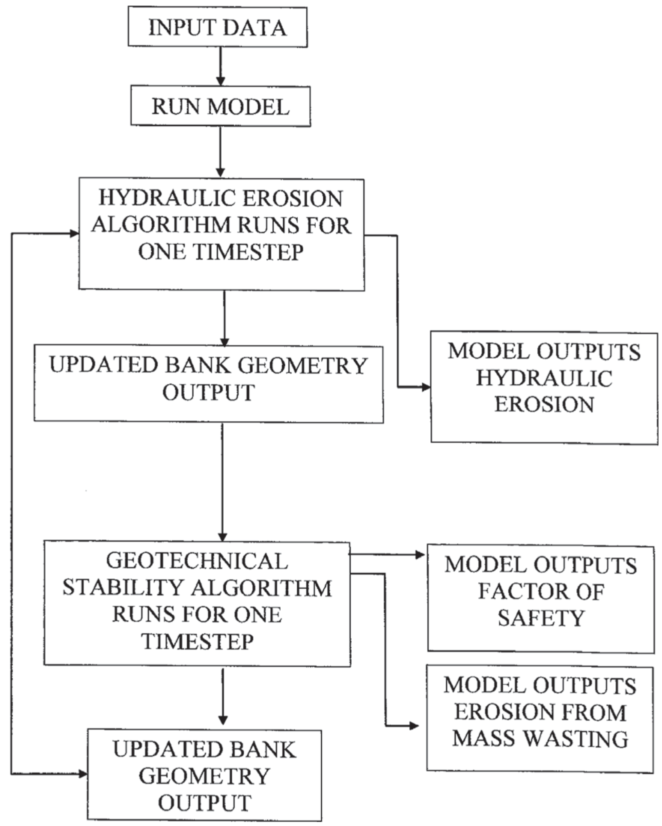


Figure 4.14. Flow chart illustrating the BSETM inner workings and output (Bankhead et al. 2013).

perpendicular to failure planes. Work by Pollen (2007) has advanced understanding of temporal and spatial variability in root reinforcement due to variations in soil type and moisture, and work by her team (Pollen et al. 2004, Pollen and Simon 2005) has shown that soil-root matrices are better simulated by fiber-bundle models that allow progressive failure of roots (weakest first) rather than the "all-roots-break-instantaneously" assumption of the older perpendicular models. The fiber-bundle model algorithm has been incorporated into the BSTEM.

A relevant example of the application of the BSTEM model can be found in Simon et al. (2008) with the application of the model to design a reach-scale restoration project. Specifically, this project deals with restoration design using environmentally sensitive stream bank treatments on Goodwin Creek in Mississippi—NCHRP Project 24-39 field site MS3 (see Section 2.4.2 and Figure 2.3).

As described by Simon et al. (2008), because of continued land loss in adjacent agriculture fields by mass failure of the stream banks on Goodwin Creek, a restoration project was designed to stabilize the banks and to protect a road running parallel to the bendway. To provide a stable alternative, the analysis of the restored configuration needed to address both hydraulic erosion and geotechnical stability. The proposed design was limited to 1:1 bank slopes due to the proximity of the road and included longitudinal stone-toe protection and bendway weirs to counter basal erosion by hydraulic shear. Worst-case geomorphic conditions under the proposed design were simulated by modeling (1) typical, annual high flows to evaluate the amount of bank-toe erosion that would occur and (2) geotechnical stability where groundwater levels were high and flow had receded to low-flow conditions in the channel (drawdown case). Results showed that the bank would still be unstable at 1:1 under the drawdown case but that the addition of specific riparian

Copyright National Academy of Sciences. All rights reserved.

vegetation on the slope would stabilize the bank even under worst-case conditions. The design was, therefore, implemented and constructed.

Thus, for the Goodwin Creek project the use of riparian vegetation to increase shear strength by root reinforcement was central to the design. Post-project monitoring for 10 months after implementation revealed that the bank slope has remained stable and that bed-material size has returned to pre-project conditions. However, some bed scour has occurred. This was expected given that flows were re-directed away from the bank toe and into the center of the channel. Further scour is not expected as bed material has coarsened. This successful project shows how deterministic approaches to design and implementation of a reach-scale restoration project can provide reasonable confidence in developing and testing designs (Simon et al. 2008).

4.2.5 Monitoring Success of the Vegetative Component

Monitoring During Initial Establishment

Since vegetative components of biotechnical stabilization countermeasures grow, develop, experience dormancy and sometimes die, periodic inspection is necessary, particularly during the critical period of early establishment just after installation. If the installation is determined to have been improper, any warranty or dispute resolution clauses in the plant installation contract may be invoked. In particular, irrigation programs require attention to see that they are effective. Inspection frequency should be high during the first growing season, particularly after high-flow events and during droughts. After the first year, semiannual to annual evaluations should be sufficient in most cases. Sites should be visually checked for drought stress, herbivory, trampling, competition from undesirable species, and vandalism (FISRWG 2001). McCullah and Gray (2005) also highlighted excessive soil moisture, insufficient soil nutrients, toxic soil conditions (high alkalinity or acidity), and inadequate light as additional issues of concern. Monitoring the effects of riparian revegetation on ecological values is discussed by Guilfoyle and Fischer (2006), and a broader protocol that includes water quality, biotic factors, and habitat for rapid bioassessment of wadeable streams is provided by Barbour et al. (1999).

Visual Assessment

Jones and Johnson (2015) adapted parts of the Barbour et al. (1999) protocol to create a damage assessment framework for wadeable, 1st to 4th order, modified streams in "urban or otherwise constrained" settings. Specifically, the types of stream projects considered were ones that aimed to improve natural channel functioning and protect infrastructure, property, or other physical assets in or near the channel. Furthermore, these streams were located in such close proximity to infrastructure that a state of static equilibrium was required. Static equilibrium was defined (after Rhoads et al. 2008) as lateral and vertical rates of change that were relatively slow on an engineering time scale, were not accelerating, and were occurring within the context of a balanced sediment regime. An adaptation of the Jones and Johnson (2015) approach is suggested here for qualitative, visual monitoring of environmentally sensitive stream bank protection measures. More quantitative assessment methods are presented below.

The visual assessment monitoring protocol for vegetative measures described here consists of scoring the treated bank in five categories, the first two of which are directly or indirectly related to vegetation (Table 4.2). The damage assessment framework developed by Jones and Johnson (2015) includes up to seven categories, but only five are used here. The omitted categories (flood hazard and thalweg degradation) deal with properties of the channel as a whole and not of a protected bank.

General health and vigor of plants may be visually assessed. Leaf color, evidence of insects, herbivory, disease, and growth vigor are readily obvious and should be considered when assigning

Copyright National Academy of Sciences. All rights reserved.

Table 4.2. Visual assessment monitoring protocol for environmentally sensitive bank protection measures (adapted from Jones and Johnson 2015).

Category	Excellent (1-3)	Good (4-6)	Poor (7-9)	Failed (10-12)
Stream bank vegetation	Stream bank vegetation is in good condition[1] and showing progress along all stream bank surfaces.	50%–70% of the bank is covered by vegetation in good condition or showing progress.	50%–70% of the bank is covered by stressed or dying plants.	Less than 50% of the bank is covered by vegetation or disruption due to grazing and mowing is evident.
Bank stability and migration	Banks are stable and vegetated.	Isolated instances of bank failures (mass wasting, undercut, etc.) or raw banks, affecting 5%–30% of treated bank.	Bank failures or raw banks frequent, describing 30%–60% of treated bank segment. Channel migration is evident anywhere in reach, but thalweg is within design channel limits.	Bank failures or raw banks prevalent, describing >60% of treated bank segment. Thalweg has migrated outside design channel limits anywhere in reach.
Infrastructure protection	Infrastructure is not in immediate danger.	Erosion has left infrastructure (1) nearer stream flow or (2) with more surface exposed to stream flow than as-built condition.	Infrastructure shows unexpected signs of vulnerability that has the potential to impact the integrity or functioning of the infrastructure. Infrastructure is exposed to stream flow.	The structural integrity of infrastructure is compromised or infrastructure has failed as a result of stream flow.
Structural integrity[2]	Structure and structural components have not been displaced and there is no visible erosion.	At least 10% of the structure is displaced from the as-built location and/or structure is attached to bank but erosion is visible everywhere structure is in contact with bank.	25%–75% of the structure is displaced from as-built location and/or structure is partially detached from bank.	More than 75% of structure is displaced from as-built location and/or structure is detached from bank.
Flow obstruction and sedimentation	Less than half of the bottom is affected by sediment deposition. Pools are not filling in and there are few to no unintended obstructions.	Occasional unintended obstructions are present; minor local scour at these obstructions.	Sediment deposition is affecting 50%–80% of the channel bottom or pool depths have measurably decreased. Moderately frequent unintended obstructions.	Unintended obstructions are frequent or have significantly altered the design capacity of the channel. Aggradation is evident or sediment deposition affects >80% of the channel bottom.

[1]Key indicators of condition include leaf color and evidence of insects, herbivory, disease, trampling, competition from undesirable species, and vandalism.

[2]Score each structure in the reach and use the median score for the overall site score.

scores for the stream bank vegetation category (Table 4.2). Assessment of the structural integrity category should be informed using failure modes tabulated by McCullah and Gray (2005), who frequently highlighted toe scour and flanking due to inadequate end treatments (keys) at upstream and downstream ends of protection structures (see Section 4.2.3). Scores from the five categories are combined by adopting the lowest score observed in any category as the overall site score. Table 4.2 has been incorporated into the proposed field data form for evaluating environmentally sensitive bank-protection treatments (see Appendix C).

Copyright National Academy of Sciences. All rights reserved.

Quantitative Assessment

Inspection of sites stabilized with biotechnical measures should include assessment of three properties of the vegetation:

a. Overall health and vitality of the plants,
b. Ability of plants to shield bank sediments from flow shear stresses by suppressing flow velocity in the near-bank region, and
c. Ability of plant roots to reinforce soils and thus make them more erosion resistant.

Each of these factors is discussed below.

Overall Health and Vitality of Vegetation. Vitality of dormant woody vegetation may be checked by testing the elasticity of stems (whether they bend rather than break when loaded) and by visually examining the cambium layer under the bark to see if it is green. Counts of living and dead individuals may be used to compute survival percentages, but survival percentages may be misleading for two reasons. First, high survival percentages may occur in cases where survival patterns are patchy and "weak spots" in coverage create vulnerabilities and potential failure zones and second, low survival percentages may occur in cases where stand development is quite strong and natural succession is causing a decline in stem density but an overall increase in the size of individual plants. In the latter case, a low survival percentage would not be a negative finding with regard to the vegetative component. Satisfactory survival rates can be established in advance based on common-sense decisions regarding the adequacy of establishment relative to the objectives. Johnson and Stypula (1993) in FISRWG (2001) suggest using a rule of thumb that open spaces should not be larger than "2 ft in dimension."

Beyond the methods described above, health and vitality of vegetation may be examined using ground-based multispectral imagery to detect chlorophyll levels (Kancheva et al. 2014). Plant vitality and vigor may be assessed using a large number of indices computed from plant reflectance, transmittance, and absorbance for a variety of wavelengths.

Efficacy of Plant Cover for Counteracting Surface Erosion. Plants protect against surficial erosion by deflecting flow and shielding bank surfaces. The effective shear forces acting on the bank are therefore reduced. In addition, shallow roots bind soils and increase effective cohesion, increasing the resistance of soils to erosion. For example, the universal soil loss equation (USLE) and its descendants are intended to predict erosion of soil due to raindrop impact and overland flow but not stream bank erosion; however, a vegetative component is considered:

$$A = R * K * LS * C * P \tag{4.3}$$

where:

A = Computed soil loss for a given storm period or time interval in tons per acre
R = Rainfall factor
LS = Slope length and steepness factor
C = Vegetation factor
P = Erosion control practice factor

The variables that control the vegetation factor, C, in the USLE for woody vegetation are indicative of the plant cover characteristics that are important in controlling erosion. Tables of C-factors for brush, bushes, and trees show variation of raised canopy height, type and cover percentage as well as ground canopy type and cover as controlling variables. The importance of these characteristics has been confirmed by more recent research (Zuazo and Pleguezuelo 2008). Selected C-factor values for "permanent pasture, grazed forest land, range, and idle land," tabulated by NRCS (2008) are presented in Figure 4.15. Erosion is inversely proportional to C,

Copyright National Academy of Sciences. All rights reserved.

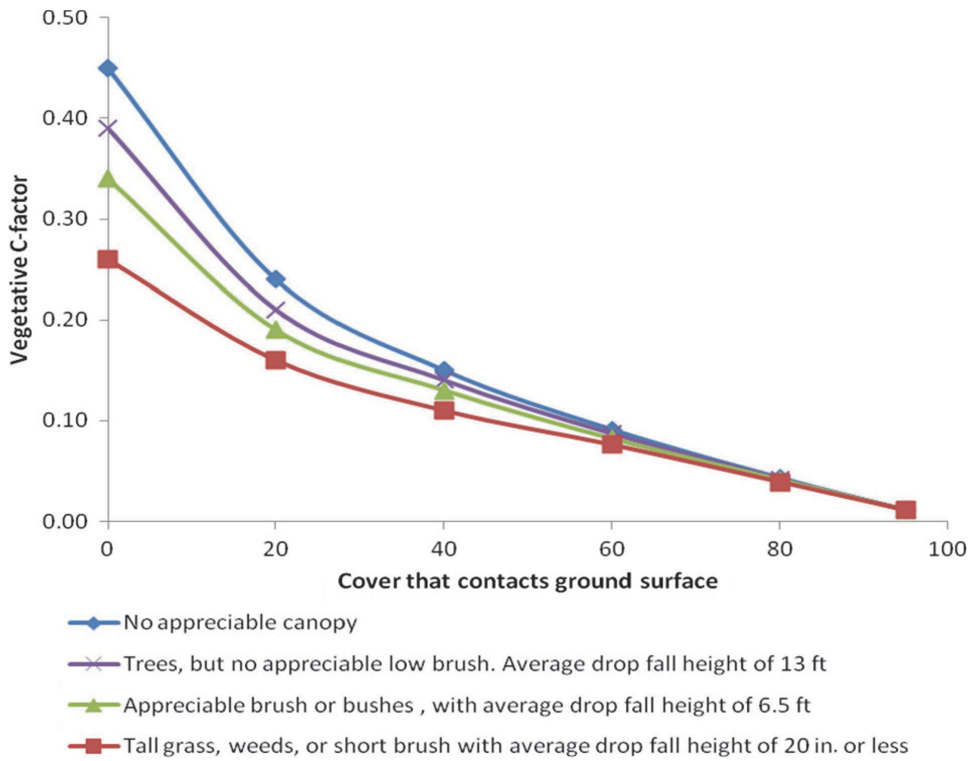


Figure 4.15. Effect of vegetation characteristics on vegetative C-factor in USLE.

so Figure 4.15 shows that predicted soil erosion is more strongly affected by the amount of cover that contacts the soil surface (reducing C-factor from 0.45 to near 0) than the type of vegetation (trees versus grass/weeds).

Beasley (2011) and Flikweert et al. (2013) examined resistance of turfed levee slopes to erosion and considered several measures of turf status as erosion protection (root length, root surface area, root volume, biomass, and ground cover). The volume of roots per unit volume of soil was selected as the best index of a continuous cover of intact turf for erosion protection because it captures both root length and thickness. Longer roots provide more interaction with the soil, and thicker roots are less likely to break. Observation and measurement of the above-ground portion ("canopy coverage") of the turf was not an adequate measure of "vegetative rooting and engineering performance." However, measures of root properties for dormant and actively growing turf were not significantly different.

Most biotechnical bank-protection measures employ woody species rather than turf. The value of this type of vegetation in countering surface erosion is directly related to its stem density and flexibility.

Density. Density may be assessed by counting and measuring stems per unit bed area within selected quadrants or by using an approach that includes the frontal area of plants as described by Petryk and Bosmajian (1975) with digital imaging. Although shrubby species can persist in dense, low, supple stands for long periods, many woody stands become much less dense as they mature due to succession or self-thinning as stronger individuals outcompete and shade out their neighbors. Larger trees, although they may provide excellent habitat features, may provide relatively little protection against surface erosion and actually accelerate or concentrate flows between trunks or underneath canopy. This hazard may be counteracted by development of a

Copyright National Academy of Sciences. All rights reserved.

healthy understory of shade-tolerant species. López and García (2001) showed that the hydraulic effects (e.g., flow depth, Manning n) of submerged, rigid vegetation were negligible until the density of stems (basal area of stems per unit area of stream bed) exceeded about 3×10^{-4}, but increased as a linear function of density beyond that threshold. White et al. (2014) surveyed riparian communities in the vicinity of Louisville, Kentucky, and found mean values of stem basal area per unit ground surface area of 11×10^{-4} to 29×10^{-4}.

Flexibility. As long as flexible plants are not broken off and destroyed by the flow, they may be assumed to provide superior protection to that provided by rigid stems since they physically shield the bank as they lay over, increasing the local stem density and reducing near-bank stresses. Vegetative flexibility has been assessed using the "board drop" test described by Kouwen (1988) and by measuring tree stem deflection associated with measured forces applied by a winch (Stone et al. 2011). These tests, although interesting, are primarily research tools. Quantitative assessment of flexibility must therefore rely on an estimate of the likely behavior of the plants growing at a given site when subjected to flow depths and velocities typical of higher flows at the site. Observation of similar stands of vegetation under typical flow conditions is most reliable. In the absence of such observations, application of the theory for bending a cylindrical cantilever beam (as shown by Stone et al. 2011) yields the following relationship between deflection angle and applied drag force:

$$\text{Tan}\,\theta = \frac{FL^2}{2IE} \tag{4.4}$$

where:

θ = Angle between plant stem and vertical
F = Applied force assumed to be concentrated at a height, L, above ground
I = Second moment of area
E = Tree's modulus of elasticity

The quantity I may be computed by assuming the plant behaves as a cylinder:

$$I = \frac{\pi D^4}{64} \tag{4.5}$$

where:

D = Stem diameter

and reasonable assumptions may be made for the value of E. Stone et al. (2011), measured values of E for three tree species and found a range from near zero to about 1.5×10^5 lb/ft^2 or 7×10^6 N/m^2. Assuming the individual plants have a frontal area when subjected to flow of 1 ft^2, an effective height of 5 ft, a stem diameter of 0.25 ft and a drag coefficient of 1.0, then an approach velocity of only about 1 ft/s would produce a deflection of 30 degrees if $E = 1.5 \times 10^5$ lb/ft^2. This is a low velocity, but considering the shielding effects of adjacent plants in the near-bank region, it might correspond to a much higher mean channel velocity.

Efficacy of Vegetative Component for Soil Reinforcement. Roots can increase slope stability when they intersect failure planes. Norris and Greenwood (2006) provide guidance on conducting geotechnical investigations of vegetation effects on slope stability at proposed construction sites (Table 4.3). Some of this material is relevant to assessment of existing biotechnical stream bank stabilization projects. Investigations may be staged, with preliminary work done in the office and more detailed investigation on site or in the laboratory with samples from the site. Desk study in the office can be done using maps, construction plans, aerial photos, and soil surveys.

Copyright National Academy of Sciences. All rights reserved.

Table 4.3. Site investigations for contribution of vegetation to slope stability (adapted from Norris and Greenwood 2006).

Study Phase	Topic	Subtopic	Information Derived
Desk Study	Soils	Topsoil	Suitability as plant-growth media
		Subsoil	Likely penetration by roots.
		Fill	Soil classification and moisture regime.
	Vegetation		Presence and distribution of vegetation.
	Analysis	Slope stability	Preliminary analysis of slope stability based on assumed properties for soil, hydrology and vegetation. Software tools such as BSTEM[1] (http://www.ars.usda.gov/research/docs.htm?docid=5044) are helpful, as they allow use of assumed default values.
Field	Soils	Shallow pits, perhaps hand dug	Classify soils using texture. Root size, depth, density, spatial distribution. Consider seasonal effects of soil moisture regime on plants.
		Borehole, direct shear tests	In situ measurement of soil shear strength (Lutenegger 1987)
	Vegetation		Verify desk study findings regarding vegetation types, sizes, density.
			Apparent effects of planted and naturally occurring vegetation on stability of adjacent sites.
	Roots	Root strength	In situ pullout resistance. (Pollen-Bankhead et al. 2009)
			In situ shear tests on root reinforced soils (larger projects).
			Seasonal monitoring of moisture content profiles. (Shields et al. 2009, Pollen-Bankhead and Simon 2010)
In-depth Assessment	Analysis	Slope stability	Analysis of slope stability based on measured properties for soil, hydrology, and vegetation. BSTEM[1] or more sophisticated tools may be used.

[1]See Section 4.2.4.

4.2.6 Aquatic Habitat Issues

Introduction

As noted, CRP-CD-58 that accompanies *NCHRP Report 544* (McCullah and Gray 2005) contains detailed coverage on a series of special topics relevant to the design of environmentally sensitive stream bank treatments (see also Section 2.1e). McCullah and Gray (2005) address issues related to "physical aquatic habitat" in some detail as a special topic on this CD. This material is presented with minor editorial changes made by this projects research team in the paragraphs that follow. This special topic has been reviewed and supplemented, as appropriate, by the a fisheries biologist on the NCHRP Project 21-39 research team.

Definitions and Diversity

Habitat is the place or environment where a plant or animal naturally or normally lives and grows. *Environment* here implies the sum total of all influences within the living space of a plant or an animal. For fish, habitat includes the stream, its boundaries (bed and banks), existing vegetation, and other animals. Physical factors such as water depth, velocity, cover, and bed material are referred to as physical habitat. In fact, these four factors are most often used to describe physical aquatic habitat. Streams tend to provide complex, dynamic physical habitat. For example, water depth and velocity vary continuously in time and space. Deep, slow pools lie adjacent to swift, shallower runs and riffles. Bed material, although slightly less dynamic than depth or velocity, also varies to produce a high level of spatial and temporal heterogeneity. The high level of physical diversity typical of natural (lightly impacted by humans) streams provides niches for many types of plants and animals, and thus supports relatively high levels of biological diversity.

Human influences often result in simplification of stream habitats, making them more uniform and adversely impacting biological communities (see Figure 4.16). Meandering streams with deep pools on the outside of bends and gravelly riffles at thalweg crossings (inflection points) between bends are often straightened and channelized to improve alignments for bridges or

Copyright National Academy of Sciences. All rights reserved.

Figure 4.16. Stone toe provides stable benthic habitat and cover for smaller fish, but little diversity or pool habitat (McCullah and Gray 2005).

highway embankments. Sinuous channels with a nonuniform cross section are sometimes altered to become a prismatic trapezoid, and pool-riffle sequences are commonly replaced with uniform runs. Woody debris, an essential component of many habitats, is usually removed or displaced as riparian vegetation is removed and banks are either cleared or stabilized. However, it is important to note that the spatial heterogeneity typical of natural streams is not random. Specific patterns occur that are essential for various populations.

For example, swift waters immediately adjacent to eddies and regions of depressed velocity allow some organisms to obtain food with minimal expenditure of energy. An engineer or geomorphologist could design a stream with a checkerboard pattern that would be physically diverse but ecologically barren since natural patterns would not occur.

Lotic (moving water) ecosystems also depend on temporal patterns. Human activities tend to perturb natural hydrographs, either exaggerating extremes or making them more uniform by removing flood peaks and elevating base flows, as is the case with reservoirs. Urbanization and other types of watershed development often increase the fraction of precipitation that reaches the stream channel as surface runoff. This makes flood peaks higher and sharper, but depresses base flows and effective precipitation since less of the total precipitation infiltrates into the soil profile or aquifer, which supplies the base flow. Occasionally, human impacts are extreme enough to cause a stream to regress from perennial to seasonal in duration.

Habitat Scale in Time and Space

The design of erosion protection countermeasures typically focuses on the hydraulic and structural properties of a relatively short reach during higher flow periods when boundary shear stresses are at a maximum. Consideration of aquatic habitat, however, requires a much larger scale of reference both in time and space. Fish (and most other organisms specialized for life in river systems) are highly mobile creatures that live out their lives in a series of places (habitats) which can be separated by up to 100 km (60 miles) of river channel. Fisheries ecologists typically partition these habitats into basic types such as feeding habitats, resting habitats, spawning habitats, and nursery habitats. Each type has relatively distinct hydraulic and structural properties. Many fish populations are limited by the quantity or quality of one or more of these habitats, or by the lack of connectivity between key habitats. While it is unlikely that a fish population would ever be entirely dependent on the relatively small areas typically affected by the installation of a

Copyright National Academy of Sciences. All rights reserved.

Figure 4.17. Weirs can create pool-riffle habitats and help stabilize beds, but should be designed carefully in streams with low bed slope to prevent eliminating current during low flow (McCullah and Gray 2005).

single erosion countermeasure, opportunities for increasing either the amounts or quality of fish habitat could potentially pay high dividends both for the environment and in terms of public appreciation and resource agency approvals. Large-scale channel restoration or stabilization work (directly affecting a reach longer than 20 channel widths) could have major effects on an aquatic community.

The design of erosion protection countermeasures typically requires a focus on high-flow hydraulic conditions. This is entirely reasonable because erosion processes are usually limited to (or maximal at) high-energy events. Habitat design, however, must again take a wider view because fish live in their habitats at all times of the year and are affected by both high- and low-flow hydraulic environments. The habitat implications of a particular erosion control or habitat improvement technique can be quite different during high-flow and low-flow periods (see Figure 4.17). Therefore, environmentally sensitive design requires consideration of hydraulics and habitat requirements across the range of flows and seasons.

Water Temperature

An important first step toward environmentally sensitive design is to recognize that water temperature and site spatial context (with regard to both landscape and river network position) do more to shape the basic structure and productivity of fish communities than local physical features. Because fish and their food organisms are cold-blooded, growth and productivity rates always vary strongly with temperature. Typically, both increase with rising temperature until a physiological maximum is exceeded. Thermal optima vary between species, but fisheries managers often make a basic distinction between sites and their fish communities based upon the thermal tolerances of the dominant species present. "Coldwater streams," for example, are dominated by a few species such as trout and salmon that have rather low thermal optima. "Warmwater streams" are dominated by a larger number of species such as sunfish and suckers with higher thermal optima. In between these extremes, scientists recognize coolwater systems where members of both groups (and other fish with intermediate thermal preferences) may coexist. Water temperature in these transitional sites is an extremely important variable, since small changes in one direction or the other can cause tremendous alterations in the composition and productivity of the fish community. This variability in thermal setting directly affects the ecological value of more local habitat features like shade and groundwater inflows.

Copyright National Academy of Sciences. All rights reserved.

Geomorphic Context

The landforms and hydrology of the upstream watershed directly affect the water temperature and the water and sediment flow regimes that govern habitat quality of a specific river reach. The details of linkages between climate, landscape position, fluvial geomorphology, and hydrology are very complex (see Section 4.2.2). Simply put, however, the flow regime interacts with the physical structure of the channel to produce physical aquatic habitat are characterized in terms of depth, velocity, substrate composition, etc. For example, coldwater streams tend to be steeper, found at higher elevations, and have coarser bed material (gravel, cobble and boulders) than warmwater streams.

Habitat Issues and Opportunities

High-Flow Issues. Both fish and invertebrates have normal ranges of velocity in which they are typically found, and threshold velocities above which they cannot survive. Habitat suitability models, for example, give standardized curves and rules for velocity and depth requirements based on published data. Local or state fisheries agencies may have developed regional hydraulic criteria for species of interest. Flow refugia are places fish and other organisms can go to escape excessive velocities. Natural current refugia can be either structural (e.g., boulders, undercuts, the downstream edge of point bars or abutments) or spatial (e.g., floodplains, high-water cross channels). The availability of refugia is obviously more or less critical, depending upon the general hydraulics in a reach during high-flow events. In high-energy channels, velocity refugia can be critical. From an environmental design perspective, the inclusion of elements providing velocity refuge can be beneficial to both fish and invertebrate populations. Boulder clusters, vegetated floodways, large woody debris, live cribwalls and live brush layering, spurs, and stone weirs etc. all may have potential application in this context (see Figure 4.18). However, these elements may not provide significant benefits in reaches where hydraulics are not an important constraint on the biological community, or where normal floodplain and geomorphic activity provides adequate refuge opportunities.

Inundation of floodplains during high flows provides large areas of refuge, but also facilitates a host of other ecological functions, particularly along larger rivers where flooding durations are measured in days or weeks. For example, fish feed on terrestrial plants and animals (insects, earthworms, etc.) trapped by rising floodwaters. Receding floodwaters carry organic matter back into the riverine ecosystem for additional cycling and spiraling. In order to spawn, some species

Figure 4.18. Spurs, barbs, and bendway weirs provide local zones of low velocity that are effective refuges (McCullah and Gray 2005).

Copyright National Academy of Sciences. All rights reserved.

of fish are dependent on the low-energy habitats found on flooded, forested floodplains. Isolation of floodplains from the stream by channel incision, channelization, levee installation, or other forms of structural flood control can be detrimental. Restoration of connections between the stream and temporarily flooded areas is often beneficial.

Localized bank erosion is often identified as detrimental to fish habitat, usually because it is thought that the eroded sediments may fill pools or cover gravelly riffles downstream. Actual effects of local bank erosion vary based on the overall sediment balance within the watershed and reach. Bank erosion is not necessarily problematic from a habitat perspective; likewise, every bank stabilization project is not necessarily a habitat improvement measure. In some rivers, gravel and cobble riffles require eroded material from banks to replace downstream transport. In other reaches, flow energy is sufficient to transport sediments from eroding banks through the reach with little or no accumulation.

Obviously, there are many river systems in which bank erosion can lead to habitat deterioration. For example, when low-flow deposition (see below) is particularly problematic, spawning substrate (coarse bed material) is in critically short supply, or erosion and transport of sand banks contribute to a lack of deep pools and hydraulic diversity in the reach. In these settings, almost any form of bank stabilization might have habitat benefits, provided the design does not adversely affect other aspects of habitat quality.

Channel Adjustment. *Systemic erosion* associated with lateral migration or other forms of channel adjustment occurs when there is a large-scale disequilibrium between water and sediment loads, channel shapes, and slope. Under these conditions, extensive bank erosion, bottom scour, sediment transport, and downstream bed aggradation usually occur, more or less simultaneously, across large sections of the channel network. Causes for large-scale/systemic erosion vary, but frequently involve natural climatic variations, human alterations of watershed hydrology, or changes in the channel base level or other downstream hydraulic controls. In such situations, high-flow erosion is evident, and biological communities are often heavily impacted. Streams in urbanizing watersheds frequently suffer from these effects, compounded by deteriorations in water quality and low-flow dewatering. Opportunities for habitat enhancement in these settings are minimal without addressing the underlying issues. From a habitat perspective, erosion control countermeasures are difficult to design, implement and justify in such a setting. Watershed management is typically the most effective scale for corrective measures.

Low-Flow Issues. Design considerations for protecting habitat quality during low flows and mitigating high-flow erosion can be quite divergent. Environmentally sensitive erosion protection should include a careful review of habitat impacts during summer and fall when habitat quality is typically limiting the reproduction and growth of both adults and juvenile fish. Low-flow magnitudes vary widely from site to site, adding further complexity.

During periods of base flow, stream water velocities usually do not produce biologically detrimental levels of shear and drag forces. However, many riverine organisms depend upon the transport of food to their relatively stationary feeding habitats. For example, in both filter-feeding insects and drift-feeding fish, rate of food capture increases (up to a limiting maximum) with increasing flow velocity. Furthermore, the relatively slow rate of molecular diffusion in water frequently limits physiological uptake of essential inputs like oxygen, and dissolved nutrients (for plants). As a result of these mechanisms, excessively low velocities (e.g., behind a weir) can be as detrimental to aquatic habitat quality as excessively high velocities.

Erosion protection countermeasure design for low-flow habitat quality includes emphasizing techniques that do not increase low-flow roughness elements or decrease low-flow hydraulic radius. Two-stage channel designs can be a useful way to mimic natural channel configurations

Copyright National Academy of Sciences. All rights reserved.

by providing a relatively high radius compact channel for low flow, and a larger but lower radius cross section during high flows (as observed naturally occurring in valley floodplains).

Fish populations generally suffer high rates of mortality throughout their life span; visual predators, typically birds, other fish, and humans, inflict the bulk of this mortality. It is not surprising then that most species of fish show a strong attraction to structural elements that obscure the vision of potential predators and provide a complex hunting stage that might favor escape by the victim. Fisheries biologists use the term "cover" to very broadly refer to any physical structure that might provide such refuge, including pools, undercut banks, submersed living vegetation, and woody debris. During low-flow periods, much of the cover near the margins of the streambed may be exposed and unusable. Likewise, pools may become too shallow to provide cover at low flow.

Design features that address needs for increased low-flow cover include using instream structures that promote pool formation (e.g., boulder clusters, spurs, stone weirs, etc.) or constructing channels with low-flow channels that contain some deep pools. Installing measures that increase pool cover in slowly moving streams must be weighed against potential reductions in flow velocity.

Bed Composition. Stream bed material is an important component of physical aquatic habitat. Key aspects of bed material include its size distribution, how frequently the particles move, and how open the interstitial spaces within the particle matrix are. In general, the diversity and abundance of aquatic insects are lowest for frequently shifting sand beds and highest for cobble and gravel beds that have a wide gradation (see Figure 4.19). When finer sediments deposit within gravel or cobble matrices, water circulation and oxygen supply to the areas beneath the surface of the bed are impeded or eliminated. These habitats are extremely important for incubating eggs of fish, like salmon, that spawn in gravel and for many species of insects (benthic macroinvertebrates). Sandy beds typically support lower densities of all but the smallest invertebrates, and stable objects such as woody debris, clay outcrops, or stone may be heavily colonized by invertebrates in sand-bed streams.

Summary

Designing erosion protection countermeasures in an environmentally sensitive way means that design decisions are made in light of the larger ecological context of the site. Here, "ecological

Figure 4.19. Stable gravelly riffles that are free of fine material typically support rich communities of aquatic invertebrates.

Copyright National Academy of Sciences. All rights reserved.

context" means the sum of the physical constraints and the relevant biological constraints. When proposing hydraulic, structural, or environmentally sensitive modifications either to abate erosion or improve biological habitat, solutions should be chosen in light of the specific hydraulic and ecological processes relevant at the site of interest. In other words, designs should be ecologically tailored to the site.

Some basic habitat improvement issues and opportunities are described above and identified by the Greenbank Decision Support Tool in *NCHRP Report 544* (McCullah and Gray 2005) (see also Section 2.1, above); however, most designers will find consultation with regional fisheries management agencies a useful step in gathering information about ecological context, and in identifying which habitat management goals might be consistent with the erosion protection goals of a particular project and at the same time, be ecologically appropriate for the site.

4.2.7 FHWA Perspective and Guidance

Overview

The FHWA's current guidance and perspective on the use of stream bank erosion protection treatments in the vicinity of highway infrastructure is contained in HEC-23, Volume 1, Chapter 6 (Lagasse et al. 2009). The following paragraphs and subsections provide extracts of this guidance as they relate to application of environmentally sensitive treatments to protect bridge waterway crossings, in particular, and highway infrastructure, in general.

FHWA notes that there are several synonymous terms that describe the field of vegetative stream bank stabilization and countermeasures. Terms for the use of "soft" revetments (consisting solely of living plant materials or plant products) include bioengineering, soil bioengineering, ground bioengineering, and ecological bioengineering. Terms describing the techniques that combine the use of vegetation with structural (hard) elements include biotechnical engineering, biotechnical slope protection, bioengineered slope stabilization, and biotechnical revetment. The terms soil bioengineering and biotechnical engineering are most commonly used to describe stream bank erosion countermeasures and bank stabilization methods that incorporate vegetation. Where riprap constitutes the "hard" component of biotechnical slope protection, the term vegetated riprap is also used.

The FHWA Perspective

Based on a 1998 scanning review of European practice for bridge scour and stream instability problems, it was observed that most hydraulic engineers in Europe would not recommend the reliance on bioengineering countermeasures as the only countermeasure technique when there is a risk of damage to property or a structure, or where there is potential for loss of life if the countermeasure fails (TRB 1999). Soil bioengineering is not suitable where flow velocities exceed the strength of the bank material or where pore-water pressure causes failures in the lower bank. In contrast, biotechnical engineering is particularly suitable where some sort of engineered structural solution is required because the risk associated with using just vegetation is considered too high. Continuous and resistive bank-protection measures, such as riprap and longitudinal rock toes are primarily used to armor outer bends or areas with impinging flows.

Since stream bank protection designs that consist of riprap, concrete, or other inert structures alone may be unacceptable for lack of environmental and aesthetic benefits, there is increasing interest in designs that combine vegetation with inert materials into living systems that can reduce erosion while providing environmental and aesthetic benefits (Sotir and Nunnally 1995). For example, the concerns over the poor aquatic habitat value of riprap, both locally and cumulatively, have made the use of riprap alone controversial in some jurisdictions (Washington

Copyright National Academy of Sciences. All rights reserved.

Department of Fish and Wildlife 2003). In general, any negative environmental consequences of riprap can be reduced by minimizing the height of the rock revetment up the bank and/or including biotechnical methods, such as vegetated riprap with brush layering and pole planting, vegetated riprap with soil, grass, and ground cover, vegetated riprap with willow (*Salix* spp.) bundles, and vegetated riprap with bent poles (see Section 4.3.3).

Combining riprap with deep vegetative planting (e.g., brush layering and pole planting) is also appropriate for banks with geotechnical problems, because additional tensile strength is often contributed by roots, stems, and branches. In contrast, trees and riparian vegetation planted only on top of the bank can sometimes have a negative impact (Simon and Collison 2002).

Correctly designed and installed, vegetated riprap offers an opportunity for the designer to attain the immediate and long-term protection afforded by riprap with the habitat benefits inherent with the establishment of a healthy riparian buffer. The riprap will resist the hydraulic forces, while roots and branches increase geotechnical stability, prevent soil loss (or piping) from behind the structures, and increase pullout resistance. Above-ground components of the plants will create habitat for both aquatic and terrestrial wildlife, provide shade (reducing thermal pollution), and improve aesthetic and recreational opportunities (see Section 4.2.6). The roots, stems, and shoots will help anchor the rocks and resist "plucking" and gouging by ice and debris (McCullah and Gray 2005).

Advantages and Limitations of Biotechnical Engineering

Specific ways vegetation can protect stream banks as part of a biotechnical engineering approach include:

- The root system binds soil particles together and increases the overall stability and shear strength of the bank.
- The exposed vegetation increases surface roughness and reduces local flow velocities close to the bank, which reduces the transport capacity and shear stress near the bank, thereby inducing sediment deposition.
- Vegetation dissipates the kinetic energy of falling raindrops, and depletes soil water by uptake and transpiration.
- Vegetation reduces surface runoff through increased retention of water on the surface and increases groundwater recharge.
- Vegetation deflects high-velocity flow away from the bank and acts as a buffer against the abrasive effect of transported material.
- Vegetation improves the conditions for fisheries and wildlife and helps improve water quality.

In addition, biotechnical engineering is often less expensive than most methods that are entirely structural and it is often less expensive to construct and maintain when considered over the long term. The critical threats to the successful performance of biotechnical engineering projects are improper site assessment, design or installation, and lack of monitoring and maintenance (especially following floods and during droughts).

Some of the specific limitations to the use of vegetation for stream bank erosion control in the vicinity of highway infrastructure include:

- Lack of design criteria and knowledge about properties of vegetative materials,
- Lack of long-term quantitative monitoring and performance assessment,
- Difficulty in obtaining consistent performance from countermeasures relying on live materials,
- Possible failure to grow and susceptibility to drought conditions,
- Depredation by wildlife or livestock, and
- Significant maintenance requirements.

Copyright National Academy of Sciences. All rights reserved.

More importantly, the type of plants that can survive at various submersions during the normal cycle of low-, medium-, and high-stream flows is critical to the design, implementation, and success of biotechnical engineering techniques. In addition, the combination of riprap and vegetation may be inappropriate if flow capacity is an issue, since bank vegetation can reduce flow capacity, especially when in full leaf along a narrow channel (see management of conveyance discussion in Section 4.2.3).

Design Considerations for Biotechnical Countermeasures

In an unstable watershed, careful study should be made of the causes of instability before biotechnical countermeasures are contemplated (see HEC-20) (Lagasse et al. 2012). Since bank erosion is tied to channel stability, a stable channel bed must be achieved before the banks are addressed. Scour and erosion of the bank toe produce the dominant failure modes and consequently, most biotechnical engineering projects documented in the literature contain some form of structural (hard) toe stabilization, such as rock riprap (Figure 4.20), rock gabions, cribs, cable-anchored logs, or logs with rootwads anchored by boulders (Figure 4.21). Note the use of a fascine bundle in Figure 4.20 as part of the rock toe protection. Toe protection should be keyed into the channel bed sufficiently deep to withstand significant scour, and the biotechnically engineered revetment should be keyed into the bank at both the upstream and downstream ends (called refusals) to prevent flanking (see discussion of "The Key" in Section 4.2.3). Deflectors such as fences, dikes, and pilings may also be utilized to deflect flow away from the bankline.

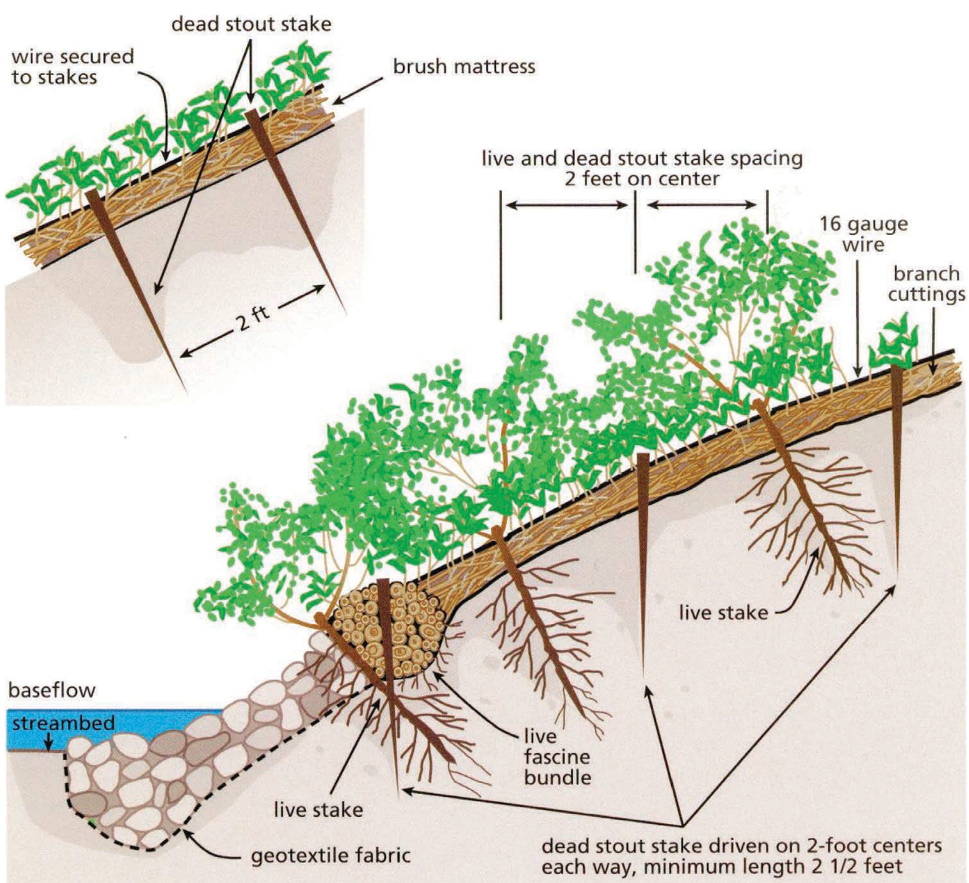


Figure 4.20. Details of brush mattress technique with stone-toe protection (FISRWG 2001).

Copyright National Academy of Sciences. All rights reserved.

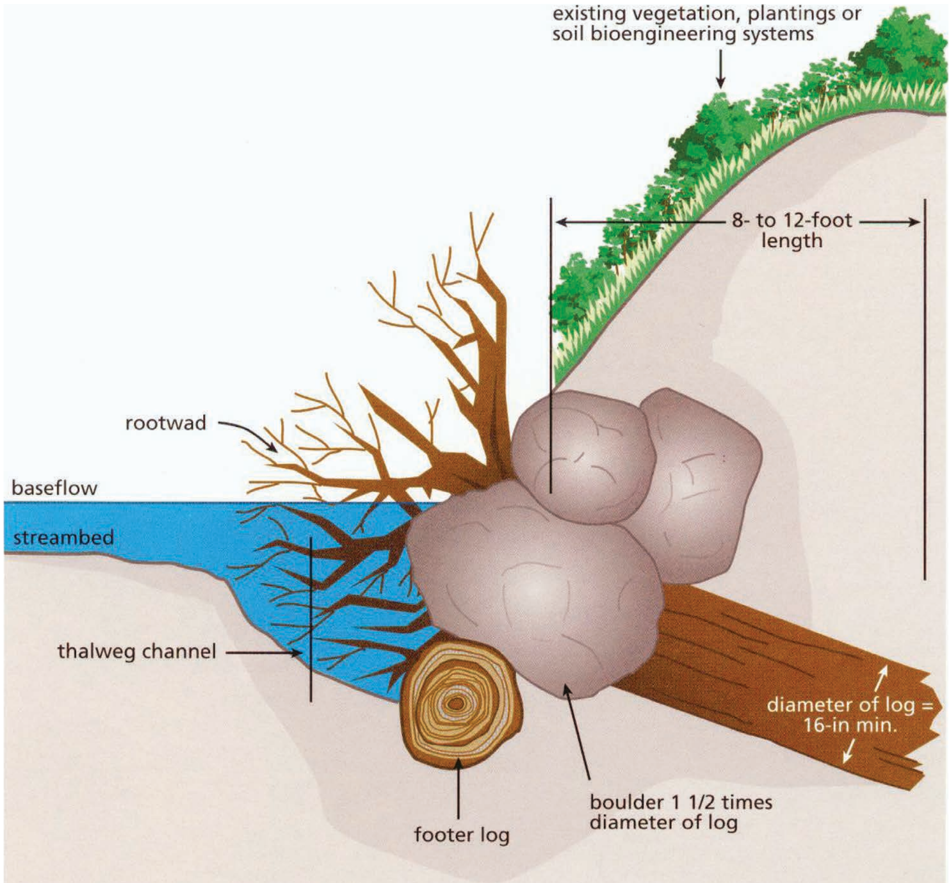


Figure 4.21. Details of root wad and boulder revetment technique (FISRWG 2001).

Other factors that need to be considered when selecting a design option include climate and hydrology, soils, cross-sectional dimensions (is there sufficient room for the countermeasure?), flow depth, flow velocity (both magnitude and direction), and slope of the bankline being protected. Most methods of biotechnical engineering will require some amount of bank regrading. Because structure design is based on flood velocities and depths, one or more design flows will need to be analyzed. Of particular interest is the bankfull or overtopping event, since this event generates the greatest velocities and tractive forces. Local (at or near the project site) flow velocities should be used for the design, especially along the outside of bends. The erosion protection should extend far enough downstream, particularly on the outer banks of bends. The highest velocities generally occur at the downstream arc of a bend and on the outer bank of the exit reach immediately downstream. As noted, the countermeasures should be tied into the bank at both ends to prevent flanking.

Summary

Biotechnical engineering can be a useful and cost-effective tool in controlling bank or channel erosion, while increasing the aesthetics and habitat diversity of the site. However, vegetation alone should not be seriously considered as a countermeasure against severe bank erosion where a highway facility is at risk. At such locations, vegetation can best serve to supplement other countermeasures. Where failure of the countermeasure could lead to failure of a bridge or highway structure, the only acceptable solution in the immediate vicinity of a structure is a traditional,

Copyright National Academy of Sciences. All rights reserved.

"hard" engineering approach. Biotechnical countermeasures need to be applied in a prudent manner, in conjunction with channel planform and bed stability analysis and rigorous engineering design. Designs must account for a multitude of factors associated with the geotechnical characteristics of the site, the local and watershed geomorphology, local soils, plant biology, hydrology, and site hydraulics. Finally, programs for monitoring and maintenance, which are essential to the success and effectiveness of any biotechnical engineering project, must be included in the project and adhered to strictly.

4.2.8 Engineering Liability Issues

The FHWA perspective on the application of biotechnical engineering treatments summarized in the preceding section brings out, by inference, a number of issues relevant to potential professional liability concerns when the treatment must be certified as having been "engineered." As noted by FHWA (Lagasse et al. 2009) certifying design and performance of biotechnical treatments becomes problematic for the PE on the design team primarily in relation to the vegetative component of the treatment. While design and performance standards are clearly established for the "hard" component of a treatment (e.g., riprap), the same cannot be said for the vegetative component. Here, unknowns and conditions generally out of the control of the engineer exist, including (1) lack of design criteria and knowledge of the "engineering" properties of vegetative materials, (2) lack of long-term performance criteria, (3) difficulty in obtaining consistent performance from the "live" material component of a treatment, and (4) introduction of factors beyond the control of the engineer (e.g., drought and/or depredation by wildlife or livestock).

Extracts from a *Journal of Hydraulic Engineering* Forum paper prepared by members of the ASCE Environmental and Water Resources Institute (EWRI) River Restoration Committee (Slate et al. 2005) highlight the issues that confront the engineer when engaged in river restoration design and the design and implementation of environmentally sensitive stream bank protection measures. The fundamental issue is that by sealing river restoration or environmentally sensitive designs, engineers assume the burden of professional liability for those designs. In many cases, stream restoration or biotechnical engineering projects require the seal of a licensed PE. Upon affixing his or her seal to design documents and drawings, the engineer assumes the responsibility for the accuracy of the design and affirms that the work was directly conducted or overseen by him or her. Professional ethics dictate that the work be within the engineer's area of expertise, that the engineer has kept abreast of the state of the practice through continuing education, and that a reasonable standard of care has been exercised in developing the project design. In many areas of civil engineering, the design standards are such that following those standards will ensure that these criteria are met. However, as enumerated above, for many environmentally sensitive treatments the factors necessary to ensure successful projects are less clear. It should be noted that engineers employed by government agencies typically are shielded from professional liability of this type; however, engineers serving as consultants to an agency are not.

Overall, the lack of rigorous engineering standards for critical elements of a restoration project produces difficulty for designers in (Slate et al. 2005):

- Identifying an appropriate design procedure and choosing which techniques are most suitable for given conditions.
- Effectively communicating with stakeholders on the suitability of a particular design procedure.
- Ascertaining the level of documentation necessary to convey design analysis into plans to ensure successful project implementation.
- Identifying measurable performance standards that can be monitored and assessed, thereby supporting an adaptive management approach to advance design methodologies.
- Managing risk and liability.

Copyright National Academy of Sciences. All rights reserved.

Slate et al. (2005) note that if engineering is required to meet project objectives, ideally the designer or project engineer works with other professionals throughout the design process in crafting a solution. Engineers may receive input from fluvial geomorphologists, geologists, fisheries biologists, ecologists, or other professionals. The engineer then converts that input into a solution (reports, drawings, specifications) affixed with seal and signature, which is presented with supporting information that clearly defines design criteria, risks, and measurable performance standards. While affixing of an engineering seal to a design does not guarantee "success" of a project, the seal does indicate that the engineer has exercised his or her best professional judgment upholding the industry "standard of care" in the design process.

Consequently, the EWRI River Restoration Committee points out that there is a need for members of the design team to appreciate and understand the roles and responsibilities of each discipline. While some disciplines fall squarely into the realm of traditional engineering practice, such as hydraulics and geotechnical engineering, others are based in physical, biological, or social sciences. Still others could be considered an indistinguishable blend of engineering and science, such as river mechanics and bioengineering. Clearly, there is a need for a suite of design approaches that combine engineering, geomorphology, hydraulics, and biology. The Committee strongly advocates the development of performance-based design guidance that incorporates a broad base of disciplines (hydrology, hydraulics, geomorphology, river mechanics, sediment transport, biology and ecology), and thus open up more options for channel design. The Committee concludes that there is a need for objective, performance-based guidelines or a manual of practice for river and stream restoration design as well as improved channel design standards.

The scope and objectives of NCHRP Project 24-39 did not include developing a broadly-based manual of engineering practice for environmentally sensitive stream bank protection treatments. However, through a compilation of design practices observed during field site visits to a wide range of restoration projects (Task 6) and by subjecting selected environmentally sensitive treatments to rigorous hydraulic engineering testing under prototype-scale laboratory conditions (Task 7), the design guidelines developed under this project together with the guidance developed under NCHRP Project 24-19 (McCullah and Gray 2005) represent advances in the state of practice in biotechnical engineering. The application examples of Section 4.4 demonstrate the successful integration of hydraulic engineering practice with a multidisciplinary design team in developing and implementing environmentally sensitive bank-protection designs responsive to the goals of stakeholders under a range of climatic and geomorphic conditions.

4.3 Guidelines for Specific Treatments

4.3.1 Live Siltation and Live Staking with Rock Toe

Introduction

As described in Chapter 3, prototype-scale laboratory testing of specific environmentally sensitive treatment configurations was a major component of this research. Tests focused on two representative biotechnical measures that were constructed with real plants in large planter boxes (6 ft wide by 20 ft long by either 12 or 18 in. deep). Plant materials were given time to establish prior to installation on the banks of an experimental trapezoidal channel. The various treatments presented in *NCHRP Report 544* (McCullah and Gray 2005) (see Appendix A) were carefully evaluated from the perspective of having wide applicability across the nation, as well as practical issues (for testing) of:

- Constructability,
- Physical testing requirements/constraints,

Copyright National Academy of Sciences. All rights reserved.

136 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

- Quantitative measurements of key hydraulic variables, and
- Condition monitoring of each component before testing and after each test flow event.

The two biotechnical bank-protection treatments tested were (see Figures 3.3 and 3.4):

1. Live siltation with live staking and rock toe at a 3H:1V slope, and
2. VMSE (sometimes referred to as FES lifts) at a 2H:1V slope.

The first treatment (live siltation with live staking and a rock toe) is referred to as "Tray 1" in Chapter 3. For the vegetative components of this treatment *NCHRP Report 544* lists the following research opportunities (see Appendix A):

Live Siltation—Research into velocities that this technique can withstand would be helpful.
Live Staking—Studies regarding the effect live staking has on increasing the ability of other measures to withstand higher velocities and shear stresses would be valuable.

Suggested design guidelines for this treatment are consolidated in this section. First, the design guidelines suggested for live siltation and live staking are summarized. Next, current guidance for the riprap toe of this treatment is referenced and updated. Finally, the results of laboratory testing of this treatment (see Chapter 3) as they address the research opportunities referenced above are summarized as an update to commonly used guidelines, specifically in relation to hydraulic issues of permissible velocities and shear stresses for this biotechnical configuration.

Live Siltation

Purpose and Advantages. Live siltation is a revegetation technique used to secure the toe of a stream bank, trap sediments, and create fish habitat. The system is normally constructed at the water's edge. Its primary purposes are to help secure the toe of a stream bank and trap sediments. Live siltation is an appropriate practice along an outer bend with significant scour if toe protection is provided.

Live siltation is a very effective and simple conservation method using local plant materials. This technique is particularly valuable for providing immediate cover and fish habitat while other revegetation plantings become established. The protruding branches provide roughness, slow velocities, and encourage deposition of sediment. The depositional areas are then available for natural recruitment of native riparian vegetation.

Design. A typical design drawing for live siltation is shown in Figure 4.22. Cuttings should be placed adjacent to the water's edge to ensure effective sediment trapping and velocity reduction at the toe of the slope. At least 12 branches per foot (40 branches per m) should be installed. This technique may be used for velocities up to 6.6 ft/sec (2 m/sec), but velocities should be at least 0.8 ft/sec (0.25 m/sec) for the system to function properly. For additional data on permissible velocities and shear stresses see Chapter 3 and the laboratory testing summary below.

Materials and Equipment. Stone (generally riprap), willow wattles, logs or rootwad revetments are needed for toe and scour protection. The live siltation will require live branches of shrub willows 3.5 to 5 ft (1 to 1.5 m) in length. The branches should be dormant, and need to have the side branches still attached. Any woody plant material, such as alder, can be installed for a nonliving system.

Construction and Installation. Construct a V-shaped trench at the AHW level, with hand tools or a backhoe. Excavate a trench so that it parallels the toe of the stream bank and is approximately 2 ft (0.6 m) deep. Lay a thick layer of willow branches in the trench so that one-third of the length of the branches is above the trench and the branches angle out toward the stream.

Copyright National Academy of Sciences. All rights reserved.

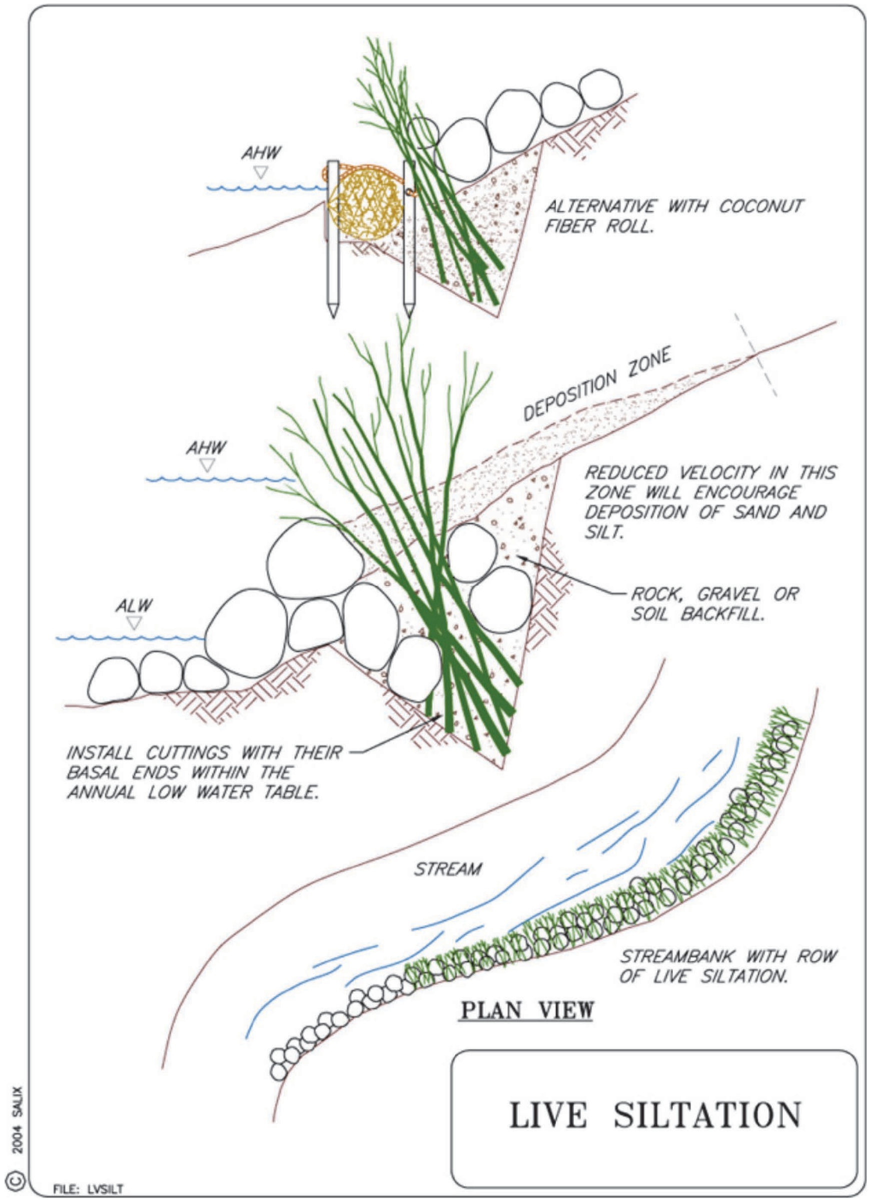


Figure 4.22. Live siltation typical drawing (McCullah and Gray 2005).

Place a minimum of 12 branches per foot (40 willow branches per m) in the trench. Backfill over the branches with a gravel/soil mix.

Both the upstream and downstream ends of the live siltation construction need to transition smoothly into a stable stream bank to reduce the potential for the system to be flanked. More than one row of live siltation can be installed running parallel to the channel. A living and growing siltation system typically is installed at AHW. If it is impossible to dig a trench, the branches can be secured in place with logs, armor rock, bundles made from wattles, or coir logs.

Figure 4.23 illustrates the construction and installation process. This project included live siltation used in conjunction with TRM on Alamitos Creek in Santa Clara County, CA. The live siltation was installed in October 2003. This site was included as a Task 6 site visit under NCHRP Project 24-39 (see Figure 2.5). For additional information see Site CA4 in Tables 2.10 and 2.11 and the Compendium available with this report.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Figure 4.23. Construction and installation of live siltation on Alamitos Creek, CA (McCullah and Gray 2005).

Cost. An estimated level of effort for installing live siltation ranges from 0.2 to 0.6 work hours per linear foot (0.7 to 2 work hours per linear m), plus willow stock if not readily available on site. For the Alamitos Creek site illustrated in Figure 4.23, the coir netting was readily available. The Alamitos Creek project had value added because it was constructed as part of a training workshop for Santa Clara Valley Water construction crews.

Maintenance and Monitoring. During the first year, a live siltation installation should be checked for failures after all overtopping flows, and repaired as necessary. During dry periods of the growing season of the first year, ensure that cuttings are not becoming dehydrated. Additional information on performance of a live siltation installation can be found in this project's Compendium for the Guadalupe River near San Jose, CA (Site CA5), and the Russian River near Geyserville, CA (Site CA6) (see Table 2.10 and Section 4.5.3). Section 4.2.5 provides additional guidance on monitoring the success of the vegetative component(s) of environmentally sensitive treatments.

Common Reasons for Failure. Cuttings will not promote siltation if not located at the water's edge. If located further up the bank, cuttings may dry out, and will only trap sediments

Copyright National Academy of Sciences. All rights reserved.

and slow velocities during high flows. Cuttings may not grow well if not handled properly prior to installation.

Live Staking

Purpose and Advantages. Live stakes are pieces of freshly cut woody plant stem planted in the ground or into erosion control or stream bank stabilization structures. The branches vary from about 20 to 39 in. (50 to 100 cm) long, and typically ¾ to 3 in. (20 to 75 mm) in diameter. Live stakes are planted with the terminal buds or leaf nodes pointing up and the basal ends down into the soil. The buried portion of the cuttings develop roots, while the exposed portion produces branches and leaves. Depending on the species, the cuttings can grow into shrubs and/or trees. Because of its ability to root from cuttings, the preferred plant species for live staking is willow (*salix* ssp.), but cottonwood (*Poplar* ssp.), dogwood (*Cornus* ssp.), elderberry (*Sambucus* ssp.), coyote brush (*Baccharis* ssp.), and others have been used successfully.

The concept behind live stake planting is that the live, vegetative cuttings are placed into the ground to allow the stakes to root and grow (see Figure 4.30). Even if the branches do not grow the stakes can provide, at least temporarily, reinforcement much like a wooden stake or steel rebar stake. Live stakes generally accomplish several purposes concurrently:

1. The stakes grow vegetatively thereby providing cover and erosion control.
2. The vegetative cover can provide improved aesthetics.
3. The cover provides shade and canopy cover where thermal pollution may be a concern.
4. The leaves, branches, and insects living on them can provide carbon and nutrient cycling and are an important food source for aquatic organisms.
5. The roots and branches provide for and improve geotechnical and soil stability. Using a system of live stakes creates a root mat that stabilizes the soil by reinforcing and binding soil particles together. Roots can also aid stabilization by extracting excess soil moisture and by binding fill soils to existing native soils.
6. Live stakes used as slope nails can stabilize slumps and slides through the mechanisms of "buttressing and arching."
7. Leafy and brushy top growth benefits the stream bank by increasing roughness, thereby reducing boundary shear stress underneath the canopy.
8. Live staking can, especially when used in conjunction with biodegradable erosion control materials, enhance conditions for colonization of native species.

Live staking has been successfully used in many different climatic, soil moisture regimes and elevations. There is a wide range of possible uses for and benefits of live staking, but the primary uses generally involve revegetation, anchoring, enhancing geotechnical strength (shear strength), or reducing erosion through increased cover (raindrop impact) and hydraulic roughness (reduced boundary shear). The practice is commonly used in combination with other treatments to provide more stable site conditions and a more environmentally sensitive design.

Among the advantages of live staking are:

- Stake sources are plentiful and inexpensive.
- Installation is rapid and inexpensive.
- Stakes can be planted with minimal surface preparation or disturbance and can be placed into irregular (but stable) slope surfaces.
- Stakes can be planted into already existing structures.
- Stakes root rapidly and help to reduce slope soil moisture soon after installation.
- Provides both environmental and aesthetic benefits.

The direct environmental benefits are cover and shade, carbon and insects for basic food web and nutrient cycling, and the ability to provide stable areas for native plant re-establishment

Copyright National Academy of Sciences. All rights reserved.

(successional reclamation). Live stakes establish a root mat that stabilizes the soil. Stake establishment can improve aesthetics and provide wildlife habitat. The stems, branches, and leaves slow high flows and provide shade, habitat, food, and shelter for stream corridor biota. When live stakes are placed on upper banks, they provide habitat, food, and shelter for terrestrial fauna as well. As a temporary, immediate measure, live staking performs an important function of stabilizing and modifying the soil, serving as a pioneer species until other plants become established. Stakes can play an important geotechnical function by providing apparent cohesion and soil reinforcement.

Design. One of the most important design considerations for vegetative success is determining whether the chosen species (willow, cottonwood, dogwood, etc.) is naturally occurring in the region and/or will allow successional reclamation—natural succession from willow shrubs to tall riparian overstory.

Live stakes are useful for the following situations:

1. Live staking is useful as a revegetation technique and for establishing riparian plants in high-flow or droughty situations.
2. Live staking can be used in irrigated or non-irrigated conditions with the latter being more prevalent. Irrigation can greatly increase vegetative success. Most often live staking is installed during the dormant season or when climatic or soil moisture conditions are favorable for establishment in non-irrigated conditions.
3. Live staking provides an environmentally sensitive anchoring technique for geotextiles and erosion control materials. The anchoring can be temporary or permanent depending on whether the stakes take root.
4. Live staking adds immediate failure resistance to the soil mass. While providing geotechnical benefits by "buttressing and arching," deep-seated failure planes underneath the bottom end of the cuttings will not usually be affected by live staking. These plants can remove excess soil moisture via evapotranspiration during the growing cycle; however, these benefits will not be realized during dormancy.

The stakes should be harvested from relatively straight, disease- and insect-free branches. Stakes shall be ¾ to 3 in. (20 to 75 mm) in diameter and a minimum of 18 in. (0.5 m) long. The upper end of the stake should be cut square and the basal end of the stake should be cut at an angle. Preparing the stakes in this manner will aide insertion into the soil and also ensure the stakes are oriented correctly when installed (see Figures 4.20 and 4.30).

Generally the deeper the branch is inserted into the soil, the better the chance of vegetative success and the greater the soil stabilization benefits, therefore the "80% Rule" should be strictly followed—at a minimum 80% of the branch should be placed in the soil and with 20% protruding above. For instance, an 18 in. (46 cm) stake will be installed at a minimum of 14.5 in. (37 cm) into the soil, and a 30 in. (91 cm) stake should be installed 24 in. (61 cm) in the soil. Deeper planting also reduces the chance that stakes can be pulled out by beavers, deer, or other wildlife. As shown in Figure 4.30 stakes should be inserted on the bank slope at a density of 1 to 3 ft (30 to 90 cm) apart. Ideally, the stakes should not be planted in rows or at regular intervals, but at random in the most suitable places at a rate of 2 to 5 cuttings/10 ft^2 (2 to 5 cuttings/m^2).

Allowable shear stress for this technique is approximately 2.5 lb/ft^2 (120 N/m^2) (Schiechtl and Stern 1996), and allowable velocity is about 3 ft/s (0.9 m/s) (Gray and Sotir 1996). For additional data on permissible velocities and shear stresses see Chapter 3 and the laboratory testing summary, below.

Materials and Equipment. Live stakes are typically made of woody riparian plant stems, although fleshy plant stems can have some success as well. Willow, cottonwood, and dogwood are the most used woody plants; however, willow cuttings make the best material for live stakes.

Copyright National Academy of Sciences. All rights reserved.

Willow species choice is highly dependent on locale; the best species for a given site are those found growing near the site. Stakes are typically harvested and planted when the willows, or other chosen species, are dormant, although the cuttings can do well other times of year when soil moisture is available.

When harvesting cuttings, select healthy, live wood that is reasonably straight, and at least 2 years old. Make clean cuts without splitting ends. Trim branches from cutting as closely as possible. Cuttings should generally be ¾ in. (19 mm) in diameter and 18 in. (46 cm) long, or larger depending on the species. The butt end of the cutting should be pointed or angled and the top end should be cut square to help identify the top and bottom when planting. The top, square end can be painted and sealed by dipping the top 1 to 2 in. (2.5 to 5 cm) into a 50:50 mix of light colored latex paint and water. Sealing the top of the stake will reduce desiccation, ensure the stakes are planted with the top up, and make the stakes more visible for subsequent planting evaluations. Stakes must not be allowed to dry out. All cuttings should be soaked in water for 5 to 7 days (a minimum of 24 hours) and planted the same day they are removed from water.

Construction and Installation. It is important not to damage the stakes during installation. Damaged and split stakes have increased incidence of dehydration, decay, and introduction of disease. Most compacted soils or soils with rocks and gravel will require the use of a "pilot bar" to make a hole prior to driving the stake. The use of a polyurethane hammer or rubber mallet will reduce splitting damage to the stake. Using a high-powered water jet to pilot the holes is also favorable as the holes are left well hydrated. The successful implementation of this technique requires care and consideration of the stakes during harvest, storage, transport, and installation. The stakes should never be allowed to dry out and should be moist and covered at all times. Soaking the stakes will increase success.

The basal ends should be planted into the ground, with the leaf bud scars or emerging buds always pointing up. Care should be taken not to damage the buds, strip the bark, or split the stake during installation. As noted above the stake should be set as deep as possible into the soil, with 80% of its length into the soil (see Figure 4.30). Deep planting will increase the chances of survival. The stake should never protrude more than one-quarter of its length above the ground level to prevent it from drying. The excess stake or any damaged or split ends can be cut off after installation. At least two buds and/or bud scars should remain above the ground after planting. Add soil to the planting hole if necessary to ensure solid contact with the stem. It is important to tamp the soil around the cutting to insure good soil-stem contact. The best installations, especially on droughty sites, will include "watering in" and slightly compacting the backfill or hole. Watering in, much like transplanting a container plant, can successfully be accomplished by pouring one to two gallons of water into the soil around the stake and planting hole, then slightly tamping or otherwise jarring the soil. This procedure will ensure intimate soil to stem contact.

Cost. Costs range from $1.50 to $3.00 per stake (circa 2005), including harvesting, transportation, storage, and installation. Costs may be higher if labor costs are especially high or the harvesting location is a long way from the project site. Estimated labor allocations are 20 to 50 ft^2 (2 to 5 m^2) of live staking per work hour or approximately 10 to 25 stakes per hour. These estimates include all preparatory work.

Maintenance and Monitoring. Without temporary irrigation, stakes have the highest survival rate when installed during the dormant season, which may not coincide with the best time for construction of the rest of the project. Stakes do not become fully effective until one growing season after installation, and thus provide limited immediate and areal stabilization unless combined with other practices. Stakes should be inspected every few weeks until well established, and irrigation, browse control (from livestock, deer, beavers, etc.), pruning, weed control, and fertilization should be implemented as needed.

Copyright National Academy of Sciences. All rights reserved.

For additional information on performance of live staking installations, see Table 2.10 which lists six sites inspected under Task 6 where live staking was part of the environmentally sensitive treatment implemented. Detailed information on these sites can be found in the Compendium. For example, live staking was included at the Malletts Creek site near Ann Arbor, MI (site M15, see Figure 2.4) and performance of the live staking component is shown in Figure 4.48g, h, and j. Section 4.2.5 provides additional guidance on monitoring the success of the vegetative component(s) of environmentally sensitive treatments.

Common Reasons for Failure. Live staking can fail if vegetation is not handled properly prior to installation, is installed incorrectly (less than 80% of the cutting in the ground, bud scars facing down, poor soil contact, etc.), or not irrigated or watered in when installed in arid areas.

Rock Toe

Purpose and Advantages. The "engineered" component of the Tray 1 treatment (see Chapter 3) consisted of a rock riprap toe. This component of a biotechnical treatment is also known as longitudinal peaked stone toe protection (LPSTP), stone toe, rock toe, stone-toe buttress, weighted riprap toe, and longitudinal fill stone-toe protection (LFSTP). When implanted with vegetation the rock toe is also referred to as "vegetated riprap" (see overview discussion in Section 4.3.3 and Figures 4.27 through 4.30).

Longitudinal stone toe has proven cost effective in protecting lower banks and creating conditions leading to stabilization and revegetation of steep, caving banks (for example, see Shields et al. 1995). Stone toe is continuous bank protection consisting of riprap placed longitudinally at, or slightly streamward of, the toe of an eroding bank. The cross section of the stone toe is triangular in shape. The success of this method depends, in part, upon the ability of stone to self-adjust or "launch" into any 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 (e.g., through the stream bend). The "smoothed" longitudinal alignment results in improved flow (less turbulence) near the toe of the eroding bank. This continuous bank-protection technique protects the toe from erosion. It is especially effective in streams where most erosion is due to relatively small but frequent events. It protects the toe so that slope failure of a steep bank landward of the stone toe will produce a stable angle. Such a bank is often rapidly colonized by natural vegetation (Figure 4.24).

Figure 4.24. Revegetation of eroding bank landward of stone toe (photo by J. McCullah).

Copyright National Academy of Sciences. All rights reserved.

Longitudinal stone toes are well suited for many situations where relatively low-cost, continuous bank protection is needed, and is particularly applicable for ephemeral, narrow, and small- to medium-sized streams. A stone toe is also well suited for areas where the toe is experiencing erosion but the mid and upper banks are fairly stable due to vegetation, cohesive soils, infrequent short-duration inundation, or relatively slow velocities.

A longitudinal stone toe can be applied in some situations where the bankline needs to be built back out into the stream, where the existing stream channel needs to be realigned, where the outer-bank alignment makes abrupt changes (scallops, coves, or elbows), or where the stream is not otherwise smoothly aligned.

Bank grading, reshaping, or sloping is usually not needed (existing bank and overbank vegetation need not be disturbed or cleared). Longitudinal stone toe is very cost effective and is relatively easy to construct. It is simple to design and specify and is a thoroughly tested method that has been used in a variety of situations and has been extensively monitored. Another advantage is that it is easily combined with other bank stability techniques that provide superior habitat compared to pure riprap. A longitudinal stone toe has documented environmental benefits, especially for aquatic habitat (see Lister et al. 1995, Dardeau et al. 1995, and Shields et al. 1995). Stone interstices provide cover and habitat for smaller fish and other organisms, and rocky surfaces provide stable substrate for benthic invertebrates (see Section 4.2.6 and Figure 4.16). Vegetative cover can become established, even growing through the rock, and can provide canopy and a source of woody debris.

Design. Longitudinal stone toe can be specified by weight per unit length or to a specific crest elevation. A specific crest elevation may be specified when the bed of the stream is uneven or deep scour holes are evident. Maynord (1994) presents a design procedure for "launchable riprap" that may apply to stone toe design in situations where scour on the water side of the toe is possible.

Longitudinal stone toe must be keyed deeply into the bank at both the upstream and downstream ends and at regular intervals along its entire length. On small streams, 75 to 100 ft (25 to 30 m) spacing between keys (tie-backs) is typical, while on larger streams and smaller rivers, one or two multiples of the channel width can be used as a spacing guide. Excavation of trenches for keys provides a good opportunity for deep planting willow (*Salix* ssp) posts or poles (Figure 4.25).

Figure 4.25. Construction of keys provides an opportunity for deep planting willow poles (McCullah and Gray 2005).

Copyright National Academy of Sciences. All rights reserved.

144 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

The key trenches at the upstream and downstream ends should be excavated into the bank at an angle of approximately 30 degrees with the primary flow direction and of sufficient length that flows will not be able to get around them during the design storm. A gentle angle is important for the end keyways, often referred to as "refusals," because it allows for smooth flow transitions coming into and flowing out of the treated reach. Tie-backs or "refusals" oriented at 90° to the bank have resulted in many failures at the downstream end of the structure, due to flow expansion at that point (see discussion of "The Key" in Section 4.2.3 and Figure 4.5).

While "launchable riprap" as described by Maynord (1994) may offer ease of installation and reduce construction costs, it does not permit the use of a granular or geotextile filter under the stone toe. As noted in *NCHRP Report 568* (Lagasse et al. 2006) and FHWA's HEC-23 (Lagasse et al. 2009), the importance of the filter component of a riprap installation should not be underestimated. Filters (either granular or geotextile) contribute to the long-term success of riprap (including a stone toe), particularly if significant toe scour is anticipated (see "The Key" discussion in Section 4.2.3). For further guidance on riprap design, reference to the publications cited above is suggested.

NCHRP Report 568: Riprap Design Criteria, Recommended Specifications, and Quality Control (Lagasse et al. 2006) provides design guidance for sizing the rock for dumped riprap used for bank protection. That NCHRP study evaluated numerous procedures for sizing revetment riprap and suggests using the method developed by Maynord et al. (1989) and Maynord (1990) and published by the USACE as Engineering Manual No. 1110-2-1601 EM-1601 (USACE 1991). The procedure uses both velocity and depth as its primary design parameters. Design guidance is provided for riprap sizing, thickness, shape, and gradation, as well as for the design of granular and geotextile filters. The results of the NCHRP riprap study have been incorporated into FHWA's HEC-23 (Lagasse et al. 2009) to include a general discussion of riprap design, filter requirements, and failure modes in Volume 1 (Chapter 5), and detailed design guidelines in Volume 2, Design Guideline 4 "Riprap Revetment" and Design Guideline 16 "Filter Design." Reference to this guidance is suggested for the design of the rock toe component of biotechnical countermeasures. The issue of appropriate engineering design of a rock toe is also addressed in Section 4.3.3. Note that Figures 4.27 through 4.29 and associated discussion in Section 4.3.3 recognize the need for a filter and include the notes:

- Filter layer of graded aggregate and/or filter fabric;
- Graded, granular filter is preferable to filter fabric to improve root penetration; and
- Inserting live poles/stakes through slits in a geotextile filter is discouraged, but can be used if no other alternative is available.

A longitudinal stone toe only provides toe protection and does not protect mid- and upper-bank areas. Some erosion of these areas should be anticipated during long-duration, high-energy flows, or until the areas become otherwise protected (e.g., by vegetation). Stone toe is not suitable for reaches where rapid bed degradation (lowering) is likely, or where scour depths adjacent to the toe will be greater than the depth of the toe. Section 4.2.3 provides specific guidance for analyzing long-term degradation trends and design procedures for toe and bendway scour.

In regard to hydraulic loading, permissible shear and velocity for a longitudinal stone toe are related to the size of rock used in construction. Other factors, such as the angularity of the stone, the thickness of the layers of stone, and the angle at which the faces of the stone structure are constructed also come into play.

Materials and Equipment. Stone for the structure should be well graded and properly sized. Detailed guidance for sizing stone for bed and bank stabilization structures is beyond the scope of this guideline, and many approaches are available (see references cited in the design discussion above).

Copyright National Academy of Sciences. All rights reserved.

Construction and Installation. All longitudinal stone toes should be constructed in an upstream to downstream sequence. This technique usually requires heavy equipment for excavation of keys (tie-backs) and efficient hauling and placement of stone. Longitudinal stone toes can be constructed from within the stream, from roadways constructed along the lower section of the stream bank itself, or from the top. The preferred method is from the point bar side of the stream (especially possible with ephemeral or intermittent streams), as this causes the least disturbance of existing bank vegetation. The least preferred is from the top of the bank, as it disturbs or destroys more bank vegetation and the machine operator's vision is limited.

Usually, the toe trenches are excavated first and a filter and rock are placed into the key. The rock is then formed into tie-backs (if needed) and finally the stone toe is constructed along a "smoothed" alignment, preferably with a uniform radius of curvature throughout the bend. In a multi-radius bend, smooth transitions between dissimilar radii are preferred.

Installation of a stone toe is illustrated in Section 4.4.3, the "Humid Region" application example (see Figure 4.48a, b, i, and j). For additional information on this installation on Malletts Creek near Ann Arbor, MI, see Table 2.11 (Site MI5) and the Compendium.

Cost. Costs of a riprap toe depend on the cost of stone, hauling, and amount of stone used. Including stone for keys and tie-backs, typically 120 to 140 tons (110 to 130 metric tons) of stone will be used for each 100 ft (30 m) of protected bank when toe is placed at a rate of 1 ton/ft (3 metric tons per lineal m) of protected bank. Based on typical unit costs for stone (including delivery and placement), cost for this type of toe ranges from $16 to $35 per foot ($50 to $115 per m) of protected bank, although costs are highly dependent on regional considerations.

Maintenance and Monitoring. Maintenance and monitoring requirements should be linked to consequences of failure. Detailed maintenance and monitoring requirements for riprap can be found in *NCHRP Report 568* (Lagasse et al. 2006) and FHWA's HEC-23 (Lagasse et al. 2009). Inspection of riprap placement typically consists of visual inspection of the installation procedures and the finished surface. Inspection must ensure (1) that a dense, rough surface of well-keyed graded rock of the specified quality and sizes is obtained, (2) that the layers are placed such that voids are minimized, and (3) that the layers are the specified thickness.

The following general guidance for inspecting riprap is presented in HEC-23 (Lagasse et al. 2009):

1. Riprap should be **angular and interlocking** (old bowling balls would not make good riprap). Flat sections of broken concrete paving do not make good riprap.
2. Riprap should have a **granular or synthetic geotextile filter** between the riprap and the subgrade material.
3. Riprap should be **well graded** (a wide range of rock sizes). The maximum rock size should be no greater than about twice the median (d_{50}) size.
4. For bridge piers, riprap should generally extend up to the bed elevation so that the top of the riprap is visible to the inspector during and after floods.
5. When inspecting riprap, the following are strong indicators of problems:
   - Has riprap been **displaced** downstream?
   - Has angular riprap blanket **slumped** down slope?
   - Has angular riprap material been **replaced** over time by smoother river run material?
   - Has riprap material physically **deteriorated, disintegrated**, or been **abraded** over time?
   - Are there **holes** in the riprap blanket where the filter has been exposed or breached?

Common Reasons for Failure. Features that should be monitored are similar to those for all stone structures: loss of stone due to subsidence, leaching of underlying sediments, raveling, or excessive launching. Extreme scour or bed lowering on the stream side of the toe can cause the entire mass of stone to launch, creating an opening or gap in the longitudinal structure. If this

Copyright National Academy of Sciences. All rights reserved.

situation is anticipated or encountered, the problem can be remedied by adding more rock to restore design conditions.

Longitudinal stone toes may be flanked during extremely high flows if the key trenches are incorrectly built or if the tie-backs are spaced too widely or are constructed with inadequate amounts of stone. Terminal keyways or "refusals" oriented at 90 degrees to the bank have resulted in many failures at the downstream end of the structure, due to flow expansion at that point. These terminal key trenches at the upstream and downstream ends should be excavated into the bank at an angle of approximately 30 degrees with the primary flow direction and of sufficient length that flows will not be able to get around them during the design storm (see Figure 4.5).

Observations relevant to the performance of this multi-component treatment from the field site visits are summarized in Section 4.5.3.

Laboratory Testing Results—Live Siltation and Live Staking with Rock Toe

Full-scale laboratory testing conducted under this research project confirmed the suitability of existing design and installation guidelines for live siltation and live staking as stream bank protection treatments as described above in this section. Observations from laboratory testing include the following:

1. At the planting densities of live siltation (toe) and live staking (upper bank) examined in the testing program, the Mannings n resistance coefficient was found to range from 0.030 to 0.035. The lower Manning n values were associated with fully pronated willows.
2. Pronation of willows occurred at a unit discharge (velocity times depth) of 5.3 cfs/ft.
3. Permissible shear stress for this treatment was found to be 2.5 lb/ft^2, which confirms existing guidance.
4. Permissible depth-average velocity V_{60} was found to be 7 to 9 ft/s, which is considerably higher than previous recommendations (3 ft/s).
5. Measurement of the vertical velocity distribution demonstrates the effectiveness of the live siltation component in moving high-velocity flow away from the bank toe and into the main channel.
6. The excellent performance of this treatment underscores the need for a stone toe component in combination with vegetative treatments.

4.3.2 Vegetated Mechanically Stabilized Earth Without Hard Toe

Introduction

As noted in Section 4.3.1 VMSE without a hard toe was the second of two environmentally sensitive treatments tested at prototype scale in an experimental trapezoidal channel (see Chapter 3 and Figure 3.4). This treatment is referred to as "Tray 2" in Chapter 3. For this treatment *NCHRP Report 544* (McCullah and Gray 2005) lists the following research opportunities (see Appendix A):

VMSE—Some uncertainty exists at present as to the exact permissible shear stresses and velocities for VMSE interfaces. Additional research would also be helpful on the nature of the interaction between roots and fabric and between root architecture and distribution in VMSE structures.

Proposed design guidelines for VMSE treatment are consolidated in this section. Then the results of laboratory testing of this treatment (see Chapter 3) as they address the research opportunities referenced above are summarized as an update to commonly used guidelines, specifically in relation to hydraulic issues of permissible velocities and shear stresses for this biotechnical configuration.

Copyright National Academy of Sciences. All rights reserved.

Purpose and Advantages. Components and variations of this treatment are also known as FES, brush layering with soil wraps, and vegetated geofabric wrapped soil. This technique consists of live cut branches (brush layers) interspersed between lifts of soil wrapped in natural fabric, e.g., coir, or synthetic geotextiles or geogrids (which are not considered in this design guidance). The live brush is placed in a criss-cross or overlapping pattern atop each wrapped soil lift in a manner similar to conventional brush layering (see live brush layering in McCullah and Gray 2005 and Bischetti et al. 2009). The fabric wrapping provides the primary reinforcement in a manner similar to that of conventional mechanically stabilized earth. The live, cut branches eventually root and leaf out, providing vegetative cover and secondary reinforcement as well.

Since the inert fabric wraps provide reinforcement and mechanical stabilization, they may permit steeper slopes to be constructed than would be possible with live brush layers alone. Brush layering treatment by itself is normally restricted to slopes no steeper than 1V:2H. The "Tray 2" VMSE as tested with a biodegradable coir fabric was installed at a slope of 1V:2H (see Chapter 3 and Figure 3.4).

Design. VMSE as defined here can be used to stabilize slopes as steep as 1V:2H. This technique provides an alternative to steep retaining structures, and to techniques that require slope flattening or bank lay back, which results in excessive right-of-way encroachment at the top of the bank. The use of geogrids permits even steeper slopes and provides greater long-term durability and security (see McCullah and Gray 2005). The fabric or geotextile wrap also provides additional protection to upper portions of stream banks that are subject to periodic scour or tractive stresses. If either steady, long-term seepage, or temporary bank return flows after flood events are a problem, the brush layers act as a drainage layer or as conduits that relieve internal pore-water pressure, and favorably modify the groundwater flow regime within this slope to minimize slope stability problems.

Design of VMSE is relatively complex, because it entails designing, melding together, and constructing two similar yet distinct methods, conventional MSE and live brush layering. Both techniques are widely used and well understood; however, simultaneous use introduces complexity. While many different types of inclusions with various shapes and properties can be used to reinforce and buttress earthen slopes, Tray 2 as tested should more properly be referred to as FES. The installation steps and design criteria for FES with brush layering are illustrated in Figure 4.26.

Live cuttings inserted as shown in Figure 4.26 also act as tensile inclusions and help to stabilize a slope, embankment, or structural fill. Live brush layers behave exactly in this fashion. Gray and Sotir (1992) discuss how brush layers can be analyzed and their contribution to slope stability determined in a rational, quantitative manner. In this combined approach, however, the contribution to mechanical reinforcement from the live cuttings is simply treated as a bonus, and the design analysis is focused on the fabric (or geogrid) reinforcements themselves.

There appears to be little or no published test data for permissible hydraulic loading of VMSE structures. There does exist, however, published data on vegetated coir mats and live brush layers, respectively, as shown in Table 4.4.

These data can be used to approximate permissible shear stresses and velocities for VMSE. However, one of the goals of testing the Tray 2 configuration under NCHRP Project 24-39 was to develop better hydraulic loading data for this particular environmentally sensitive bank-protection treatment. For additional data on permissible velocities and shear stresses see Chapter 3 and the laboratory testing summary below.

Materials and Equipment. Select long branches of native tree species that are capable of vegetative propagation. Willows (*Salix* spp) are the most commonly used plant material, because

Copyright National Academy of Sciences. All rights reserved.

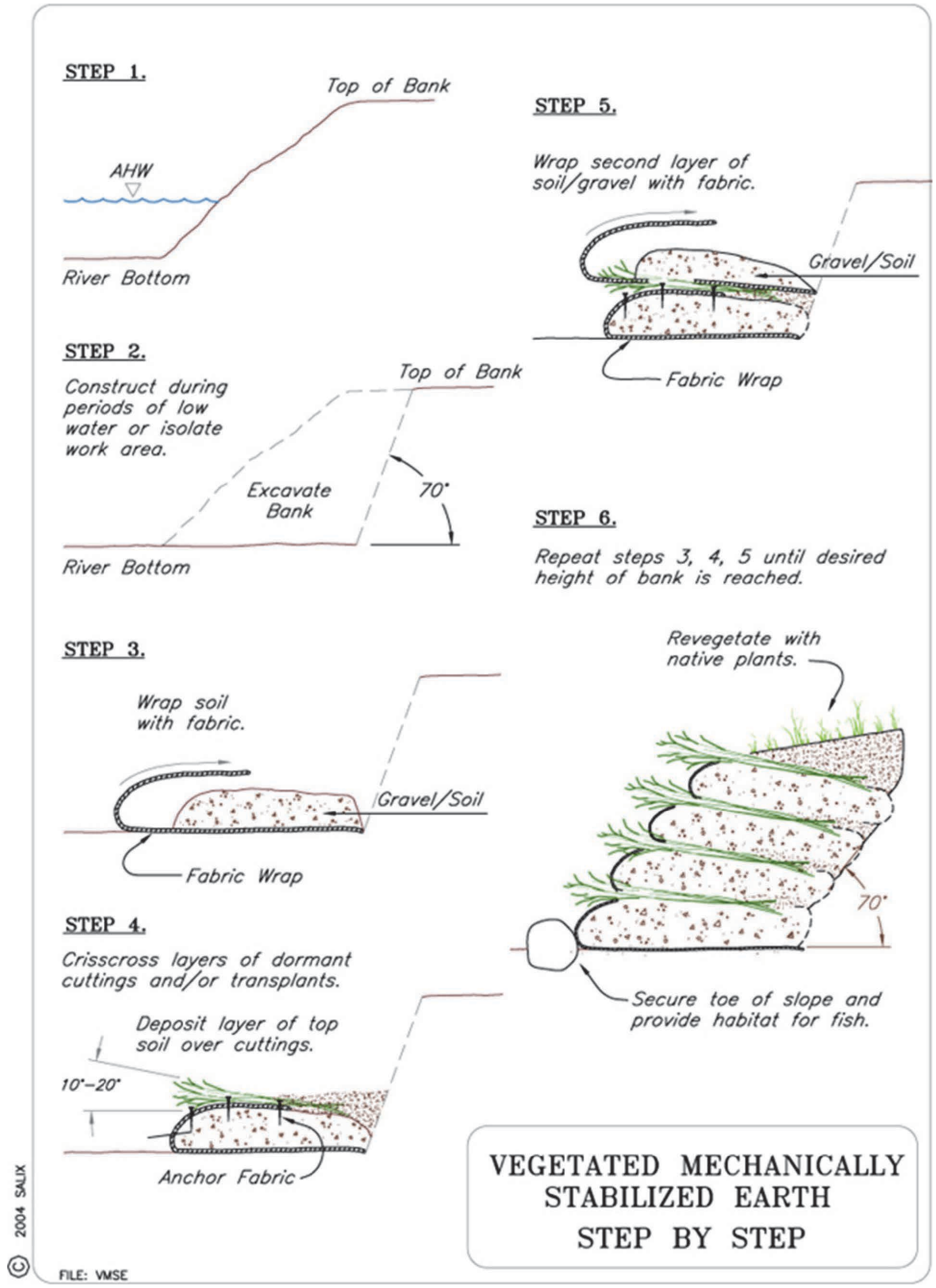


Figure 4.26. VMSE typical drawing (McCullah and Gray 2005).

Table 4.4. Limiting shear stress and velocity levels for selected soil bioengineering treatments (adapted from Fischenich 2001).

Treatment Type	Limiting Velocity ft/sec (m/sec)	Limiting Shear Stress lbs/ft^2 (Kg/m^2)
Vegetated coir mat	4 - 8 (1.2 - 2.4)	9.5 (46.4)
Live brush mattress (initial)	0.4 - 4.1 (0.1 - 1.2)	4.0 (19.5)
Live brush mattress (established)	3.9 - 8.2 (1.2 - 2.5)	12.0 (58.6)
Brush layering (initial/established)	0.4 - 6.5 (0.1 - 2.0)	12.0 (58.6)

Copyright National Academy of Sciences. All rights reserved.

they generally root well from cuttings. Alder, cottonwood (*Populus deltoides*), and dogwood (*Cornus* spp) can also be used effectively, particularly when mixed in with willow. The length of the branches will vary depending upon the desired depth of reinforcement, but they should be long enough to reach the back of an earthen buttress placed against a stream bank while protruding slightly beyond the face (see Figure 4.26). The diameter of the live cuttings will also vary depending on their length, but typically should range from ¾ to 2 in. (19 to 51 mm) at their basal ends.

The inert construction materials in the configuration tested consisted of a natural geofabric. The coir netting is visually less obtrusive than other manufactured materials (e.g., geogrids) and can retain moisture helpful to vegetative establishment. As with most biotechnical structures, the vegetation is intended to provide long-term stability. Material properties such as longevity, durability, and resistance to abrasion/corrosion should be considered. Coir fabric or netting comes in various grades that have different size openings and unit tensile resistances.

Construction and Installation. A VMSE structure must be constructed during the dormancy period to ensure good vegetative propagation and establishment. Alternatively, the live cuttings may be harvested during dormancy, and placed in temporary cold storage until they are ready for use during an out-of-dormancy period (e.g., during the summer months). The latter recourse increases the unit cost of the technique. For this treatment, materials procurement is more demanding, and installation more complex, because of the blending of two distinct methods, i.e., conventional MSE/FES and live brush layering, into a single approach. Costs will also be more than brush layering used alone, because of the added expense of the geotextile and the additional labor required to handle and construct the wraps.

A VMSE installation begins at the base of the slope and proceeds upwards. A series of schematic drawings illustrating the installation procedures step by step are shown in Figure 4.26. The structure should generally be supported on a rock toe or base (not shown in Figure 4.26 schematic) and be battered or inclined at an angle of at least 10 to 20 degrees to minimize lateral earth forces (as shown in Figure 4.26). It is critical that factors such as toe scour depth be determined for each particular project and be incorporated into project design. Note—the VMSE treatment as tested for NCHRP Project 24-39 had no hard toe in response to a tendency of some resource agencies to prefer a treatment with no rock component (see Figure 3.4 and summary of testing results, below). The following general guidelines and procedures apply:

1. Excavate a trench below the likely depth of toe scour and backfill it with rock to provide a base for the VMSE structure. The top surface of the rock should be inclined with the horizontal to establish the desired minimum batter angle for the overlying structure.
2. Construct an earthen structure reinforced with coir fabric and live brush on top of the rock base. For this purpose, select fabric rolls with a minimum roll width of 13 ft (4 m) and unit tensile strength predetermined from a stability analysis that takes into account the height and slope angle of the reinforced, earthen buttress fill (see McCullah and Gray 2005 for additional guidance).
3. Place select fill material on the fabric and compact it in 3 in. (7.5 cm) lifts to a nominal thickness ranging from 12 to 30 in. (30 to 76 cm). Thinner lifts are used at the base of the structure, where shear stresses are higher. Temporary batter boards may be required at the front face to confine the select fill during the installation process and to form an even face.
4. The fabric sheet should be allowed to drape down or protrude beyond the front edge of each underlying lift of earthen fill to create at least a 3 ft (0.9 m) overlap when it is pulled up and over the next lift. The exposed sections of fabric layers are pulled up and over the faces of the fill layers (see to Figure 4.26) and staked in place. The fabric should be pulled as uniformly as possible before staking to develop initial tension in the fabric. A tractor or winch pulling on a long bar with hooks or nails along its length works well for this purpose. The tensioned fabric

Copyright National Academy of Sciences. All rights reserved.

overlap sections should be secured in place using wood construction stakes spaced every 3 ft (0.9 m).

5. Layers of live cut branches are then placed criss-crossed atop the underlying wrapped soil lift (see Figure 4.26). In addition, 1 to 2 in. (22 to 50 mm) of topsoil should be mixed in with the cut branches. The top soil can be placed beforehand or spread over the top of a brush layer. Up to three (3) layers of live, cut branches interspersed with 1 to 2 in. (25 to 50 mm) of topsoil can be placed in this manner.
6. The process is repeated with succeeding layers of earth fill, live brush and fabric until the specified height or elevation is reached.

Cost. Costs for VMSE structures are likely to be on the high end of environmentally sensitive bank-protection measures because of both design/construction complexity and material acquisition costs. In addition, site-specific considerations, such as access, also have a significant influence. VMSE treatments will obviously cost more than live brush layering used alone because of the presence of geotextile material reinforcements.

Maintenance and Monitoring. For VMSE, monitoring should consist of inspecting the fabric for signs of breakage or tearing from scour damage or possibly from excessive tensile stresses due to higher than expected lateral earth pressures. Signs of uncontrolled seepage, such as weeping or wet spots in the structure, should also be noted. Finally, the site should be examined for possible signs of flanking erosion, which must be addressed with ancillary protective measures as the flanking will threaten the integrity and effectiveness of the VMSE structure itself. For additional guidance on monitoring of the brush layering component see Section 4.2.5.

Common Reasons for Failure. As of 2005 no known instances of failure had been published. The most likely causes of a hypothetical failure, however, would be the following (McCullah and Gray 2005):

1. Inadequate primary reinforcement from the inert tensile inclusions (fabric or geotextile), i.e., improper vertical spacing or lift thickness, insufficient allowable unit tensile resistance in the selected fabric or geotextile, and too short an embedment length for the given soil and site conditions, e.g., slope height, slope angle, and soil shear strength properties.
2. Failure to properly consider seepage conditions and install adequate drainage measures, e.g., chimney drain behind VMSE structure.
3. Inadequate attention to construction procedures and details.
4. As with all resistive, bank line protective structures, flanking, toe scour, and undermining are always potential problems.

Observations relevant to the performance of this treatment from the field site visits are summarized in Section 4.5.3.

Laboratory Testing Results—VMSE Without Hard Toe

As modifications to the *NCHRP Report 544* guidance extracted above, the following additional guidance based on the Task 3 laboratory testing is recommended.

1. The vegetative treatment of Tray 1 (live siltation willow and live staking with stone toe) exhibited significantly lower Mannings n resistance coefficients, bed shear stresses, and erosion compared to Tray 2 (VMSE soil lifts with soft toe) at the same discharge. As tested, the Tray 2 VMSE treatment resulted in Mannings n resistance coefficients ranging from 0.040 to 0.045. The lower Mannings n values were associated with fully pronated willows.
2. Pronation of willows occurred at a unit discharge (velocity times depth) of 5.3 cfs/ft.
3. A higher density of willows per square yard of surface area does not necessarily result in better performance. Rather, the overall geometry of the bank slope and planting configuration appears

Copyright National Academy of Sciences. All rights reserved.

to be the more important factor in the overall performance of the vegetative component. For example, the stair-step configuration of the VMSE creates preferential pathways for high-velocity flow that results in the potential for damage to the coir/jute fabric of the soil lifts.

4. Vulnerable areas of the VMSE treatment include the faces of the individual soil lifts. In particular, the lowermost lift at the toe of the bank slope is subject to damage if left unprotected by other means, such as a stone (i.e., riprap) toe armor or other "hard" engineered treatment. Qualitative observations suggest that preferential pathways for high-velocity flow along the faces of the soil lifts appear to be a shortcoming of this bank-protection treatment.
5. The uppermost soil lift of VMSE is also vulnerable to soil loss if it becomes fully submerged and is not vegetated on its top surface. In contrast, the top surfaces of soil lifts that are lower down on the slope were seen to be protected by the pronated willows of the lift above, which provided a "shielding" effect.
6. The point velocity, V_{60}, corresponding to the onset of tears in the coir/jute fabric, as well as areas of significant soil erosion, was found to be in the range of 5 to 7 ft/s. The corresponding shear stress at these conditions was 2.5 lb/ft^2. In the stair-step 2H:1V configuration of VMSE, the limiting values for velocity and shear stress are much lower than those for similar materials on a graded 3H:1V slope (see Table 4.4). At even higher velocities (7 to 9 ft/s) and shear stresses (3 to 4.5 lb/ft^2), excessive damage and soil loss were observed.
7. The laboratory testing of this treatment configuration underscores the need for a hard armor toe component for vegetative stream bank protection measures.

4.3.3 Vegetated Riprap—An Overview

Introduction

Vegetated riprap is a layer of stone and/or boulder armoring that is vegetated, optimally during construction, using pole planting, brush layering, 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. The analysis of performance and design guidelines presented for the rock toe with live siltation and live staking in Section 4.3.1 has direct application to this environmentally sensitive treatment for both the design of the stone and the need for a filter.

One of the main conclusions drawn from extensive research on stream bank erosion and protection in the 1970s was that simply grading the bank to a stable slope and planting vegetation without toe protection is ineffective (USACE 1981); similar conclusions have been reached by others (Shields et al. 1995). In most stream channels, shear stress reaches a maximum at the toe of concave banks, and this region is unsuited for terrestrial plants because it is either permanently or frequently inundated.

Combining treatments allows maximum flexibility in meeting the objectives of bank stabilization and habitat development. Selection of an appropriate toe protection structure, e.g., longitudinal stone toe with spurs, can create ideal water/shore interface conditions and scour holes that may provide stable pool habitats. A well vegetated (or revegetated) bank can improve aquatic and riparian habitat in addition to providing important functional benefits (Coppin and Richards 1990). Stream bank vegetation provides cover, shade, and insect food sources for fish and other aquatic organisms near the water's edge. Upper and mid-bank vegetation yields cover and habitat opportunities for small mammals and other riparian wildlife (McCullah and Gray 2005).

Based on the results of the Task 2 survey of practitioners, vegetated riprap is a fairly common approach to designing environmentally sensitive stream bank treatments (17 out of 35 responses)

Copyright National Academy of Sciences. All rights reserved.

(see Table 2.9). Of the 16 field sites visited under Task 6, 11 used willow posts and poles and five sites included, specifically, vegetated riprap as a stream bank treatment. The following sections provide general design guidance for several vegetated riprap alternatives.

Commonly Used Vegetated Riprap Techniques

Five methods for constructing vegetated riprap have proven effectiveness. Typical design concept sketches of four of these five methods are provided as Figures 4.27 through 4.30. These sketches are reproduced from *NCHRP Report 544* (McCullah and Gray 2005). While the key hydraulic design variable "design high water" is not defined in these sketches, AHW and ALW criteria are discussed in Section 4.2.3 under the Bankfull Discharge section.

1. Vegetated riprap with willow bundles (Figure 4.27): Vegetated riprap with willow bundles is the simplest to install, but it has a few drawbacks. This technique typically requires very long 10 to 23 ft (3 to 7 m) poles and branches, as the cuttings should reach from 6 in. (15 cm) below the low water table to 1 ft (30 cm) above the top of the rocks. In addition, only those cuttings that are in contact with the soil will take root, and therefore, the geotechnical benefits of the roots from those cuttings on the top of the bundle may not be realized.
2. Vegetated riprap with bent poles (Figure 4.28): Vegetated riprap with bent poles is slightly more complex to install. A variety of different lengths of willow cuttings can be used because they will protrude from the rock at different elevations.
3. Vegetated riprap with brush layering and pole planting (Figure 4.29): Vegetated riprap with brush layering and pole planting is the most complex type of riprap to install, but also provides the most immediate habitat benefits. The installation of this technique is separated into two methods; one method describes installation when building a bank back up, while the other is for

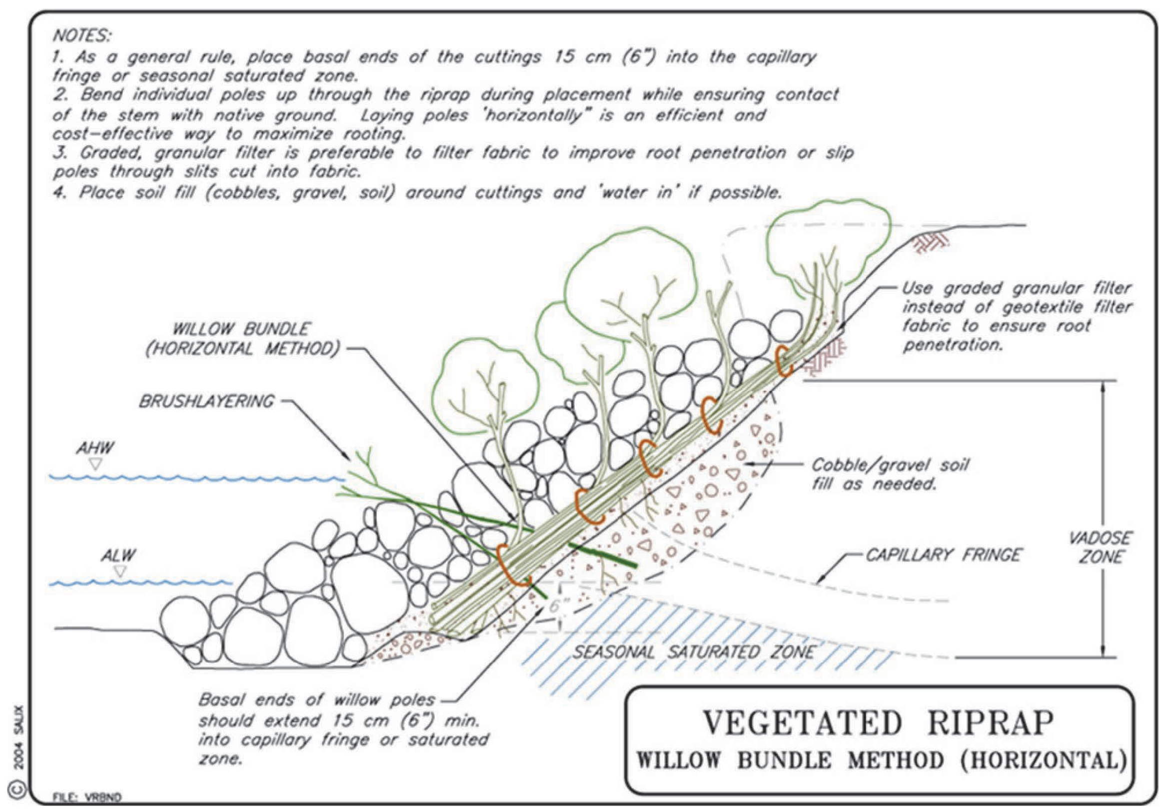


Figure 4.27. Vegetated riprap—willow bundle method (McCullah and Gray 2005).

Copyright National Academy of Sciences. All rights reserved.

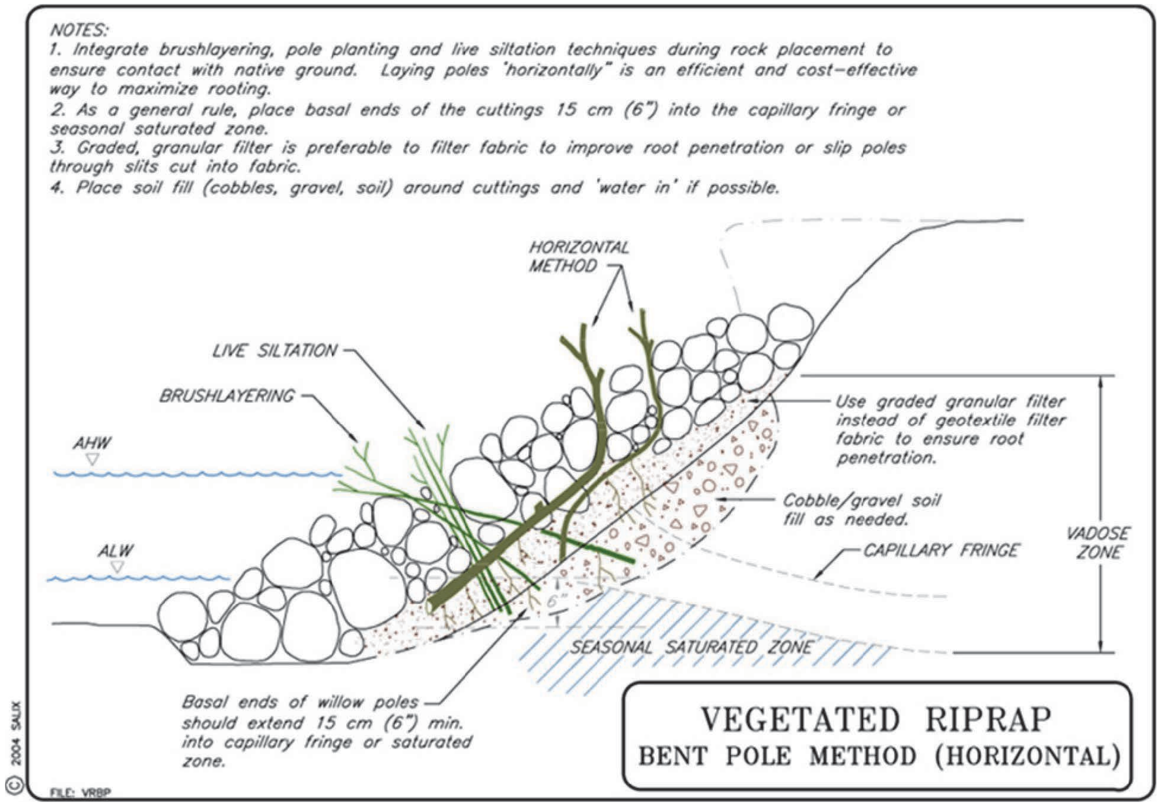


Figure 4.28. Vegetated riprap—bent pole method (McCullah and Gray 2005).

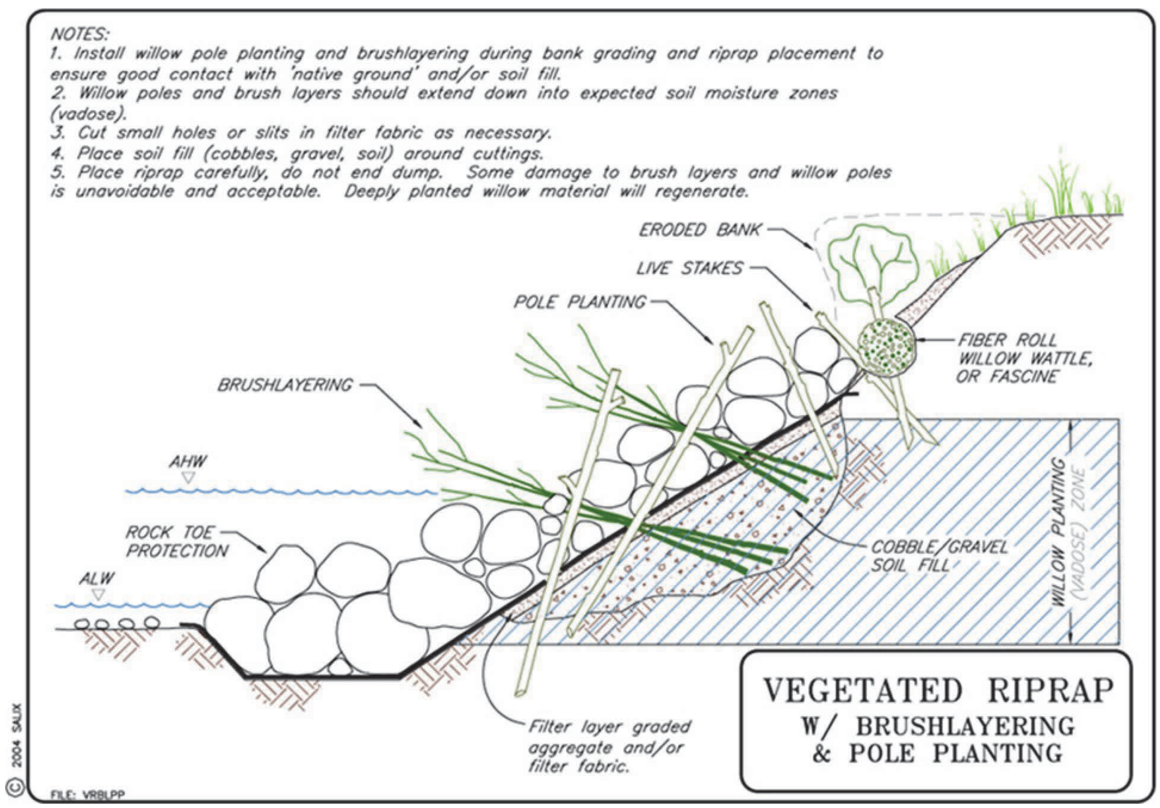


Figure 4.29. Vegetated riprap—brush layering with pole planting (McCullah and Gray 2005).

Copyright National Academy of Sciences. All rights reserved.

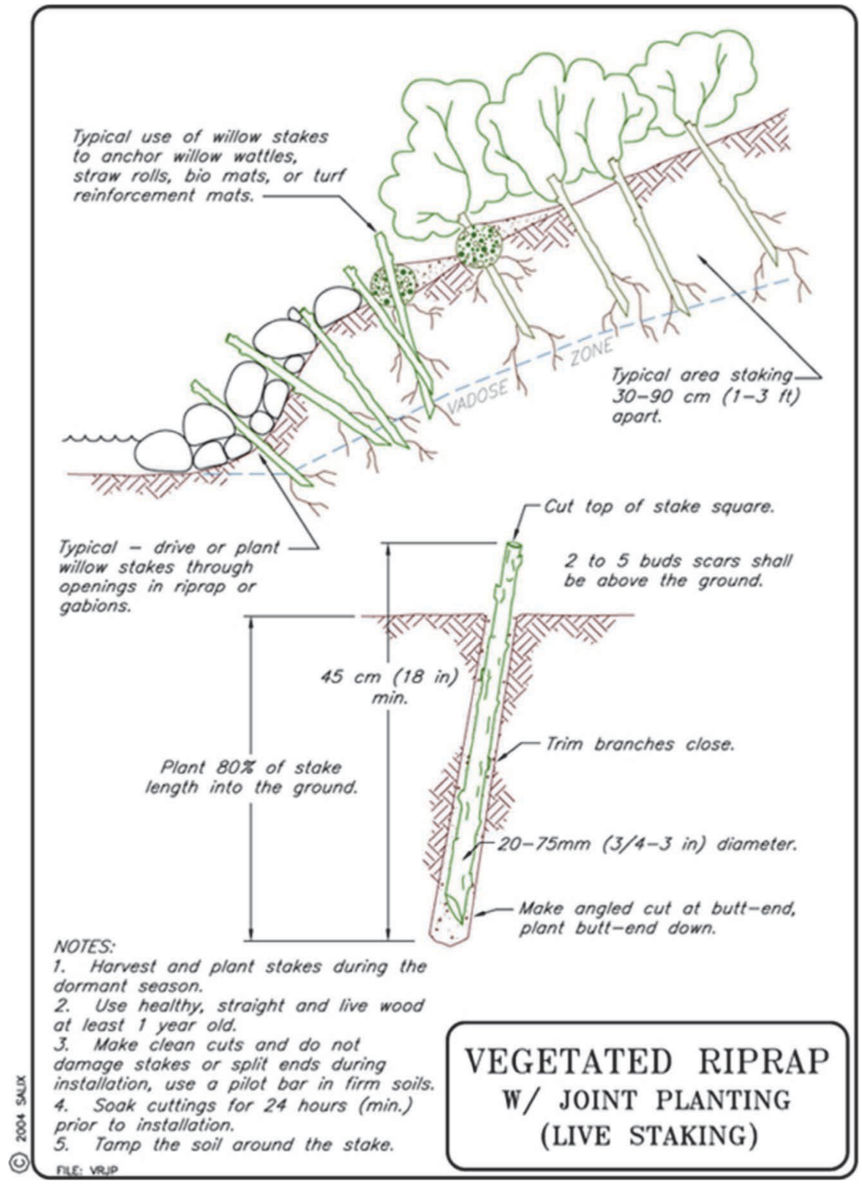


Figure 4.30. Vegetated riprap with joint planting (McCullah and Gray 2005).

a well-established bank. If immediate aquatic habitat benefits are desired, this technique should be used. However, vegetated riprap with brush layering and pole planting may not provide the greatest amount of root reinforcement, as the stem contact with soil does not extend up the entire slope. Combination of this technique with pole- or bundle-planted riprap will perform well, as the latter techniques typically have higher rooting success.

4. Vegetated riprap with soil cover, grass and ground cover: This technique is also known as "buried riprap," and consists of infilling and covering a standard rock riprap installation with soil and subsequently establishing grass vegetation. Some stripping of the soil and grass may be expected during severe events.
5. Joint or live stake planted riprap (Figure 4.30): Joint or live stake planted riprap is *revegetated* riprap, as opposed to the other techniques, which are true vegetated riprap methods. This technique should be used only when attempting to get vegetative growth on previously installed riprap.

Copyright National Academy of Sciences. All rights reserved.

Environmental Considerations and Benefits

There are many environmental benefits offered by vegetated riprap, most of which are derived from the planting of willows or other woody species in the installation. Willow provides canopy cover to the stream, which gives fish and other aquatic fauna cool places to hide. The vegetation also supplies the river with carbon-based debris, which is integral to many aquatic food webs; birds that catch fish or aquatic insects will be attracted by the increased perching space next to the stream (Gray and Sotir 1996). The small spaces between the rocks also provide benthic habitat and hiding places for small fish and fry (also see Section 4.2.6).

Construction/Installation Guidelines

Vegetated Riprap with Willow Bundles (Figure 4.27):

- Grade the bank to the desired slope where the riprap will be placed, such that there is a smooth base.
- Dig a toe trench for the keyway below where the riprap will be placed on a granular or geotextile filter.
- Place 5 to 6 in. (10 to 15 cm or 5 to 8 stem) bundles on the slope, with the butt ends placed at least 1 ft (30 cm) in the low water table. This will probably involve placing the poles in the toe trench before the rock is placed, if standard riprap rock is being used. Digging shallow trenches for the willows prior to placing them on the slope will decrease damage to the cuttings from the rocks, and may increase rooting success because more of the cuttings will be in contact with soil.
- The bundles should be placed every 6 ft (1.8 m) along the bank and point straight up the slope. Once the bundles are in position, place the rock on top of it at the top of the slope. The bundles should extend 1 ft (.3 m) above the top of the rock. If the bundles are not sufficiently long, they will probably show decreased sprouting success, and therefore, a different technique should be chosen.

Vegetated Riprap with Bent Poles (Figure 4.28):

- Grade back the slope where the riprap will be placed, such that there is a smooth base.
- Dig a toe trench for the keyway below where the riprap will be placed on a granular or geotextile filter.
- If filter fabric is being used, lay the fabric down on the slope, all the way into the toe trench, and cut holes in the fabric about 2 to 3 ft (0.6 to 0.9 m) above the mean low water level. Slip the butt ends of the willow poles through the fabric and slide them down until the bases are at least 6 in. (15 cm) into the perennial water table, or at the bottom of the toe trench, whichever is deepest (Hoag and Fripp 2002).
- If using filter gravel, lay it down on the slope, and place a layer of willow poles on top of the gravel, with the bases of the cuttings at least 6 in. (15 cm) into the perennial water table, or at the bottom of the toe trench, whichever is deepest.
- Ensure that rocks in the toe trench lock together tightly, as they are the foundation for the structure.
- Place the next layer of boulders such that it tapers back slightly toward the stream bank.
- Bend several willow poles up, such that they are perpendicular to the slope, and tight against the first layer of rocks. Now place the next layer of rocks behind these poles. Placement will require an excavator with a thumb, as someone will have to hold the poles while the rocks are placed. As the poles are released, they should be trimmed to 1 ft (30 cm) above the riprap.
- This last step should be repeated until all the poles have been pulled up and the entire slope has been covered.

Copyright National Academy of Sciences. All rights reserved.

Vegetated Riprap with Brush Layering and Pole Planting (Figure 4.29):

There are two methods of constructing brush layered riprap; one involves building up a slope, and the other works with a pre-graded slope.

Method 1:

- Lay the bank slope back to somewhat less than the desired finished slope.
- Dig a toe trench and lay the key rocks into the trench on a granular or geotextile filter. Pack soil behind these rocks, with filter gravel in between the soil and rocks. Continue installing riprap 3 to 4 ft (0.9 to 1.2 m) up the bank.
- Slope the soil back into the bank at a 45 degree angle, such that the bottom of the soil slope is in the vadose zone (see Figure 4.1 and associated discussion). Place a layer of willow cuttings on top of the soil, with the butt ends extending into the vadose zone, and the tips of the branches sticking out 1 to 2 ft (30 to 60 cm).
- Place the next layer of stones on top of the initial rocks, but graded slightly back, and repeat the soil and brush layering process. When finished, trim the ends of the willow branches back to 1 ft (30 cm). Do not cut shorter than 1 ft (30 cm) as the plant will have difficulty sprouting.

Method 2:

- Lay the bank slope back to the desired finished grade, and dig a toe trench if self-launching stone is not being used.
- Place the rocks in the keyway on a granular or geotextile filter, and fill in behind with filter gravel and soil. Continue installing riprap 3 to 4 ft (0.9 to 1.2 m) up the bank.
- Place the bucket of an excavator just above the layer of rocks at a 45 degree angle. Pull the bucket down, still at a 45 degree angle, until the water table is reached, or if the stream is dry, to the elevation at the bottom of the key trench. Pull up and back on the bucket: this will provide a slot in the bank into which willow poles can be placed.
- Throw in some willow poles [6 poles per linear foot (about 18 poles per linear meter)], ensuring that the butt ends are at the bottom of the trench.
- Release the scoop of earth, and allow it to fall back in place on the slope. Then place the next layer of rock on top of the branches, flush with the slope. If self-filtering stone is not being used, filter gravel should be placed behind the rocks. Repeat the process, beginning again with pulling back a scoop of soil. Continue this process to the top of the slope, or, if preferred, use joint-planted riprap on the upper slope, where it is difficult to reach the perennial water table with the excavator bucket.
- When finished, trim the ends of the branches back such that only 1 ft (30 cm) extends beyond the revetment.

Cost

Installation of vegetated riprap will require about 2.5 to 6 work hours/m^2 (2 to 5 work hours/yd^2). The cost of rock will vary depending on availability in the local area, but typically ran between \$20 to \$60 per ton (\$22 to \$67 per metric ton), delivered (in 2005).

Maintenance/Monitoring

Riprap should be visually inspected following any one-year return interval or greater flow, with focus on potential weak points, such as transitions between undisturbed and treated areas. Soil above and behind riprap may show collapse or sinking, or loss of rock may be observed. Inspect riprap during low flows annually, to ensure continued stability of the toe of the structure. Treat bank or replace rock as necessary. See Section 4.3.1 for additional guidance on monitoring and inspection of the riprap component of any environmentally sensitive treatment.

Copyright National Academy of Sciences. All rights reserved.

Common Reasons/Circumstances for Failure

Flanking, overtopping, or undermining of the revetment due to improperly installed or insufficient keyways is one of the biggest reasons for failure of riprap. Improperly designed or installed filter material can also cause undermining and failure of the installation. Undersized stones can be carried away by strong currents, and sections of the revetment may settle due to poorly consolidated substrate. Vegetation may require irrigation if planted in a nondormant state or in extremely droughty soils. Also, vegetation may be limited by excess soil moisture (Pezeshki et al. 1998).

Observations relevant to the performance of this treatment from the field site visits are summarized in Section 4.5.3.

4.4 Applications

4.4.1 Overview

This section presents two detailed examples of the application of environmentally sensitive stream bank protection measures employed in conjunction with stream channel restoration projects. Recognizing that dryland landscapes are quite different from those of more humid regions, one example involves the application of environmentally sensitive techniques on an arid region perennial stream—the Rio Grande near Bernalillo, NM. The second example deals with a smaller stream in a humid region with significant infrastructure issues—Malletts Creek near Ann Arbor, MI.

Compared to a humid region, the topography and landforms of an arid or semi-arid region are more abrupt, the soils are thinner, the bedrock exposures are usually more pronounced and the streams are smaller, carry larger sediment loads, and are likely to be dry for at least part of the year. Overall, the physical environment reflects the lack of water, and mechanical weathering and erosion predominates over chemical weathering and solution, as compared to a humid environment. As a consequence, dryland stream morphology significantly differs from that of humid-zone streams. In a humid environment, high precipitation produces vegetation and soils that are well developed and stabilized. Under these conditions, natural streams generally carry small suspended sediment loads, reflecting this stability in the upland watersheds. Additionally, high precipitation produces a dilution effect on the sediments that are eroded. While these projects present certain commonalities in the design, implementation, and monitoring phases, the differences in the climatic, hydrologic, and geomorphic conditions, as well as the characteristics of the cultural environment bring out interesting contrasts in the approaches necessary to achieve project success.

The examples have been chosen to illustrate the integration of hydraulic engineering analysis and design with the multidisciplinary approach necessary to achieving success with a river restoration project. The examples involve the cooperative efforts of multiple agencies and the challenges of meeting stakeholder goals and expectations. In both cases monitoring and maintenance issues are addressed and lessons learned are summarized.

4.4.2 Arid Region Example

Problem Identification

Water resource management activities (diversions, dams, levees, drains, channelization, jetty-jacks) by federal agencies and other entities have altered the hydrologic, ecologic, and sediment transport characteristics of the Rio Grande within New Mexico. Jemez Canyon, Cochiti, Abiqui, and Gallisteo Dams, operated for flood and sediment control, have contributed, in part, to the degradation of ecosystem functions and values of the Rio Grande in the restoration area.

Copyright National Academy of Sciences. All rights reserved.

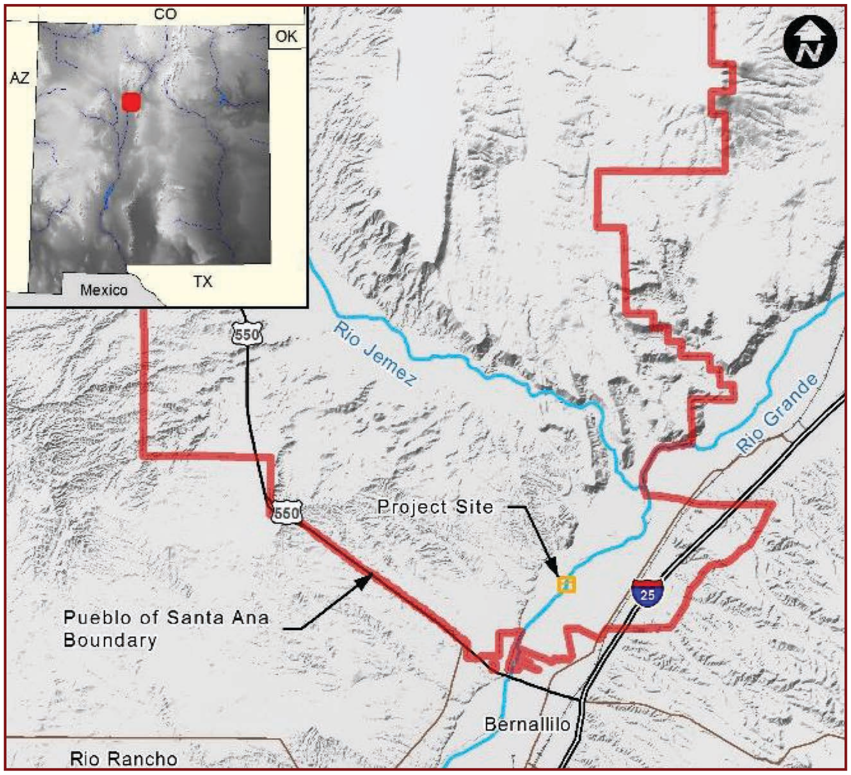


Figure 4.31. Santa Ana Reach of Santa Ana Pueblo.

The restoration area is located approximately 25 miles downstream of Cochiti Dam on the Rio Grande in what is designated as the Santa Ana Reach (Figure 4.31) of the Pueblo of Santa Ana (Pueblo—a sovereign tribal nation). This reach encompasses the length of the Rio Grande beginning immediately downstream from the confluence with the Jemez River (also known as Rio Jemez) to the Highway 550 bridge in Bernalillo, approximately 4.4 river miles.

Along the approximately 4.4 miles of the Rio Grande within the Santa Ana Reach, several hydrologic and ecological problems have been identified:

- The historically broad channel has incised up to 10 feet during the past 30 years, resulting in a narrow, entrenched channel.
- The extent and quality of aquatic habitat for native fish have deteriorated due to increased water depth and velocity.
- Channel incision has resulted in lowering the local water table in certain locations.
- The lack of inundation, scouring, and sediment deposition within the "bosque" (riparian woodland) has curtailed native cottonwood and willow seedling recruitment.
- Widespread invasion of non-native saltcedar and Russian olive trees has decreased the value of wildlife habitat and increased the threat of damaging fire.

In cooperation with the U.S. Bureau of Reclamation (Reclamation) and the USACE, the Pueblo of Santa Ana has implemented restoration activities to restore the river channel, active floodplain, and the historic floodplain.

Channel Instability and Geomorphic Response

A number of publications provide a detailed discussion of the history and response of the Rio Grande within the project reach to the construction of flood control measures, bank revetment,

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

channelization works, and the construction of upstream dams (for example, see Lagasse 1980, Salazar 1998, Richard 2001, USACE 2002a, Grassel 2002, Sixta 2004, Ortiz 2004, Ayres Associates 2006a). Historically, the fluvial characteristics of the Middle Rio Grande were those of a wide and shallow river prior to the influence of flood control activities. The channel was described as a sand-bed stream, (Nordin and Beverage 1965), with a braided pattern (Lane and Borland 1953), probably due to sediment overload (Woodson 1961). The referenced studies indicate that the river followed a pattern of scour and fill during floods and was in an aggrading regime.

Flood hazards associated with the aggrading riverbed prompted the Middle Rio Grande Conservancy District to build levees along the floodway during the 1930s. However, the levee system confined the sediment and increased the aggradation in the floodway. By 1960 the river channel near Albuquerque was 6 to 8 ft above the elevation of lands outside the levees (Lagasse 1980). Additional channel rectification works included the Kellner jack system (Figure 4.32) for bank stabilization, which was installed during the 1950s and 1960s. (Note: In the Middle Rio Grande Valley, the Kellner jacks are referred to as "jetty-jacks.") By 1962, a total of 115,000 jacks were in place along the river (Lagasse 1980). Jetty-jack fields placed along the river were highly effective. By trapping sediment, they filled in and trees grew on the new banks created by the jetties. These jetties and the new banks they created protected the newly constructed levees. The jetty fields and bosque vegetation have been considered as largely responsible for the stable channel position observed in the current river planform (Grassel 2002). In fact, Lagasse (1980) notes that the stabilization and rectification of the floodway channel between 1954 and 1962 had, by the early 1970s, begun to accomplish the desired effect of reversing the long-term aggradational trend and lowering bed elevations.

Regardless of the effectiveness of the jetty-jack fields, under the Comprehensive Plan of Improvement for the Rio Grande in New Mexico, construction of dams at Cochiti (1973), Abiqui (1963), Jemez Canyon (1953), and Galisteo Creek (1970) were expected to slow aggradation or reverse the trend to degradation in the Middle Rio Grande Valley. As a result of the flood and sediment control measures, the Middle Rio Grande has experienced significant channel degradation and streambed coarsening. Construction of these dams has also cut off the historical floodplain from the river (Woodson and Martin 1963).

By the early 1980s the resultant post-dam degradation and the development of streambed armoring (Lagasse 1980, 1981) within the project reach created unfavorable conditions for further jetty-jack stabilization. By the early 1990s the loss of frequent inundation of flood plain areas and the control of major sediment source areas such as the Jemez River resulted in significant channel degradation (Figure 4.33) and, as a result, significantly reduced the effectiveness of the jetty-jack fields. This ongoing degradational environment and the significantly reduced sediment supply

Figure 4.32. Jetty-jacks on the Rio Grande.

Copyright National Academy of Sciences. All rights reserved.

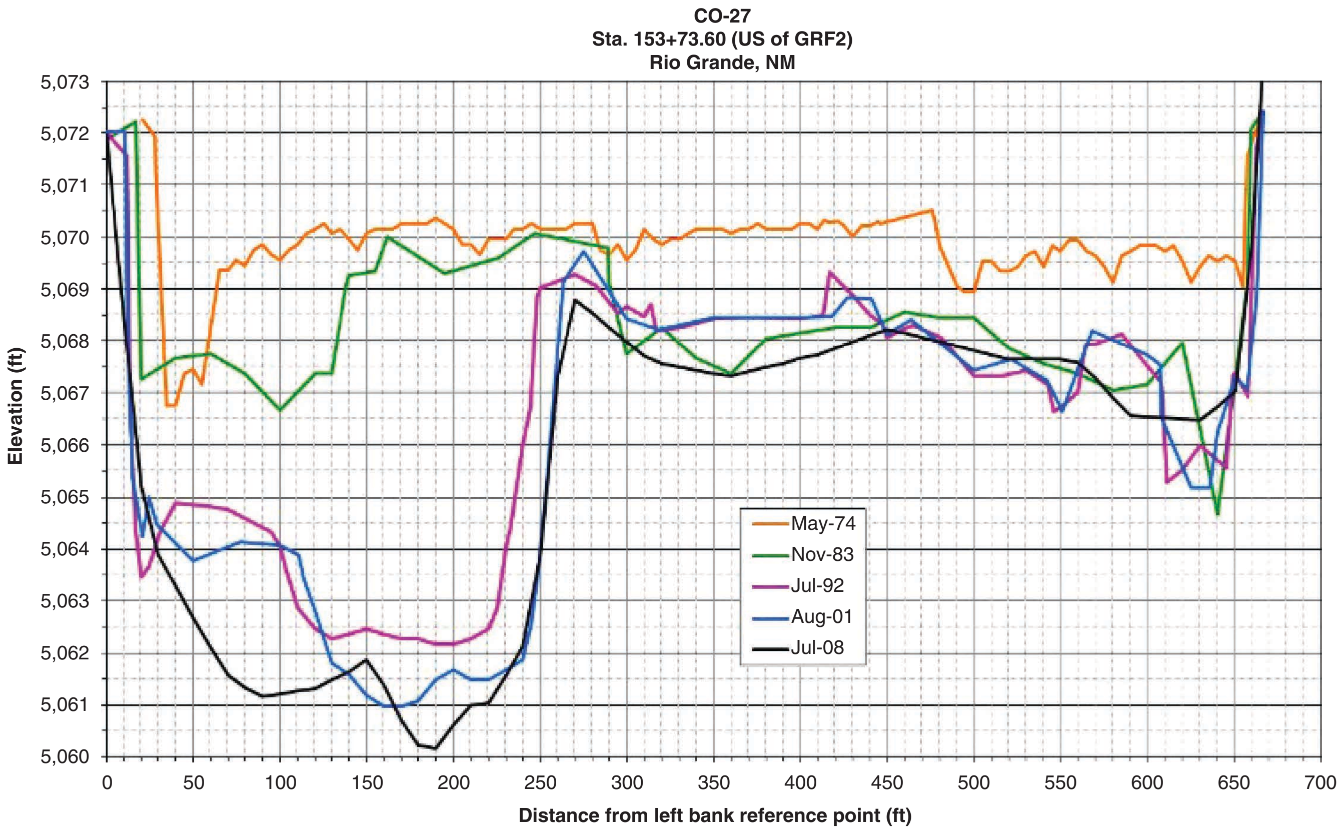


Figure 4.33. Comparison of historic surveys at Cochiti transect CO-27 in the Santa Ana reach.

have induced scour of the remaining jetty-jack fields exposed along the eroding river banks resulting in undercutting and burial of the jacks.

Hydromodification

Hydrology in the Middle Rio Grande Valley (i.e., Cochiti Lake to Elephant Butte Lake) follows a pattern of high flows during spring snowmelt runoff and low flows during the fall and winter months (USACE 2008). Additional, short-duration, high flows result from thunderstorms that occur in late summer and fall. Middle Rio Grande hydrology has been altered due, in part, to the influence of flood control dams. Cochiti Dam primarily acts to decrease peak flows and has a much smaller impact on low flows; therefore, average annual flows have been less affected, while peak flows have been reduced. Average yearly hydrographs for pre- and post-Cochiti Dam periods through 1999 are shown in Figure 4.34. The annual hydrographs illustrate that the closure of Cochiti Dam has reduced the peak flows and extended the duration of the high-flow period. Average winter base flows are somewhat larger during the post-dam period.

Review of annual peak discharge data also exhibits the influence of flood control. Historical annual peak discharges recorded at the San Felipe gage (approximately 15 river miles downstream from Cochiti Dam) illustrate the effects of regulation on the Rio Grande (Figure 4.35). From 1927 to 1945 flows in excess of 20,000 cfs were experienced approximately every five years. From 1945 to the construction of Cochiti Dam in 1973, floods in excess of 10,000 cfs were fairly common with the exception of drought years. Following construction of Cochiti Dam, regulation has prevented downstream flows from exceeding 10,000 cfs. This has reduced the average annual instantaneous peak discharge from 9,800 cfs to 5,700 cfs for the pre- and post-dam periods, respectively.

Copyright National Academy of Sciences. All rights reserved.

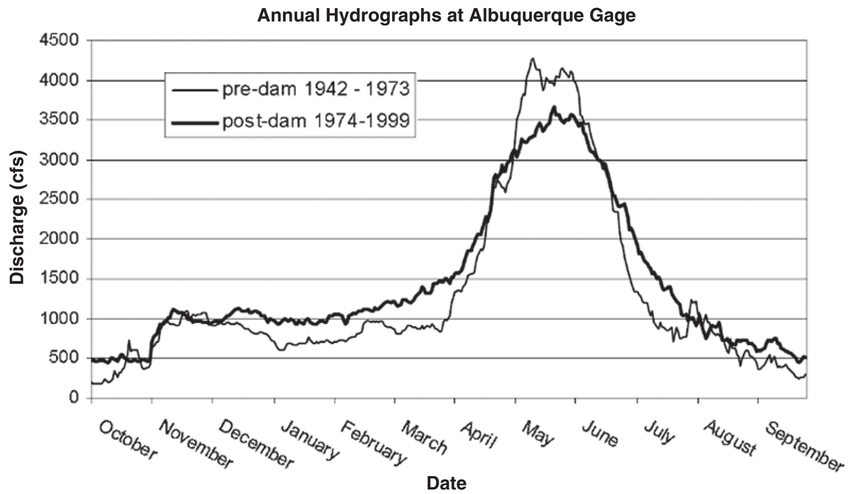


Figure 4.34. Average annual mean daily hydrograph at Albuquerque gaging station for pre- and post-Cochiti Dam periods.

Ecological Issues

Historically, the Middle Rio Grande Valley had one of the highest-value riparian ecosystems in the Southwest (Crawford et al. 1993). However, the existing riparian community in much of the Middle Rio Grande Valley and in the project area specifically, is a result of alteration of the flow regime, drainage for agriculture and development, flood control, channelization and jetty-jack fields, livestock grazing, beaver activity, and the spread of non-native tamarisk (salt cedar) and Russian olive. For example, natural wetlands, which were common, no longer occur within the Santa Ana Reach of the Rio Grande.

As the quality and quantity of the fish and wildlife habitat within the Middle Rio Grande Valley has decreased over time, so has its ability to sustain native flora and fauna. Several species endemic to the valley have been placed on the federal threatened and endangered species list under the Endangered Species Act. Listed species that could potentially occur within the project area include the Rio Grande silvery minnow and Southwestern willow flycatcher. No

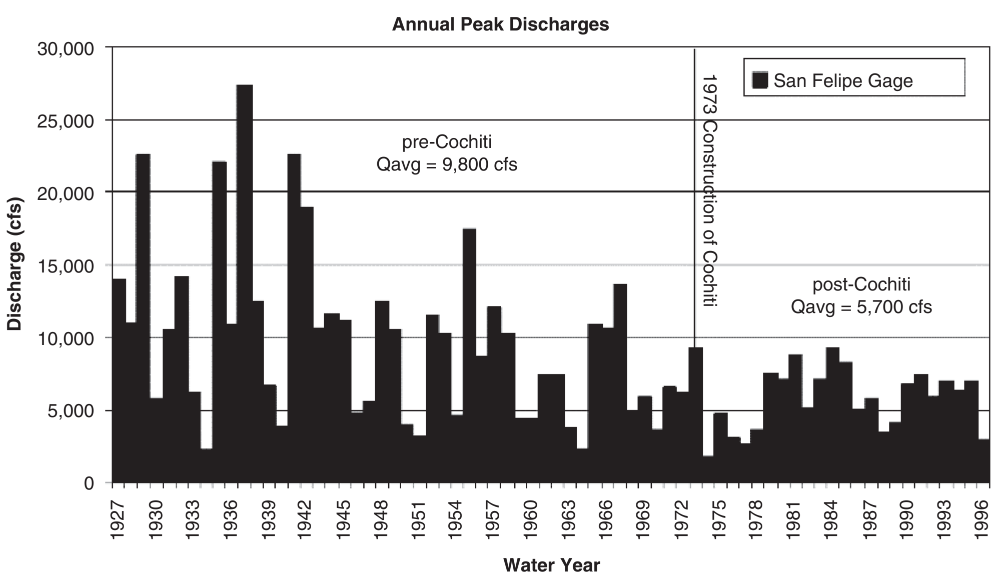


Figure 4.35. Annual peak discharges at the San Felipe gage.

Copyright National Academy of Sciences. All rights reserved.

federally-listed plant species are likely to occur within the project area, and none have been detected by USACE and Pueblo biologists.

Stakeholder Activities

The Pueblo has implemented an ecosystem-based restoration program, designed to reverse the impacts of 60 years of flood and sediment control and channelization projects on the Middle Rio Grande and restore a healthy, functioning Rio Grande ecosystem. The Pueblo has been assisted in implementing their overall restoration plan by several agencies. The Bureau of Indian Affairs and U.S. Environmental Protection Agency provided financial assistance in clearing non-native vegetation for the purpose of fire management and habitat improvement. The USFWS provided funding toward soil, wildlife, and vegetation surveys, and native riparian vegetation plantings. The Albuquerque area Reclamation office provided analysis, design, and construction support under their River Maintenance, Priority Site Program and the USACE Albuquerque District provided similar support under the USACE's Section 1135 program.

In 1996, in response to the hydrologic and ecological problems within the reach, the Pueblo initiated a restoration plan encompassing approximately 1,400 acres of riparian communities adjacent to the Rio Grande. The Pueblo has discontinued livestock grazing in the area and manages it as a nature preserve. Baseline vegetation, soil, and hydrologic data have been compiled. A mature cottonwood overstory is present throughout approximately one-third of this area. Saltcedar and Russian olive are common understory plants, replacing native vegetation such as cottonwood and coyote willow in many areas. In accordance with their overall restoration plan, the Pueblo has cleared non-native vegetation from nearly 720 acres, leaving large cottonwoods and native shrubs intact. The Pueblo has encouraged natural establishment or specifically revegetated cleared-bosque areas with a suite of native vegetation such as cottonwood and Gooding's willow, coyote willow, seep-willow, and New Mexico olive. Remediation of nearly 115 acres of saline and sodic soils was accomplished to facilitate successful planting of native grassland vegetation. In addition, the Pueblo has removed 1,600 obsolete (nonfunctional) jetty-jacks from the abandoned floodplain adjacent to the river. Monitoring is being conducted to document the response of plant and wildlife species to the various riparian restoration activities (see Ayres Associates 2006a).

Program highlights include:

- Creating over 100 acres of riparian wetland habitat,
- Restoring the reach of the Rio Grande traversing the Pueblo,
- Restoring 1300 acres of cottonwood bosque by clearing saltcedar and Russian olive thickets; and
- Restoring native wildlife habitat throughout the Santa Ana Rio Grande bosque.

Restoration Program objectives include providing the following benefits to the Pueblo and the entire Middle Rio Grande Valley:

- Preserve the bosque for cultural and recreational uses by tribal members and guests;
- Reduce risk of wildfire and protect the Pueblo's residential communities and economic interests;
- Preserve water resources by preventing further declines in the groundwater table;
- Enhance economic development (e.g., Hyatt Tamaya Resort) and provide employment for tribal members;
- Provide habitat for the endangered Rio Grande silvery minnow and the Southwest willow flycatcher; and
- Creating openings in the bosque to enhance wildlife habitat for all species utilizing the Rio Grande corridor.

Today, resource managers throughout the Middle Rio Grande Valley look to the Pueblo of Santa Ana for guidance on how to restore and manage their riparian lands.

Copyright National Academy of Sciences. All rights reserved.

Channel and Stream Bank Stabilization Measures

In 1998, the Reclamation investigated routine bank stabilization measures where active bank erosion persistently threatened the riverside levee on the east side of the Rio Grande about 0.5 miles downstream of the Jemez River confluence. Rather than continue long-term maintenance, a more permanent solution to the problem was sought in coordination with the Pueblo of Santa Ana. Under their River Maintenance Program, Reclamation restored riverine habitat in the two-mile reach near the Jemez River confluence through the creation of a wider operational channel and floodplain, resulting in reduced water velocities, decreased flow depth, increased width-to-depth ratios, and increased sediment deposition. The project consisted of three phases to be implemented over three to five years.

In Phase 1 (completed in 2001), Reclamation realigned the river channel to direct flow away from the deteriorating east-side levee bank. Two portions of the former channel were retained as backwater areas, and bioengineered bank stabilization along the new channel alignment was installed. A long, gently sloped riprap grade control structure [referred to locally as Gradient Restoration Facilities (GRFs)] to restore and hold the vertical position of the river bed, including a 500-foot-long fish-passage apron, was installed by Reclamation approximately four miles upstream of the New Mexico Highway 550 bridge (GRF #1). An adjacent overbank area was lowered to facilitate inundation by flows with a return frequency of two to five years. Phases 2 and 3 of the project consisted of planting 45 acres on bank lines, backwater areas, and floodplain zones with coyote willow, black willow, and Rio Grande cottonwood. In 2003 aquatic and riparian habitat restoration work was completed in the vicinity of the Jemez River confluence. In addition, a program of bar modification that included bar lowering and chute channel formation was conducted from 2003 to 2009.

In 2005, the USACE (under the Section 1135 Program) and the Pueblo completed construction of two additional GRFs (GRF #2 and GRF #3) approximately 0.9 and 1.9 miles, respectively, downstream from Reclamation's GRF structure. The USACE's structures consist of a perpendicular sheet pile wall extending approximately two feet above the channel bed and a gently sloped, downstream riprap apron approximately 400 ft long. The apron facilitates upstream passage of small native fish including the endangered Rio Grande silvery minnow. Additionally, a 200-ft-long Bed Sill composed of launchable gravel was installed downstream from the GRFs to provide a transition between the stabilized channel and the downstream reach which is expected to continue to degrade. Bioengineered bank stabilization along the new GRF and Bed Sill channel alignments was also installed.

Design of River Bed Stabilization Measures

As indicated, the Santa Ana/USACE project consists of GRF #2 and GRF #3 and a Bed Sill (Figure 4.36). The following design information is provided in the Design Letter Report by Ayres Associates (2003). The primary function of the GRFs is to provide grade control for the project reach and halt the degradational trend that has resulted in lowered bed elevations. In addition to providing stabilization of the channel bed and banks, the GRFs also result in greater levels of overbank inundation than the preconstruction condition. Based on 2-dimensional hydraulic modeling, the hydraulic conditions created by the GRFs were designed to mimic those found in natural riffles.

The river channel within the active floodplain is dynamic and migrates laterally over time. The GRFs and Bed Sill are designed to account for this potential movement. Additionally, the main channel position of the GRFs was widened slightly from an initial feasibility design to better accommodate lateral changes in the channel alignment. After observing the operation of Reclamation's GRF #1, the wider section appears to allow temporary bar features and a more braided low-flow channel configuration. The wider section allows for some lateral movement

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

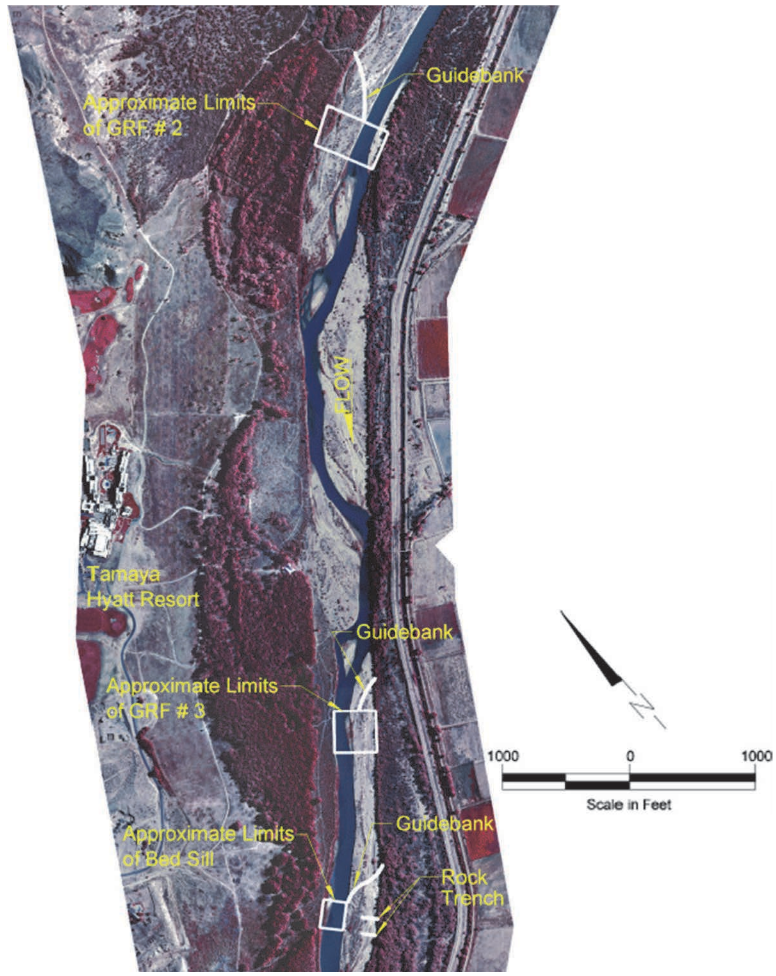


Figure 4.36. Plan view of the project reach showing the GRF and Bed Sill locations (Ayres Associates 2003).

of the river channel within the GRF itself. Guide banks were added to the design to maintain a favorable upstream channel alignment (Ayres Associates 2003 and USACE 2008).

GRF #2. The increase in water levels generated upstream of each GRF will locally increase the frequency and depth of overbank inundation in comparison to existing conditions. To maximize the benefit created by the GRFs, the upstream floodplain surfaces were lowered and reshaped to ensure that the overbanks were inundated at a 2-year recurrence interval. The overbank elevations of each GRF were designed to ensure a smooth transition from upstream floodplains.

The active channel at GRF #2 is roughly 150 ft wide. A relatively narrow (125 ft) bar is present along the left edge of the channel and a natural riffle is located just downstream of the site where flow branches into two paths around a large mid-channel bar. The location selected for the GRF allowed for the extension of an existing riffle, which minimized the size of the structure needed to achieve the desired grade control function.

Figure 4.37 shows a representative cross section of GRF #2 (looking downstream). The GRF was designed to tie into the left high bank, rather than into the transient bar feature. As such, the template results in a wider cross section than previously existed. During construction, the small bar located along the left bank was excavated and then recreated on top of the GRF. This

Copyright National Academy of Sciences. All rights reserved.

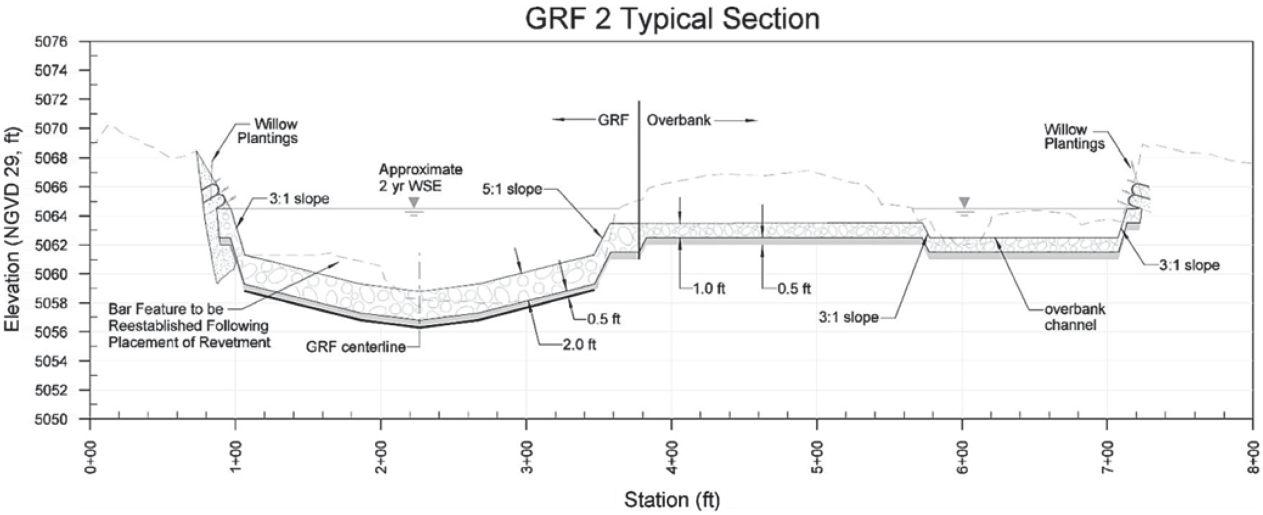


Figure 4.37. Representative cross section for GRF #2 (Ayres Associates 2003).

accommodates some channel movement and allows for the erosion of the bar surface and deposition of new material at any location across the active width.

The left bank of GRF #2 was tied into the existing channel bank along the bosque and has a 3H:1V slope. The right bank of the GRF has a milder slope as it ties into the large bar surface that comprises the right overbank. Overbank armor continues across the entire floodplain to the ultimate right bank along the bosque. Bank revetment (riprap) on both sides of the structure extends vertically to approximately the 2-year water surface elevation. Willow (*Salix exigua* referred to locally as sandbar willow or coyote willow) plantings have been added above the revetment to stabilize and protect the upper bank VMSE, in this case. FES lifts were used to stabilize the upper-bank slope.

GRF #3. GRF #3 is located approximately one mile downstream of GRF #2 (see Figure 4.36) The GRF is centered along an eroding portion of the right bank adjacent to the recreation trail for the Hyatt Tamaya Resort. This location allowed for the realignment and stabilization of the eroding bankline as a part of the GRF design. The left overbank consisted of a large bar surface that extended 2,000 feet downstream. A smaller, sub-bar surface was present along the left bank near the center of the GRF location.

Figure 4.38 presents a representative cross section of the GRF #3 design (looking downstream) in the vicinity of the active channel. The template maintained the existing channel width of approximately 175 feet.

The right side of GRF #3 is tied into the eroding right bank of the channel and required fill along the bankline to create a more desirable alignment. The slope of the GRF right bank revetment is 3H:1V and extends vertically to approximately the 2-year water surface elevation. Above the top of the riprap, the right bank was stabilized using FES lifts and willow plantings. The left bank of the GRF tied into the existing bar surface. Overbank armor extends across the bar to the toe of the left bank along the bosque. The revetment carries up the left bank to approximately the 2-year water surface elevation and ties into the jetty-jacks located along the bankline.

Bed Sill. The Bed Sill is located approximately 1,800 feet downstream of GRF #3 and just above the New Mexico Highway 550 bridge. The location is in a relatively straight reach of the river where the channel width is roughly 200 feet. This location provides for more efficient grade control.

Copyright National Academy of Sciences. All rights reserved.

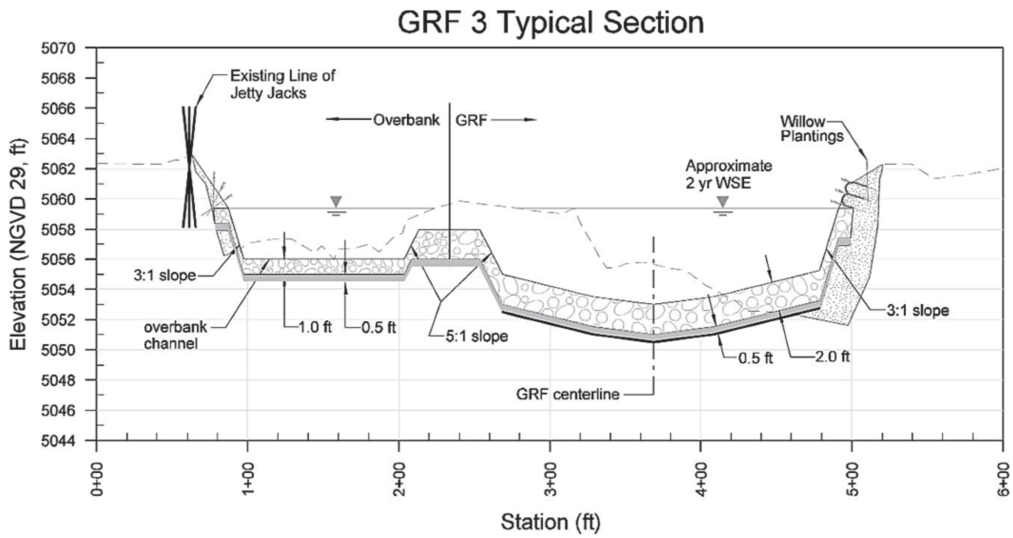


Figure 4.38. Representative cross sections for GRF #3 (Ayres Associates 2003).

Figure 4.39 presents a representative cross section of the Bed Sill design. The Bed Sill was constructed at a constant elevation across the channel. This required additional excavation during construction but reduced the amount of gravel required to construct the feature. Along the right bank, a rock toe section of riprap was placed to protect the toe of the slope from scour that could lead to lateral erosion of the channel banks. Along the left bank, the slope has been protected with riprap up to approximately the 2-year water surface elevation, with FES lifts and willows providing stabilization above that elevation.

Revetment Components

The revetment components of the project were based on hydraulic modeling conducted as part of the project. These components include the main channel riprap and overbank armor used to construct the GRFs and the gravel used in the Bed Sill.

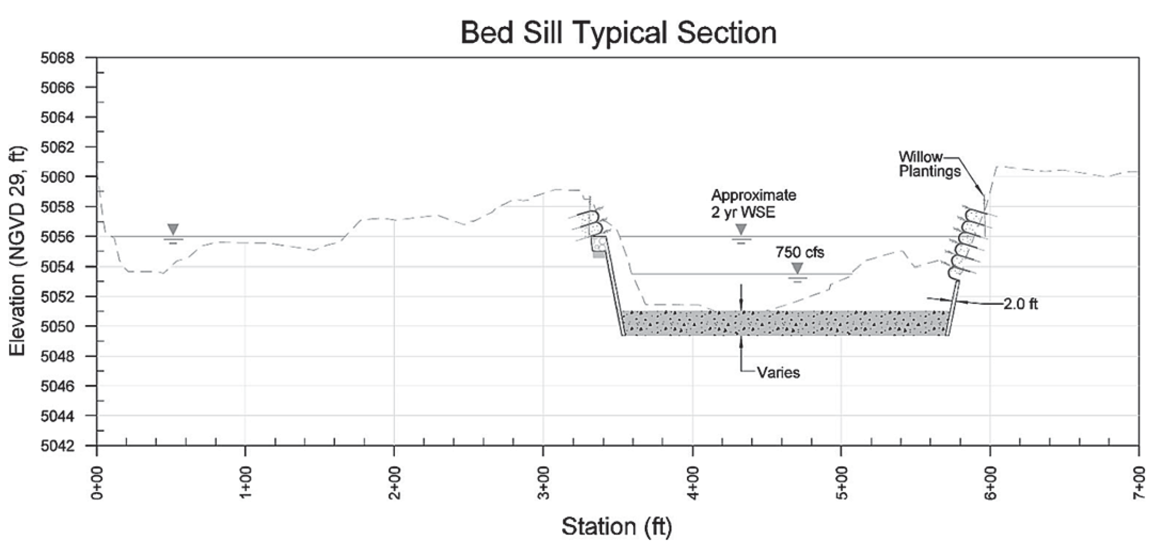


Figure 4.39. Representative cross sections for the Bed Sill (Ayres Associates 2003).

Copyright National Academy of Sciences. All rights reserved.

GRF Riprap. The riprap components of the GRFs were designed to withstand the hydraulic forces associated with the 100-year flood (22,300 cfs) and lesser events. During a feasibility study, the results of the 2-D modeling were used to determine the location of maximum shear stress acting on the structures. The main channel and overbank sections of each GRF were analyzed separately. These shear stress values were used to size the main channel and overbank riprap, resulting in median sizes (D_{50}) of 1.0 ft and 0.5 ft for the main channel and overbank, respectively.

Bed Sill. The Bed Sill was designed to provide grade control by armoring a portion of the channel bed. It consists of a large mass of gravel placed in an excavated trench across the channel. The material was sized to develop into a riffle as the downstream channel degrades. A median rock size of 2 in. was selected to develop a slope of 0.005 ft/ft, but not to wash away during a 100-year flood event. Enough rock is included in the Bed Sill to armor a 400-foot length of the channel and protect against a downstream degradation depth of 2 ft. The 0.005 ft/ft slope is the average slope associated with natural riffles in the vicinity of the project reach and was also the slope used to design the GRFs.

Filter and Bedding Layers

The design included a gravel filter layer between the GRF and overbank riprap layers and the underlying substrate materials. The main function of this gravel layer is to prevent the loss of fine material from beneath the riprap.

For the invert of the channel beneath the GRFs, filtration and providing for the relief of hydrostatic pressures are not concerns. Consequently a bedding layer was used to protect the underlying soils from the potentially erosive velocities in the void spaces of the riprap. Since the magnitude of these forces is difficult to predict and the protection of the main channel revetment is essential, a dual layer of geotextile fabric and gravel was chosen for providing a protective bedding layer (Figure 4.40).

Similar to the invert of the channel, a bedding layer was designed to protect the soils underlying the overbank armor. In contrast to the channel invert, which includes a dual layer of geotextile fabric and gravel, this bedding layer consists simply of gravel. This is due to the fact

Figure 4.40. Granular filter placement over geotextile fabric.

Copyright National Academy of Sciences. All rights reserved.

that the overbank velocities and associated shear stresses are less than those in the main channel. The same gravel used to provide the filter on the bank slopes was used as the bedding under the overbank armor.

GRF Transitions to Existing Banks

The sloping riprap used to stabilize the banks of the GRF extends beyond the limits of the structure to protect the banks up- and downstream and to provide a uniform alignment of flow into and out of the structure. The top elevation of riprap along the banks of the GRF was set to approximately the 2-year water surface elevation to allow integration of bioengineering methods. Above this elevation the bank was recreated with fill material and then planted with willows for stability and habitat enhancement. The same type of bankline revetment that was used in the GRFs was extended to create the up- and downstream transitions. Typical cross sections for these transitions are shown in Figure 4.41 for both the right and left banks of GRF #2 and GRF #3. A launchable riprap toe was included to provide protection against local scour. In this case, a launchable toe was considered appropriate because the GRF/Bed Sill structures provide significant vertical control and limit toe scour. Accordingly, the launchable toe provided an additional margin of safety, not the first line of defense.

Vegetation Planting

During the process of analyzing and revising the project design, one objective was to incorporate, to the extent feasible, areas for planting vegetation and enhancing ecological and habitat values within the project footprint. In addition, the USFWS made a number of recommendations to prevent and reduce adverse project effects on fish and wildlife resources.

Of those recommendations, several were geared toward the establishment of vegetation in the project footprint, including:

- Backfilling with uncontaminated earth of alluvium suitable for revegetation with indigenous plant species and
- Scarifying compacted soils or replacing topsoil and revegetating all disturbed sites with a suitable mixture of native grasses, forbs, and woody shrubs.

Proposals for reducing cost that would also enhance environmental aspects of the project included using combinations of hard and soft (biological) revetment features in lieu of simply riprap on the GRF side slopes, and stabilizing non-riprap side slopes with plant material.

As a result of these recommendations and proposals, environmentally sensitive bank-protection features and revegetation components were added to various elements of the project as summarized below:

Bank Protection. The original design called for using riprap to protect up to the top elevation of the banks. This was revised so that the riprap now extends up to an elevation that is 1 ft below the 2-year water surface level. Above this elevation, the bank was created with excess excavation material. At locations where there are jetty-jacks, the jacks were buried or removed and the slope revegetated. Along banks where there are no jetty-jacks, the soils in the first few feet above the top of the riprap were stabilized using FES lifts (Figure 4.42). FES lifts consist of native alluvium wrapped with two layers of biodegradable coconut fabric, and reinforced with high densities of deeply planted willow cuttings. As these plants mature, their root systems provide stabilization to the soils, replacing the structure of the fabric as it deteriorates over time. Guidelines for FES and brush layering similar to those in Section 4.3.2 were followed.

- Vegetated bank slopes—Upper-bank slopes that were not appropriate for FES lifts, such as locations with jetty-jacks, were planted with clumps of native willows and other shrub species.

Copyright National Academy of Sciences. All rights reserved.

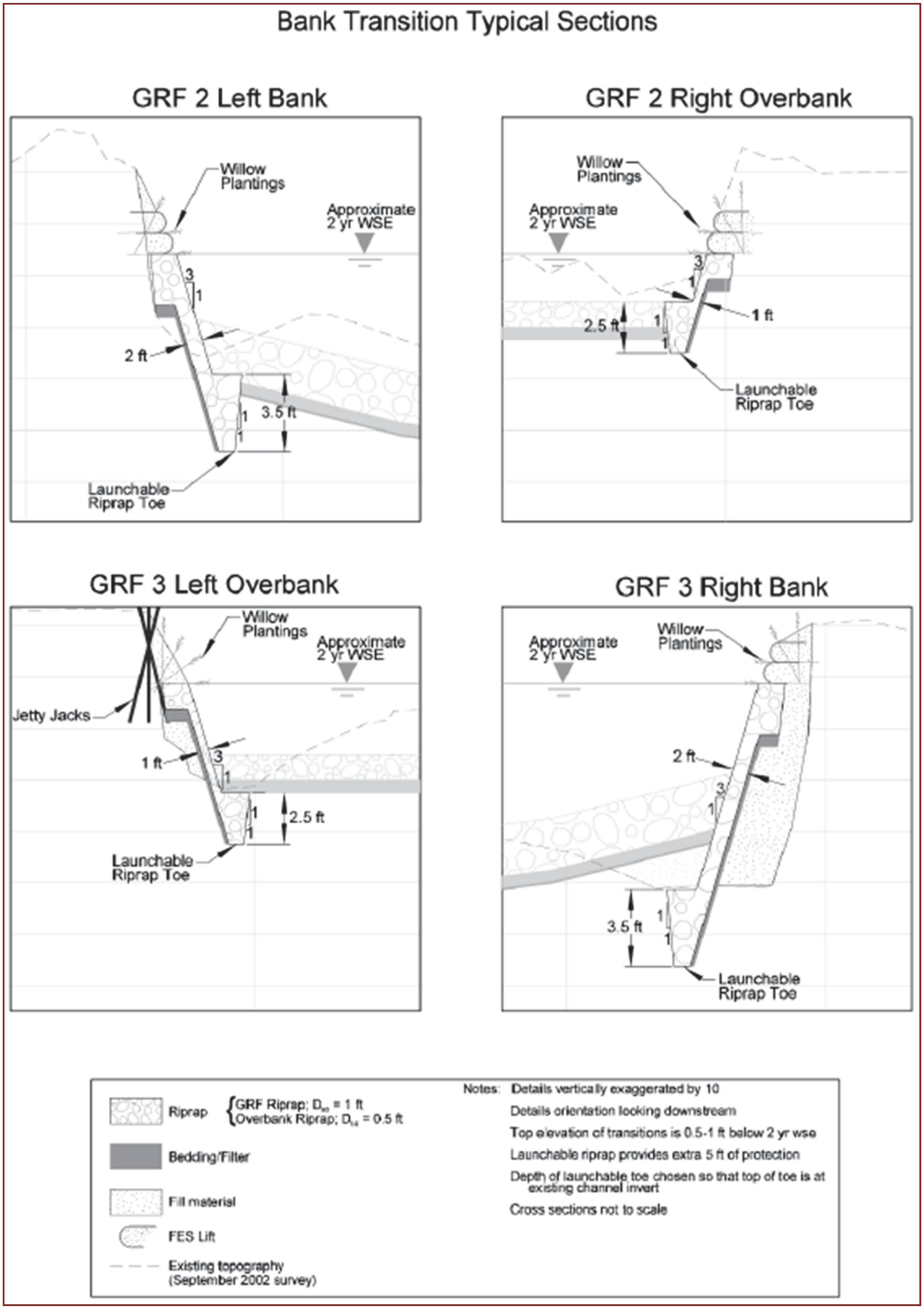


Figure 4.41. Typical sections of bank transitions (Ayres Associates 2003).

Copyright National Academy of Sciences. All rights reserved.

Figure 4.42. View of FES and willow plantings immediately after installation.

Native species were selected with regard to hydrologic regimes and corresponding depths to water table that occur along the slope of the upper bank. Guidelines for pole planting similar to those in Section 4.3.1 were followed.

- Vegetation in overbank areas—Willows are a primary component of the guide banks that are part of the GRFs and Bed Sill and help maintain the desired alignment into the structures while still allowing flood flow to access the entire channel width. Vertical willow plantings (Figure 4.43) were also used because they are well adapted to fluctuating water tables, are resistant to erosional forces associated with flood flows, and can withstand anticipated deposition of sediments.

Installation

Construction of both GRFs and the Bed Sill began in July 2004 and was completed by March 2005. Construction of the GRFs and Bed Sill required diversion of the Rio Grande, installation

Figure 4.43. View of willow-planted FES bankline and planted willow poles in overbank area.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

of coffer dams, dewatering of the structure sites, and in-channel excavation as well as installation of access roads and staging and stockpiling sites.

Pertinent Data. Pertinent data applicable to the design and construction of the GRFs and Bed Sill are summarized in Tables 4.5 through 4.7. This data is categorized according to each project component and includes physical criteria that govern the dimensional parameters of the structures. The front-end specifications for the project components were provided by the USACE Albuquerque District Office. Many of the front-end specs were in "guide-spec" form and needed specific revision and/or tailoring to fit this project.

Construction Issues and Problems. A number of problems arose during construction of the GRFs and Bed Sill:

- Bank erosion was an ongoing problem along the diversion channels during construction. In most cases, temporary placement of riprap was needed to counter the erosion.
- During construction of the GRFs, the initial rock placement within the main channel portion of the structures was not acceptable and several thin spots were noted throughout the structures resulting in exposure of the granular filter material in several locations. The contractor added rock and reworked several sections.
- At GRF #2, the contractor was unclear on the riprap transition along the channel banks to the FES lifts. The plans showed an embankment backfill area between the existing bankline and the limit of the riprap. Rather than placing embankment backfill below the rock, the contractor chose to use additional riprap for the fill which was an acceptable alternative (see Figure 4.41).

Performance

Monitoring and Maintenance. The *Operation, Maintenance, Repair, Replacement, and Rehabilitation (OMRR&R) Manual* (Ayres Associates 2006b) provided assistance to the Pueblo

Table 4.5. Pertinent data for GRF #2, Rio Grande, Santa Ana Reach, New Mexico.

GRF #2						
Physical Characteristics						
Length of GRF (in-river portion)	400 ft					
Width of main channel portion	Approximately 260 ft					
Width of overbank portion	Approximately 380 ft					
Thalweg elevation at crest	5059.8 ft, National Geodetic Vertical Datum (NGVD) 29					
Thalweg elevation at Toe	5057.8 ft, NGVD 29					
Longitudinal slope	0.005					
Sheet pile driving depth	12 ft below final grade					
Length of buried guide bank	720 ft					
Length of bank transitions	50 to 70 ft					
Material Quantities						
Item	Unit of Measure	Upstream Transitions	Main GRF	Downstream Transitions	Guide Bank	Totals
Geotextile fabric	SY	1,530	12,940	1,540	NA	16,010
Granular filter	CY	250	4,550	280	NA	5,080
Riprap, Type 1	CY	1,230	8,660	1,250	NA	11,140
Riprap, Type 2	CY	80	5,040	320	460	5,900
Vinyl sheet pilling	SF	NA	9,670	NA	NA	9,670
FES	LF	240	1,604	244	NA	2,088
Type 1 willows	LF	240	1,604	244	NA	2,088
Type 2 willows	LF	NA	NA	NA	720	720
Type 1 seed mix	SF	1,560	10,426	1,586	NA	13,572
Type 2 seed mix	SF	1,560	10,426	1,586	NA	13,572
Type 3 seed mix	SF	390	2,607	397	NA	3,394

Note: SY = square yard, CY = cubic yard, LF = linear foot, SF = square foot.

Copyright National Academy of Sciences. All rights reserved.

Table 4.6. Pertinent data for GRF #3, Rio Grande, Santa Ana Reach, New Mexico.

GRF #3	
Physical Characteristics	
Length of GRF (in-river portion)	400 ft
Width of main channel portion	Approximately 240 ft
Width of overbank portion	Approximately 170 ft
Thalweg elevation at crest	5054.0 ft, NGVD 29
Thalweg elevation at toe	5052.0 ft, NGVD 29
Longitudinal slope	0.005
Sheet pile driving depth	12 ft below final grade
Length of buried guide bank	385 ft
Length of bank transitions	50 to 210 ft

Material Quantities

Item	Unit	Upstream Transitions	Main GRF	Downstream Transitions	Guide Bank	Totals
Geotextile fabric	SY	1,330	14,780	1,320	-	17,430
Granular filter	CY	425	3,050	410	-	3,885
Riprap, Type 1	CY	1,660	8,450	1,290	-	11,400
Riprap, Type 2	CY	500	2,060	170	230	2,960
Vinyl sheet pilling	SF	-	7,460	-	-	7,460
FES	LF	1,020	1,600	352	-	2,972
Type 1 willows	LF	1,020	1,600	352	-	2,972
Type 2 willows	LF	-	-	-	385	385
Type 1 seed mix	SF	6,630	10,400	2,288	-	19,318
Type 2 seed mix	SF	6,630	10,400	2,288	-	19,318
Type 3 seed mix	SF	1,658	2,600	572	-	4,830

of Santa Ana in carrying out its obligation for the operation, maintenance, and replacement requirements for the GRFs, Bed Sill, and other features associated with these structures. Semi-annual inspections are being made of all project features and components. Such inspections are made immediately prior to the beginning of the flood season (normally prior to April 1) and after the flood season. Regular inspections consist of visual observations and field surveys as necessary to confirm elevations of various project features and verify the condition of inundated features. Other inspections are made immediately following each major high-water period, and at such intermediate times, as necessary. Immediate steps are taken to correct dangerous conditions disclosed by the inspections. Regular maintenance repair measures are accomplished during

Table 4.7. Pertinent data for the Bed Sill, Rio Grande, Santa Ana Reach, New Mexico.

Bed Sill	
Physical Characteristics	
Length Bed Sill	280 ft
Width of main channel portion	Approximately 240 ft
Invert elevation	5051.0 ft, NGVD 29
Length of buried guide bank	540 ft
Length of buried grade control	140 to 160 ft

Material Quantities

Item	Unit	Bed Sill	Guide Bank	Totals
Granular filter	CY	90	-	90
Riprap, Type 1	CY	310	-	310
Riprap, Type 2	CY	-	570	570
Gravel	CY	3,730	-	3,730
FES	LF	560	-	560
Type 1 willows	LF	560	-	560
Type 2 willows	LF	-	540	540
Type 1 seed mix	SF	3,640	-	3,640
Type 2 seed mix	SF	3,640	-	3,640
Type 3 seed mix	SF	910	-	910

Copyright National Academy of Sciences. All rights reserved.

Figure 4.44. Before, during, and after views of willow-planted FES over rock riprap at GRF #3.

the appropriate season as scheduled by the Pueblo. The Pueblo is required to obtain all permits applicable to any repair work. Maintenance and repair of damaged project components helps to ensure that project benefits are maintained throughout the life of the project. General repair guidelines are described in the OMRR&R (Ayres Associates 2006b).

Performance Assessment. Over the past 10 years (2005–2015) the structures have performed as anticipated. The structures are stable and a good growth of willows and other vegetation has naturally colonized the banks and bar surfaces at the structures. Within a year of construction, the willow branches planted between the FES lifts at both GRFs and the Bed Sill had become well established and have survived and thrived since then. Figure 4.44 shows the eroding bankline before treatment, construction of the willow-planted FES over rock riprap, and the well-established willow-planted FES after construction at GRF #3. Figure 4.45 provides an overview of the finished GRF #3 with the vegetated FES along the right bank, planted willow poles and vegetated right overbank area, and the left bank transition guide bank with the planted willows.

Conclusions and Lessons Learned

Design. In a follow-up value engineering study after completion of the initial design (USACE 2002b), proposals were made for reducing cost that would also enhance environmental aspects of the project. These included using combinations of hard and soft (biological) revetment features in lieu of simply riprap on the GRF side slopes, and stabilizing non-riprap side slopes with plant material. As a result of these recommendations and proposals, environmentally sensitive bank-protection features and revegetation components were added to various elements of the project.

Figure 4.45. View looking upstream of upstream end of GRF #3 with vegetated FES along right bank, planted willow poles and vegetation in right overbank area, and left bank transition guide bank with planted willows.

Copyright National Academy of Sciences. All rights reserved.

174 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Construction. During construction, it was noted that materials were either improperly or inadequately placed or that, in some cases, the size or gradation of bedding materials used in a number of locations were not as specified. These were immediately corrected by regular onsite construction inspections and meetings between the contractor, USACE, and the Pueblo.

Post-Construction Monitoring/Maintenance. Ongoing work being conducted along the project reach indicates that the structures and associated riparian and wetland restoration activities are stable and appear to require little or no maintenance (Ayres Associates 2012).

Once the GRFs were installed, a program of bar modification that included bar lowering and chute channel formation was conducted and completed by 2009. Some of this work has been conducted in close proximity to or at the GRFs and Bed Sill, which may have an impact on the structures in the future. Continued monitoring will be necessary to ensure that the structures and bank protection remain in a stable condition.

Restoration of the sediment supplied to the Rio Grande from the Jemez River as a result of opening of the Jemez Canyon Dam and draining the upstream reservoir pool is currently having an impact. As noted during recent sediment sampling efforts, significant amounts of sand and gravel are currently being transported by the Rio Grande in the vicinity of the GRFs and Bed Sill. Although the supply may be insufficient to cause any significant aggradation or induce active channel migration, the reach and structures must continue to be monitored for any instability.

Vertical Stability of the Channel. The effort and cost associated with the design and construction of the GRFs and Bed Sill for this project underscore the absolute necessity of establishing vertical control of the channel before attempting any stream bank protection treatments (see Section 4.2.3 for further discussion).

References

Ayres Associates, 2003. *Design Letter Report, Supporting Final Design and Preparation of Construction Plans and Specifications for the GRFs, Bed Sill, and Associated Vegetation Planting, Rio Grande Riparian and Wetland Restoration, Section 1135 Project*, prepared for Pueblo of Santa Ana, New Mexico.

Ayres Associates, 2006a. Middle Rio Grande Santa Ana Reach Geomorphology, Technical Appendix A, In: *Section 1135 Program, Detailed Project Report and Environmental Assessment for Aquatic Habitat Restoration at Santa Ana Pueblo, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

Ayres Associates, 2006b. *Operation, Maintenance, Repair, Replacement, and Rehabilitation (OMRR&R) Manual for GRF on the Rio Grande, Pueblo of Santa Ana Reservation, New Mexico*, prepared for U.S. Army Corps of Engineers Albuquerque District, Contract No. W912PP-04-C-0003.

Ayres Associates, 2012. *Geomorphic Assessment of the Rio Grande in the Vicinity of the RM 205.8 Nick Point Site*, prepared for Pueblo of Santa Ana Reservation, New Mexico.

Crawford, C. S., Cully, A. C., Leutheuser, R., Sifeuntes, M. S., White, L. H., and Wilbur, J. P., 1993. *Middle Rio Grande Ecosystem: Bosque Biological Management Plan*, U.S. Fish and Wildlife Service, Albuquerque, NM, 291 pp.

Grassel, K., 2002. *Taking Out the Jacks—Issues of Jetty Jack Removal in the Bosque and River Restoration Planning*, Water Resources Program, University of New Mexico, Publication No. WRP-6, 46 pp.

Lagasse, P. F., 1980. *An Assessment of the Response of the Rio Grande to Dam Construction, Cochiti to Isleta Reach*, a technical report by the Science Research Laboratory, U.S. Military Academy, for the U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Lagasse, P. F., 1981. *Geomorphic Response of the Rio Grande to Dam Construction*, New Mexico Geological Society, Special Publication No. 10, pp. 27–46.

Lane, E. W., and Borland, W. M., 1953. River Bed Scour During Floods, *Transactions of the American Society of Civil Engineers*, Vol. 119, Paper No. 2712, pp. 1069–1080.

Nordin, C. F., and Beverage, J. P., 1965. *Sediment Transport in the Rio Grande*, New Mexico, USGS Professional Paper 462-F.

Ortiz, R. M., 2004. *A River In Transition: Geomorphic and Bed Sediment Response to Cochiti Dam on the Middle Rio Grande, Bernalillo to Albuquerque, New Mexico*, Master's Thesis, University of New Mexico, Albuquerque, NM.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Richard, G. A., 2001. *Quantification and Prediction of Lateral Channel Adjustments Downstream from Cochiti Dam, Rio Grande, NM*, Ph.D. Dissertation, CSU, Fort Collins, CO.

Salazar, C. L., 1998. *Morphology of the Middle Rio Grande from Cochiti to Bernalillo Bridge, New Mexico*, Master's Thesis, CSU, Fort Collins, CO.

Sixta, M. J., 2004. *Hydraulic Modeling and Meander Migration of the Middle Rio Grande, New Mexico*, Master's Thesis, CSU, Fort Collins, CO.

USACE, 2002a. *Middle Rio Grande Santa Ana Reach Geomorphology, Section 1135 Program, Detailed Project Report and Environmental Assessment for Riparian and Wetland Restoration, Pueblo of Santa Ana Reservation, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

USACE, 2002b. *Value Engineering Study Summary Report, Riparian/Wetland Restoration Project, Pueblo of Santa Ana Reservation, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

USACE, 2008. *Section 1135 Program, Draft Detailed Project Report and Environmental Assessment for Aquatic Habitat Restoration at Santa Ana Pueblo, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

Woodson, R. C., 1961. Stabilization of the Middle Rio Grande in New Mexico, *Journal of the Waterways and Harbors Division: Proceedings American Society of Civil Engineers*, Vol. 87, No. WW4, Paper 2980, pp. 1–15.

Woodson, R. C. and Martin, T. J., 1963. The Rio Grande Comprehensive Plan in New Mexico and Its Effects on the River Regimen Through the Middle Valley, *Proceedings of the 2nd Federal Interagency Sedimentation Conference*, Jackson, MS.

4.4.3 Humid Region Example

Problem Identification

Malletts Creek drains an 11 mi^2 urban watershed in Ann Arbor (Washtenaw County), MI, and is tributary to the Huron River (Figure 4.46). Malletts Creek has been degraded as a result of water quality and flow capacity problems associated with urbanization. Major water quality problems include high phosphorus loading and sedimentation. Prior to this project, water quantity problems

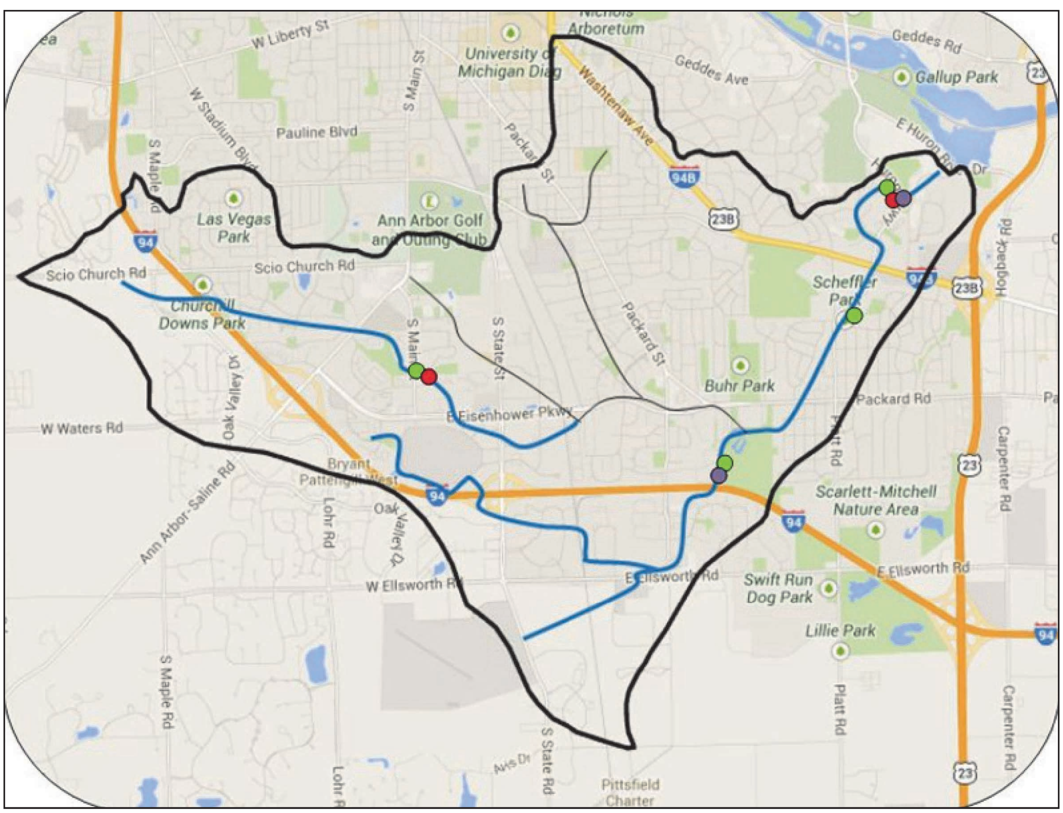


Figure 4.46. Malletts Creek watershed.

Copyright National Academy of Sciences. All rights reserved.

were indicated by high-flow velocities that resulted in both bank and channel erosion. Degraded stream beds and frequent and severe peak flows diminished aquatic habitat. Bed materials are dominated by cobble, but bank soils are primarily fine sands and sandy loams with little clay that are susceptible to fluvial erosion (Figure 4.47). A Bank Erosion Hazard Index (BEHI) analysis (Rosgen 2001a, Rathburn 2006) indicated that, of 14 channel reaches, five received BEHI ratings of high, four were very high, and two were extreme [Orchard, Hiltz and McCliment, Inc. (OHM) 2011]. Several sites along the creek presented special erosion, flow conveyance or infrastructure problems which were listed in the basis of design technical memorandum (OHM 2011) (Table 4.8).

Reconnaissance data presented by OHM (2011) showed that preconstruction bank heights ranged from 3 to 7 ft except in one reach where banks were up to 40 ft high. Several reaches were incised to the point that little channel-floodplain connection occurred. Reach-mean channel widths ranged from 9 to 50 ft and averaged 25 ft. Infrastructure occurs frequently in the stream

(a)

(b)

Figure 4.47. ***Bank soils and sediments, Malletts Creek: (a) preconstruction bank erosion, Malletts Creek. Photo courtesy of Harry Sheehan, environmental manager, Washtenaw County, MI. and (b) typical bar sediments, Malletts Creek.***

Copyright National Academy of Sciences. All rights reserved.

Table 4.8. Tabulation of erosion and infrastructure problems along Malletts Creek Channel prior to construction (from OHM 2011).

Major Problem Area	Subreach (SR)	Identified Problems	Suggested Improvements
Problem Area #1	SR 2	1. Massive debris jam	1. Remove debris
		2. Bank erosion/split flow creating island around oak tree	2. Create overflow "control" at split flow and stabilize bypass channel
Problem Area #2	SR 4	1. Mass wasting at 17-ft-high steep bank with oak trees at risk of falling into stream	1. Vane arms Boulder toe protection Floodplain shelf Slope 1.1 back to top of grade Stabilize slope with live stakes/fabric Cut inside bank and use as fill Observation area with wood fence Interpretive signage
Problem Area #3	SR 6	1. Skewed culvert alignment	1. W-Weir upstream of culvert inlet
		2. Bank erosion/split flow	2. Create overflow "control" at split flow and stabilize bypass channel
		3. Large debris jam	3. Remove debris
Problem Area #4	SR 8	1. Flow blocked upstream of one culvert barrel	1. Remove blockage W-Weir upstream of culvert
		2. Bank erosion/split flow on opposite bank	2. Create overflow "control" at split flow and stabilize bypass channel
Problem Area #5	SR 8	1. Sanitary crossing	1. Grade control/riffle creation
		2. 42" storm outfall	2. Grade control/riffle creation
		3. Sanitary manhole in channel	3. Grade control/riffle creation
Problem Area #6	SR 11, 12, and 13	1. Stream disconnected from floodplain	1. Floodplain storage Trail relocation Interpretive signage
Problem Area #7	SR 14	1. Failed culvert end section at Manchester Road	1. Repair failed end section
		2. Large scour hole	2. Install pre-formed scour hole

corridor in the form of roadway crossings, utility poles, manholes, storm sewer outfalls, and culverts. The primary bank erosion process is fluvial erosion; limited amounts of mass failure occur where the channel has simultaneously incised and impinged against a high bank.

Hydromodification. During the past 40 years, the watershed has been extensively developed with shopping malls, new subdivisions, parking lots, etc. (Lawson et al. 2008). About 37% of the land is covered with impervious surfaces (Water Resources Commissioner undated). Reports of channel reconnaissance indicated moderate levels of conditions symptomatic of urbanization. Much of the Huron River watershed was historically characterized by undulating topography characterized by depressions and internally drained valleys of glacial origin.

Richards and Brenner (2004), using numerical hydrologic modeling, argued that the effective size of Malletts Creek watershed had been doubled by anthropogenic features such as storm sewers and drains. The Richards-Baker Flashiness Index, developed for wadeable Michigan streams, varies from 0 to over 1, where an index of 0 represents unchanging flow rate, and 1 would indicate a highly variable flow. An analysis of mean daily discharges (1999–2010) at the Chalmers Road USGS gage yielded a 3-year average (2009–2011) flashiness index value of 0.723, which is higher than 75% of all similarly sized streams in Michigan and well above the median stream flashiness in a six-state midwestern survey (Fongers et al. 2007).

This level of hydromodification, in conjunction with the increasing level of impervious land cover, would be expected to trigger the type of channel erosion that has been reported for Malletts

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Creek. Hydraulic modeling of the 100-year event indicated that maximum velocities occurred at bankfull flow, and that these velocities ranged from 2.75 ft/s to 7.75 ft/s, varying by reach. Modelers attributed higher velocities to encroachments on the channel that prevented overflow onto floodplains at lower discharges. Hand calculations and local soil characteristics produced an estimate of critical shear stress of 0.40 lb/ft^2, while HEC-RAS produced reach-averaged shear stresses that varied from 0.27 lb/ft^2 to 0.73 lb/ft^2 and shear stresses at specific locations as great as 1.66 lb/ft^2 (OHM 2011).

Water Quality and Ecology. Water quality issues are linked to hydromodification. Lawson and Weiker (2008) analyzed water quality from several sites in the Huron River watershed for 2002–2007, including Malletts Creek, and noted the strong relationship between discharge and loads of suspended sediment [total suspended solids (TSS)] and total phosphorus (TP) for Malletts Creek. They also noted excessively high levels of specific conductance (>800 μS) despite generally acceptable pH and dissolved oxygen levels. OHM (2011) described estimation of the pre-project annual TSS erosion rate (tons/yr) and annual TP load based on the Bank Assessment for Non-point Source Consequences of Sediment (BANCS) procedure (Rosgen 2001b) and the *Pollutants Controlled Calculation and Documentation for Section 319 Watersheds Training Manual* [Michigan Department of Environmental Quality (MDEQ) 1999], respectively. The analysis yielded estimates of 1,283 tons/year of TSS and 1,091 lb/yr of TP yield from all project reaches, total.

Data collected by the Huron River Watershed Council and partners at the monitoring station Malletts Creek at Chalmers Drive (2003–2011) yielded an the average TSS concentration of 18.1 mg/L, with a slight declining trend over that period of time (Lawson et al. 2008). Wet weather monitoring resulted in event concentrations of 33 and 222 mg/L or an average of 127.5 mg/L. Steen (2014) summarized data for the period 2003–2012 and noted that mean flow-weighted TP concentrations for Malletts Creek were >0.1 mg/L, well above the target concentration of 0.05 mg/L.

Benthic invertebrate and habitat quality assessments conducted in 1999 revealed conditions were fair to poor (Wuycheck 2004) and conditions were unchanged as of 2011 (Middle Huron Partners and Stormwater Advisory Group 2012). Key factors included flashy hydrology and nonpoint source pollution (sediment and organics). Overall ecological status as assessed by an index based on 10 indicators of "stream health" is only 20 on a scale of 0 to 100 (Steen 2014) based on data from 2003–2012. This places Malletts Creek among the lowest-rated subwatersheds in the Huron River watershed.

Infrastructure Issues. As of 2004, there were at least 161 storm water outfalls to Malletts Creek watershed covered by the Phase I storm water runoff permit program (Wuycheck 2004). Several outfalls and culverts needed maintenance (Table 4.8).

Stakeholder Concerns. Riparian landowners and concerned members of the public were anxious about tree removals required for project construction. A tree monitoring committee was established by the neighborhood association and a "geosocial network" was used to keep track of trees tagged for preservation and those tagged for removal (Arlinghaus and Arlinghaus 2012). Additional concerns included reduction in privacy due to project construction, since the channel borders several residential back yards.

Selection of Treatment Types

Restoration Objectives. Multiple restoration objectives were developed for both the creek and its watershed (Goldsmith et al. 2014). A public information component was included to inform and involve citizens about proposed restoration activities. Project goals were to address needed structural repairs (e.g., broken culverts and cracked outlet structures), to reduce phosphorus

Copyright National Academy of Sciences. All rights reserved.

loading to downstream waters by 50%, to increase habitat quality for fish and wildlife, to control stream velocities, and to stabilize stream banks. Project measures included stream bank stabilization, channel bed erosion controls, and storm water detention basins. A total length of 8,700 linear feet of stream channel was treated for stream bank erosion. Both conventional and environmentally sensitive measures were selected for bank stabilization. All stabilization was preceded by extensive removal of invasive woody vegetation accompanied by preparatory grading work. The in-channel work featured in this case study was part of a larger, systemic effort throughout the watershed to retain and treat storm water with a range of management practices.

Selected Treatments. Selected treatments included bank grading to create surfaces for revegetation and to increase the channel cross-sectional area to decrease high flow velocities. In some cases, narrow, deeply incised channels were graded to produce two-stage (benched) cross sections. Additional conventional measures included stone bank protection and storm water detention basins placed on the floodplain. Within the channel, the project included rock vanes to deflect high velocities from banks and increase physical habitat diversity, stone grade controls (cross vanes) to limit bed degradation and trap sediments, and coir logs placed along bank toes for erosion control. Protection of upper and middle banks featured ECBs and planting of live willow stakes and seeding.

Design

Design of erosion controls, both stone and vegetative components, was based on orthodox guidance. A computer modeling study was conducted to predict flow rates and flood elevations, as well as phosphorus levels in the creek subsequent to project implementation.

Channel. The channel geometry was modified in both the longitudinal and cross-channel directions to improve stream function. The channel width was widened along its bottom to accommodate increased flow; the sides were also graded back to a more stable 2H:1V angle (Figure 4.48a and b). Where space allowed, the stream bank was "stepped" to provide a shallow terrace or bench above the rock toe to accommodate and slow down intermediate flood flows (Figure 4.48e).

Riprap. Conventional rock armor (riprap) was widely used on this project as toe protection. Rock armor was used in higher-velocity (>5 ft/s) reaches and along outside bends. There was no attempt to purposely vegetate the rock with live cuttings using either the "joint-planting" or "bent willow pole" method (see Section 4.3.3). The rock selected was relatively rounded and attractive in appearance (Figure 4.48a, c, and d); however, angular rock is generally preferred for riprap. To compensate for the rounded characteristics of the rock, larger rocks were placed at the bottom and inset into the channel to forestall displacement and undermining during high-flow events. Geotextile fabric was placed on the stream bed under the vanes to prevent subsidence (Figure 4.48i).

Coir Logs. Coir logs consisting of coir fiber rolls approximately 1 ft in diameter were staked in place at the toe of the stream bank with lumber stakes (Figures 4.48e and f). These were placed either singly or stacked vertically in a double row. Coir logs were used as an alternative to rock armor in lower-velocity reaches of the channel. Coir logs can be vegetated by inserting live stakes or cuttings; they also lend themselves to natural vegetation by volunteer plants. Coir logs were occasionally protected with rock as well.

Rock Vanes and Stone Grade Controls. Rock vanes were placed at strategic locations to deflect impinging flow away from the bank. The vanes were oriented in an upstream direction at roughly 30 degree with the bank (Figure 4.48a and b). Cross vanes served a similar purpose but extended from both banks and created a V-upstream when viewed in plan (Figures 4.48c and d). They

Copyright National Academy of Sciences. All rights reserved.

a. Graded bank, stone toe, and upstream-angled rock vane shortly after construction.

b. Same view as for (a), two years after construction. Note forked tree in right background.

c. Graded bank with coir logs at toe and stone cross vane shortly after construction.

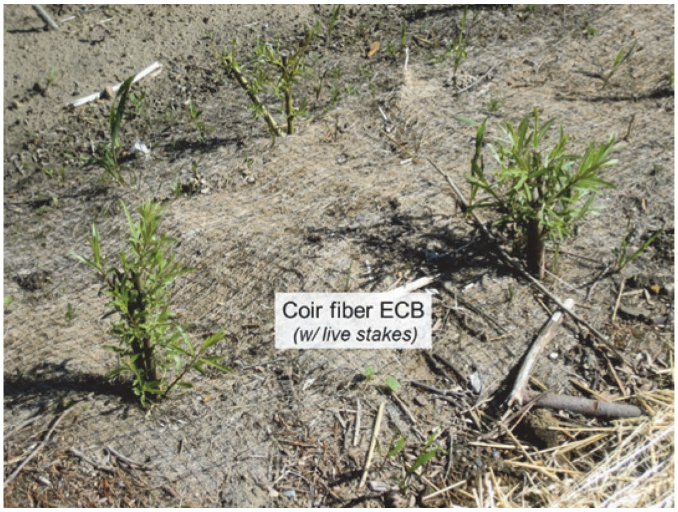
d. Stone cross vane two years after construction.

e. View shortly after construction. Cross section graded to produce bench. Coir log toe protection, rock vanes.

f. Close-up view of channel bank with coir log toe two years after construction. Red arrow indicates about 1.5 ft of bed degradation.

Figure 4.48. Key components of Malletts Creek Restoration Project during or shortly after construction and two years later.

Copyright National Academy of Sciences. All rights reserved.



g. Cuttings planted in coir fiber ECB showing initial growth shortly after planting.

h. Cuttings and ECB two years after planting. One cutting appears to be dead, while the other shows minimal growth.

i. Construction crew installing filter fabric on graded bank prior to placing stone. Permission from OHM, Inc.

j. Reach similar to the one that includes the bank shown in (i), two years later.

Figure 4.48. (Continued).

deflected the current into the center of the stream. Rock was placed along the bottom of steeper reaches in a manner that resembled "boulder cascades" to limit bed degradation. Scour analysis was used in cross vane design in accordance with Equation TS14B-23 provided by Shields (2007) (OHM 2011).

ECBs and Live Stakes. Both straw and coconut fiber ECBs were used to protect stream banks above either the rock armor or coir logs placed at the toe (Figure 4.48e). Live stakes cut largely from phreatic species such as willow (*Salix* spp) were inserted through the ECBs to provide additional protection and to help reestablish vegetation on stream banks. ECBs were anchored with stakes placed at 4-ft intervals. Geotextile mesh was used in high-velocity zones, while biodegradable coir was used elsewhere.

Installation

Public Meetings with Stakeholders. Well-publicized meetings were held with stakeholders, and frequent interactions with homeowners occurred during construction.

Copyright National Academy of Sciences. All rights reserved.

Mistakes and Learning Curve. Construction was scheduled for winter months to take advantage of frozen ground, but an unusually warm, wet winter complicated construction operations due to muddy conditions. One construction fatality occurred early in the project that involved a mishap with heavy equipment and a pedestrian worker. Work proceeded very slowly at first as workers learned techniques. The contractor used a perennial turf grass seed mix for floodplain reseeding in the park rather than the native grass seed mix that was specified.

Plant Materials. Plant materials were imported from Pennsylvania. Primary plant materials were live stakes (see Table 4.9). Dozens of balled and burlap gallon-size plantings were used, primarily in the park. The warm spring of 2011–2012 caused problems for plant materials, and cold storage was used to maintain dormancy. Microclimate and timing of plantings made a big difference in survival.

Costs. The project was completed during the winter of 2011–2012. The total estimated cost of all restoration activities in the watershed including stream bed and bank stabilization was about $19.1 million. The largest cost components were initial structural repairs to streams ($4.8 million) and detention pond improvements ($4.4 million). The estimated cost of stream bank stabilization was $2.1 million (11% of total). Some funding was received from the state Department of Environmental Equality—Michigan's NonPoint Source (DEQ NPS) program for control of sediment and phosphorus.

Performance

Monitoring and Findings. The project was tested by intense rainstorms shortly after construction in March 2012. A severe drought occurred during first summer after completion (2012). Discharges since completion have been moderate relative to the four years prior to construction. A 1-year event overflowed banks at Site 3 (see Table 4.8), but overall flooding is not a major issue within this corridor. The 10-year event only floods one residential lawn.

The system performed well during and immediately after intense rainstorms shortly after construction in March 2012. This was a severe test for a stream bank protection system that was likely vulnerable at this time since the live cuttings and seedings (under the ECBs) did not have sufficient time by then to grow and establish fully. The coir logs were still visible during the NCHRP Project 24-39 site visit in 2014 and appeared to have performed quite well. However, bed degradation (up to 1.5 ft) was noted along some coir logs (Figure 4.48f).

The rock vanes provide diverse aquatic habitat (see Section 4.2.6). In addition sediment has started to collect behind the vanes. The conventional measures (rock armor) and bio-stabilization techniques (coir logs, ECBs, and live staking) have functioned well together. Stones used for bank protection, toe armor, and vanes were very rounded with a D_{100} of about 24 inches. As of 2014,

Table 4.9. Species and numbers of live stakes installed in Mallett's Creek project.

Scientific	Common	Quantity
Cephalanthus occidentals	Buttonbush	1,489
Cormus amomum	Silky Dogwood	1,489
Comus sericea (C. stolonifera)	Red Osier Dogwood	1,489
Physocarpus opuifolius	Ninebark	1,489
Salix discolor	Pussy Willow	1,489
Salix exigua ssp interior	Sandbar Willow	1,489
Salix sericea	Silky Willow	1,489
Sambucus canadensis	Elderberry	1,489
Viburunum dentatum	Arrow Wood	1,489
	Total	**13,400**

Copyright National Academy of Sciences. All rights reserved.

much of this stone had been moved or dislodged, both along stone toes and at the small drop structures. Some local erosion was noted at one site immediately downstream from a protected bank likely due to a poorly designed transition from the protected bank to a convex bank (point bar).

A severe drought occurred during first summer after completion (2012), but no irrigation was provided for plantings. During Fall 2012, stakes were replanted at locations where low survival occurred. However, the high density of initial plantings allowed survival as low as 50% to produce acceptable levels of cover (Figure 4.48j). Several examples of poorly growing stakes were noted in the 2014 inspection, perhaps due to infertile soils (Figure 4.48h). There are no beaver in the watershed, which alleviates herbivory of plantings. However, plantings do face strong competition from invasive exotics (buckthorn, Mack's honeysuckle, Japanese knotweed, black locust). Many of these invasive plants returned quickly from old root masses.

In general, not enough time has elapsed since construction to allow assessment of water quality and ecological effects. Post-construction invertebrate sampling (Spring 2014) showed improvement over pre-project conditions. At the time of the NCHRP Project 24-39 inspection in October 2014 (see Section 2.4), water quality appeared marginal, and no fish were seen. However, bed sediments were primarily clean gravel and cobble.

Maintenance. To date, the project proper has not required maintenance. Vegetation in adjacent natural areas in parks is maintained by annual prescribed burning, but this practice does not extend into the stream corridor. Poor alignment of a sheet pile outlet structure that controls flow from a detention basin into the channel has required some adjustment due to undesirable sedimentation.

Damage Assessment. Jones and Johnson (2015) present a framework for describing the damage status of stream modification projects in constrained settings (see Section 4.2.5, Table 4.2). The framework is based on widely accepted evaluations of physical habitat quality and stream stability. Their approach was adapted for this study. Based on visual observations made in October 2014, the project was rated as "excellent" in categories of stream bank vegetation, bank stability, and infrastructure protection and rated "good" in the categories of structural integrity, and flow obstruction, and sedimentation.

Summary of Conclusions and Lessons Learned

The overall impact of the project on several ecological stressors has been positive, based on visual evaluations of the channel and frequency of bank erosion. Public support for the project has generally improved as the project has been implemented. Effort invested in communication with stakeholders is well worth the resources required.

Installation of vegetative components is complex, and contingency plans for changes in weather (e.g., cold storage for cuttings or irrigation if needed during period of establishment) should be in place. Close inspection is required to ensure plant materials are handled and installed correctly. Fertility of soils should be assessed before planting, especially if banks are re-sloped. Microclimate and timing of plantings is very influential for survival and performance. Invasive exotic plants are very difficult to control in stream corridors.

Naturally rounded stone is aesthetically pleasing, but less stable than angular quarry stone.

Recovery of stream corridor aesthetics and physical habitat is typically more rapid than improvements in water quality and ecology.

Long-term stability of project features may be at risk if the fluvial system responds to bank stabilization and retention of sediment in storm water detention ponds by bed degradation.

Copyright National Academy of Sciences. All rights reserved.

References

Arlinghaus, D. E. and Arlinghaus, S. L., 2012. Geosocial Networking: A Case from Ann Arbor, Michigan, *Solstice: An Electronic Journal of Geography and Mathematics*, 23(1), http://deepblue.lib.umich.edu/handle/2027.42/58219 (accessed April 14, 2015).

Fongers, D., Manning, K. and Rathbun, J., 2007. *Application of the Richards' Baker Flashiness Index to Gaged Michigan Rivers and Streams*, Michigan Department of Environmental Quality, Lansing, MI.

Goldsmith, W., Gray, D. H., and McCullah, J., 2014. *Bioengineering Case Studies*: *Sustainable Stream Bank and Slope Stabilization*, Springer Verlag, New York, NY.

Jones, C. J. and Johnson, P. A., 2015. Describing Damage to Stream Modification Projects in Constrained Settings, *Journal of the American Water Resources Association*, 51(1): 251–262.

Lawson, R., Bouma, D., Olsson, K., Rubin, L., and Powell, E., 2008. *Watershed Management Plan for the Huron River in the Ann Arbor—Ypsilanti Metropolitan Area*, prepared on behalf of and with funding support from Janis A. Bobrin, Washtenaw County Drain Commissioner, Huron River Watershed Council, Ann Arbor, MI.

Lawson, R. and Weiker, D., 2008. *Middle Huron Stream Nutrient Monitoring Program: Analysis of Results: 2002–2007*, Huron River Watershed Council, Ann Arbor, MI.

MDEQ, 1999. *Pollutants Controlled Calculation and Documentation for Section 319 Watershed Training Manual*, Lansing, MI.

Middle Huron Partners and Stormwater Advisory Group, 2012. *Total Suspended Solids Reduction Implementation Plan for Malletts Creek, October 2011–September 2016, For the Purpose of Achieving the Total Maximum Daily Load (TMDL) and Removing the Biota Impairment of Malletts Creek*, Huron River Watershed Council, Ann Arbor, MI.

Orchard, Hiltz, and McCliment, Inc., 2011. Malletts Creek Stream-Bank Stabilization Project, Washtenaw Water Resources Commissioner's Office, City of Ann Arbor, MI.

Rathburn, J., 2006. *Standard Operating Procedure: Assessing Bank Erosion Potential Using Rosgen's BEHI*, Michigan Department of Natural Resources and Environment, Nonpoint Source Pollution Unit, Lansing. Available: www.michigan.gov/deq/1, 1607, 7–135.

Richards, P. L. and Brenner, A. J., 2004. Delineating source areas for runoff in depressional landscapes: Implications for hydrologic modeling, *Journal of Great Lakes Research*, 30(1), 9–21.

Rosgen, D. L., 2001a. A Practical Method of Computing Streambank Erosion Rate, In *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Vol. 2, No. 2, pp. 9–15.

Rosgen, D. L., 2001b. *Watershed Assessment of River Stability and Sediment Supply (WARSSS)*, Wildland Hydrology, Fort Collins, CO.

Shields, F. D., Jr., 2007. Scour calculations, Technical Supplement 14B in Stream Restoration Design, *National Engineering Handbook Part 654*, USDA-NRCS, Washington, D.C., CD-ROM. 2007.

Steen, P., 2014. *The State of the Huron's River and Tributaries*, The State of the Huron Conference. Huron River Watershed Council, Ann Arbor, MI. http://www.hrwc.org/wp-content/uploads/2014/05/Steen_StateofAffairs.pdf (accessed April 13, 2015).

Water Resources Commissioner, Undated. *Malletts Creek Restoration Project*, Final Report, Washtenaw County Water Resources Commissioner, Washtenaw County, MI. http://www.ewashtenaw.org/government/drain_commissioner/project-status/malletts_creek/dc_mc_mcrp.html (accessed October 8, 2014).

Wuycheck, J., 2004. *Total Maximum Daily Load for Biota for Malletts Creek, Washtenaw County*, Michigan Department of Environmental Quality, Water Division, Lansing.

4.5 Appraisal of Results

4.5.1 Advances in the State of Practice

In 2005, the results of NCHRP Project 24-19 were published as *NCHRP Report 544: Environmentally Sensitive Channel- and Bank-Protection Measures* (McCullah and Gray 2005). After conducting an extensive literature review and evaluation of commonly used environmentally sensitive techniques, McCullah and Gray identified 44 techniques for study. The channel- and bank-protection techniques were grouped into four major categories, including (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 application were developed. The work by McCullah and Gray (2005) served as a starting point and foundation for the present study (NCHRP Project 24-39).

Given the objectives of the present study (see Section 1.1.2), which included assessing and evaluating existing guidelines and development of expanded guidelines for selected environmentally

Copyright National Academy of Sciences. All rights reserved.

sensitive stream bank stabilization and protection measures, 16 treatments from the river training and bank armor and protection categories of *NCHRP Report 544* were selected for further consideration (see Appendix A for a summary of issues related to hydraulic loading, common reasons/circumstances for failure, and research opportunities for these 16 treatments as identified in *NCHRP Report 544*).

In selecting two of these treatments for rigorous hydraulic flume testing, consideration was given to treatments or treatment components that would have the widest applicability nationwide. One treatment included a stone (riprap) toe, live siltation, and live staking. The hydraulic data from testing this treatment has broad applicability to either multi-component systems or treatments using just individual components (i.e., using live siltation or willow staking, alone) for stream bank protection. Testing a multi-component system also provided insight on the hydraulic response of the transitions between treatment types having different roughness characteristics. The second treatment (VMSE without a hard toe) recognized that many resource agencies tend to discourage, and in some cases prohibit, the use of rock in stream bank protection. Thus, testing the hydraulic limits of a treatment without a hard toe but incorporating FES lifts with live brush layering between the lifts could have wide potential applicability and interest.

The laboratory testing task of this project represents a technological breakthrough in developing quantitative hydraulic engineering design guidance for environmentally sensitive treatments. The in-channel (not stream bank) roughness characteristics of living plants have been tested (by others) previously in a laboratory flume, primarily to investigate the influence of vegetation on roughness characteristics under varying flow conditions. However, the testing of the vegetative components of selected stream bank treatments following recommended design criteria, including fabricating the structural component(s), planting the vegetative component(s) and growing them to maturity, and, finally, moving them to a flume for fully instrumented hydraulic testing at prototype scale under a range of flow conditions represents a "first" in the development of quantitative guidance for environmentally sensitive bank-protection treatments. The detailed results of the laboratory testing task are presented in a standalone format in Chapter 3.

Of the two treatments tested in the laboratory, one (live siltation and live staking with a stone toe) met or exceeded all performance expectations. The second treatment (VMSE without a hard toe) exhibited vulnerabilities to damage and soil loss under the same conditions of discharge and longitudinal slope.

The laboratory testing task did not represent the only contribution of this study. A synthesis of the current state of practice for environmentally sensitive treatments based on both a literature review and survey of practitioners was completed. The synthesis updated the 2005 findings from the *NCHRP Report 544* (McCullah and Gray 2005). Specifically, the literature review concentrated on work completed between 2005 and 2014. While advances have been made in the past 10 years in developing treatment-specific guidance documents for environmentally sensitive bank protection, hydraulic design criteria are still scarce and with few exceptions rely on the literature that was summarized in NCHRP Project 24-19. The available hydraulic criteria were drawn from a variety of sources and varied in quality from qualitative anecdotal rules of thumb to isolated spot measurements of velocity. In this regard, the treatments tested under NCHRP Project 24-39 were designed to respond to specific hydraulic research needs identified by McCullah and Gray in 2005, including:

- **Live siltation**—Research into velocities that this technique can withstand would be helpful.
- **Live staking**—Studies would be valuable regarding the effect live staking has on increasing the ability of other measures to withstand higher velocities and shear stresses.
- **VMSE**—Some uncertainty exists at present as to the exact permissible shear stresses and velocities for VMSE interfaces. Additional research would also be helpful on the nature of the interaction between roots and fabric.

Copyright National Academy of Sciences. All rights reserved.

Sixteen site visits to existing field installations of a variety of treatment types in three geographic regions (Southeast, upper Midwest, and the West Coast) were also completed. A highly detailed site visit data form was developed and completed for each site and significant additional effort was applied to gathering design and monitoring information, reports and specifications, cost data, and photographic documentation for each site. Additional effort was devoted to obtaining hydrologic and hydraulic data that supported the design and influenced the level of functionality achieved at each site. While much of this information was qualitative and anecdotal, observations from each site visit provided insight on best management practices, and, in several cases, failure mechanisms and lessons learned that will improve the state of practice. Moreover, the site visit reports and data obtained were assembled into a Compendium to provide easy access for the practitioner to a wealth of experiential information on environmentally sensitive bank-protection treatments. The Compendium is presented in a searchable database format to permit the practitioner to employ SQL in searching the database.

General hydrologic, hydraulic, and geomorphic considerations and site-specific physical processes that influence the design, installation, and monitoring of environmentally sensitive stream bank protection treatments were presented in a standalone format in this chapter. The site-specific physical process topics include bankfull discharge and conveyance; assessing the stage of evolution for incising channels; analyzing aggradation, degradation and lateral channel stability; predicting meander migration; guidance for protecting the upstream and downstream "flanks" and "toe" of a stream bank treatment; and estimating toe down requirements and hydraulic stress on a bendway. Geotechnical considerations, guidance for monitoring the success of the vegetative component(s) of environmentally sensitive treatments, and aquatic habitat issues that can influence the design and installation of any treatment were also discussed in this chapter.

Detailed, updated design guidelines for three widely used treatments were the focus of this chapter. These include the two treatments tested under Task 7 of this study and an overview and updated guidance for vegetated riprap. These design guidelines were presented in a format that addressed the specific topics listed with the objectives statement of the NCHRP research problem statement and included:

- Purpose and advantages (selection),
- Hydrologic and hydraulic design parameters,
- Materials and equipment,
- Construction and installation,
- Cost,
- Maintenance and monitoring, and
- Common reasons for failure.

In addition, two detailed case studies of the application of environmentally sensitive stream bank protection measures employed in conjunction with stream channel restoration projects were presented in this chapter. One example involved the application of environmentally sensitive techniques on an arid region perennial river. The second example deals with a smaller stream in a humid region with significant infrastructure issues. The examples illustrated the integration of hydraulic engineering analysis and design with the multidisciplinary approach necessary to achieve project success and included, by example, additional guideline topics such as hydrologic and hydraulic design parameters, performance and longevity, and ecological issues.

For the engineer involved in the multidisciplinary design of an environmentally sensitive treatment, this chapter also provided current guidance from FHWA on the use of biotechnical treatments in proximity to transportation infrastructure. In addition, for the PE on a design team, aspects of professional liability in environmentally sensitive design were explored.

Copyright National Academy of Sciences. All rights reserved.

The following sections highlight relevant observations that contribute to advancing the current state of practice for environmentally sensitive design based on the survey of practitioners and the field site visits conducted under this study.

4.5.2 Observations from the Survey of Practitioners

Under Task 2 a survey form was prepared, approved by the NCHRP project panel, and distributed by email to 319 individuals representing all 50 state highway agencies (DOTs) and other federal, state, and local government agencies. Selected Native American nations, consultants, and academic institutions involved in stream bank protection measures were also included in the survey outreach effort. The purpose of the survey was to gather information on the current state of practice with respect to a variety of topics related to environmentally sensitive stream bank protection and included detailed performance-related issues/questions for 16 specific protection treatments (see Section 2.3 and Appendix A). A copy of the survey instrument is included at Appendix B.

The survey was constructed to elicit specific information regarding the relative frequency of use of 16 specific environmentally sensitive bank-protection treatments, and their performance. By far, the most widely used was live staking (27 out of 35 responses). The survey responses indicated that vegetated riprap (17 responses) and rootwad revetments (16 responses) were the second and third most common treatments in current practice. While rootwad revetments were not investigated under this research project, live staking was a component of "Tray 1" tested in the hydraulic flume under Task 7 (see Chapter 3 and design guidelines in Section 4.3.1). Updated design guidelines for vegetated riprap were provided in Section 4.3.3.

The survey revealed that in general, environmentally sensitive bank-protection measures typically result in satisfactory to good performance at most installation sites. The two most common causes of substandard performance were drought and erosion of the bank slope. These factors were a recurring theme across nearly all of the 16 bank-protection measures listed in the survey. Protection measures incorporating live cuttings tended to indicate that improper plant selection or improper installation resulted in poor performance. Protection measures that incorporated a "hard" or "engineered" component such as rootwad revetment, riprap, articulated blocks, gabions, etc. exhibited failure modes associated with toe or edge scour, undermining, flanking, or geotechnical slope instability.

For the treatments (or treatment components) tested under Task 7 and the three treatments for which detailed design guidelines were given in Section 4.3, the following specific comments were received:

- Live staking—Performance ranged from "failure" to "excellent." Most respondents indicated experience with multiple sites and reported generally satisfactory performance. When mortality was indicated, the cause was typically lack of moisture, poor soil conditions, poor quality of cuttings, or a combination of these factors. California respondents indicated that they do not use this as a standalone measure but incorporate a hard armor toe.
- Live siltation—Generally satisfactory performance, but not much usage reported.
- VMSE—Generally good performance reported by nine respondents. Montana reported some poor performance due to improper installation, while California and Washington, D.C., noted both slope erosion and drought as factors leading to substandard performance.
- Live brush layering—Seven respondents indicated experience with multiple sites and reported generally good performance. Montana reported some poor performance due to improper installation, and California noted both slope erosion and drought as factors leading to instances of substandard performance.
- Vegetated Riprap—Generally good performance. Slope erosion and drought were the most commonly reported causes of substandard performance.

Copyright National Academy of Sciences. All rights reserved.

4.5.3 Observations and Lessons Learned from the Field Site Visits

Introduction

Under Task 6, field investigations were conducted at 16 sites where a variety of environmentally sensitive treatments had been installed and monitored. The sites were grouped in three specific regions as follows:

- Southeast (Mississippi)—5 sites (Figure 2.3),
- Upper Midwest (Ann Arbor, Michigan)—5 sites (Figure 2.4), and
- West Coast (Northern California)—6 sites (Figure 2.5).

Priority was given to visit sites where measurements have been made and where those measurements can be correlated to original design intent and hydrologic/hydraulic history. The final list of sites included a diversity of stream bank protection measures and geographic locations.

The following sections summarize observations from the site visits as they relate to the treatments tested under Task 7 and the three treatments for which detailed design guidelines were given in Sections 4.3.1 through 4.3.3.

Selected Observations and Lessons Learned from Site Visits

Observations on the installation and performance of the components of "Tray 1" (live siltation and live staking with rock toe—see Chapter 3 and Figure 3.3) are summarized below. Six sites included live staking, three sites included live siltation, and four sites included a stone toe. These treatment components were not necessarily installed together in the combination tested with "Tray 1" under Task 7. An additional three sites (all in California) included a riprap bench or berm as a variation of the stone-toe theme.

Live staking:

- Willow stakes with split or broken ends will invariably die. Split or broken ends should be cut off.
- Willow stakes do poorly when planted in cohesive soils. For success, plant willow stakes in sandy, noncohesive soils that are moist but well drained. If they are not planted deeply, however, the willows will float away or scour out when inundated.
- High mortality can be expected if roots are not adequate to anchor plants against buoyant and drag forces during high flows, especially when the plants trap leaves and other debris.
- Competition by invasive exotic woody species (e.g., buckhorn, European alder, honeysuckle, black locust) should be anticipated in the monitoring and maintenance plan.
- Live staking and other vegetative treatments struggle where soils used to fill an eroded slope are droughty, and some replanting may be necessary. If chimney drain systems are included in the treatment design, they may also depress soil moisture in the root zone.
- Straw, curled wood excelsior, and coconut fiber ECBs can be used to protect stream banks above either a riprap armor or coir logs placed at the toe. Live stakes cut largely from phreatic species such as willow (*Salix* ssp) can be inserted through the ECBs to provide additional protection and to help reestablish vegetation on stream banks. ECBs can be effectively anchored with live stakes placed at 4-ft intervals. Geotextile mesh can be used in high-velocity zones where necessary.
- In a humid region, a wide variety of woody species are available to be planted as live stakes.
- At the Guadalupe River site in Northern California, it was observed that plantings should be performed with minimal disturbance to the geotextile blanket (holes cut for the vegetation were quite large and could provide a potential point of undermining). The project emphasized the importance of installing geotextile blankets parallel to the flow of water within channels where inundation will occur.

Copyright National Academy of Sciences. All rights reserved.

Live siltation:

- As a biotechnical practice live siltation can be self-mitigating as it establishes into a row of riparian shrubs. At the Alamitos Creek site in Northern California, cuttings of Baccharis (mule fat) were also used successfully in lieu of willow.
- Live siltation can produce a vigorous riparian strip of vegetation (e.g., at the Russian River site in Northern California, where live siltation resulted in a 15- to 20-ft side band of shrubs greater than 12 ft tall with 100% coverage).
- At the Russian River site in Northern California, live siltation experienced high flows (11,000 cfs) with 9 ft of flooding over nearby structures (rock vanes). Performance during the 4-year period (2010–2014) after installation was considered excellent. During flooding, the willows attenuated flow velocities and helped to trap and hold sediments on the flood terrace.
- At the Guadalupe River site in Northern California, live siltation willow cuttings were staked into the soil and rock above and within log structures at the toe of the bank. Deep, voided areas from previous erosion allowed the stakes to be planted as fill was placed without digging. Willows proved to be capable of withstanding periodic inundation and high-velocity flows, and helped anchor the toe with roots and provide shading and habitat for the treated reach.

Rock toe:

- Broken concrete should not be used for stone toe in lieu of quarry stone riprap. This material is undesirable because it is not self-launching and can create stream-side hazards particularly when it contains rebar (see Figure 2.6).
- At the Goodwin Creek site in northern Mississippi the longitudinal stone toe was completely covered by deposition and excellent vegetation seven years after installation (2007–2014).
- At the Hotophia Creek site in northern Mississippi both a stone toe and stone groins (similar to bendway weirs) were installed with willow posts and poles in the upper bank. Fish habitat was monitored for one year before and four years after construction and again 10 to 11 years after construction. Fish numbers, biomass, and species richness increased sharply following construction and these changes persisted over ten years. Inspection in 2014 found the water clear, low current velocity, depths 1 to 3 ft, and numerous fish. Overhanging vegetation at this site provides shade over water.
- At the Malletts Creek site near Ann Arbor, Michigan, conventional rock armor (riprap) was used as toe protection. Rock armor was used in higher-velocity (>5 ft/s) reaches and along outside bends. There was no attempt to purposely vegetate the rock with live cuttings using either the "joint-planting" or "bent willow pole" method (see Section 4.3.3). The rock selected was relatively rounded and attractive in appearance. In addition, larger rocks were placed at the bottom and inset into the channel in an attempt to forestall displacement and undermining during high-flow events (see Figure 4.48). The combination of conventional measures (rock armor) and bio-stabilization techniques (coir logs, ECBs, and live staking) at this site has functioned well together.
- At several sites on the LAR near Sacramento, California, a unique "stone toe" configuration was installed. Based on hydraulic modeling and slope stability analysis, several mitigation measures were incorporated into project designs. These included a variety of surfaces capable of supporting vegetation; low riverside berms (small constructed floodplains) with varying berm-surface elevations and shoreline configuration; and woody materials submerged in constructed embayments or smaller bank scallops (see Figures 2.9–2.11). Native woody and herbaceous riparian vegetation was planted on the surfaces with the goal of creating a self-sustaining, mixed-canopy riparian forest and riparian scrub habitat. In the 15 years (1999–2014) since project construction, this "rock toe" configuration has been monitored on an annual basis and continues to perform as designed.

Copyright National Academy of Sciences. All rights reserved.

Observations on the installation and performance of "Tray 2" (VMSE without hard toe—see Chapter 3 and Figure 3.4) are summarized below. Two sites included VMSE (specifically, FES lifts) with vegetation inserted in a live brush layering configuration.

VMSE:

- At the Buttahatchee River site northeast of Columbus, Mississippi, VMSE was installed to protect the secondary upper-bank slope. In addition, rock "refusals" (stone-filled trenches running upslope perpendicular to the channel) were placed at the upstream and downstream ends of the treatment at this site to prevent flanking. In general, plantings at this project may have performed better in more fertile, less droughty soil. It was concluded that it would have been advisable to stockpile the topsoil stripped from the stream bank and reuse it before planting.
- A VMSE retaining structure with a 1H:1V sloping face was selected to support a roadway parallel to the stream at the Huron River (Nichols Drive) site near Ann Arbor, Michigan. A rock footing was placed in an excavated trench beneath the VMSE structure. At this site a polymeric geotextile was used for the VMSE. A temporary sheet pile wall was constructed in the river channel running parallel to the bank toe prior to VMSE construction. This allowed for dewatering and excavation of a trench at the bank toe that was filled with stone as foundation support for the VMSE bank retaining structure.
- To control roadway runoff at the Huron River (Nichols Drive) site, a sloping drainage course (chimney drain) consisting of a polymeric blanket drain with a high in-plane hydraulic conductivity was placed behind the VMSE retaining structure. This drainage blanket intercepts seepage and conveys it to a subdrain system that discharges directly to the river. This measure was an attempt to minimize undesirable saturation of the fill beneath the roadway and of the fill in the VMSE (see potential negative consequences, below).
- Based on experience at the Huron River (Nichols Drive) site, it was concluded that close supervision is needed to correctly install chimney drains and VMSE. Also, plant materials used in the VMSE at this site were not dormant when planted. The cuttings were held too long in stagnant water in plastic barrels and inserted into the ground well after the end of dormancy. In addition, the stakes were not buried deep enough. As a result, vegetation has struggled and some replanting has occurred at this site. Contributing to the problem, soils used to fill the eroded slope were droughty, and soil moisture in the root zone may be depressed by the chimney drain system. Poor survival rates (<30%) have required replanting. Grass seeding, live staking, and woody transplants were used in addition to the live, cut branches placed between horizontal lifts in the VMSE structure at this site. The grass seed mix was placed by hydroseeding the top of the stream bank and also directly on the face of the VMSE structure.
- During the 2014 visit to the Huron River (Nichols Drive) site it was noted that the site looks visually attractive as observed by the public who use the road frequently to access the Arboretum. However, the vegetation is very sparse and small relative to the vegetation at the River Landing (Nichols Arboretum) site just downstream. Closer inspection during the site visit revealed that the polymeric geotextile used for the VMSE was visible at the soil surface, and it was unsightly.

While vegetated riprap was not tested during Task 7, a design guideline overview for this common treatment was provided in Section 4.3.3. Five sites visited during Task 6 included vegetated riprap as a component of the treatment installed. Observations of the installation and performance at several of these sites are summarized below.

Vegetated riprap:

- At the Huron River (Nichols Arboretum/River Landing) site near Ann Arbor, Michigan, the bank toe was armored with riprap (see Figure 2.6). The riprap was vegetated using the joint-planting method (see Figure 4.30), i.e., live stakes representing 6 to 8 woody tree and shrub species were inserted between openings or interstices in the riprap (sandbar willow, red osier dogwood, ninebark, silky dogwood, native roses). Not all stakes were dormant when planted.

Copyright National Academy of Sciences. All rights reserved.

- At the Nichols Arboretum site the live stakes in the riprap have not fared well. Many stakes were damaged when driven through the rock blanket to plant them in interstices. A year after installation only about 30% of the live stakes survived and sent out shoots. The willow bundle method or bent willow pole, which eliminates many of the problems associated with the joint-planting method (see Figures 4.27 and 4.28), should be considered in the future. Red osier dogwood was the most successful species planted, and quite prolific when the site was inspected in 2014. The riprap toe has survived several high-water events but has not been tested by floods approaching peak flows of record.
- At several sites on the LAR near Sacramento, California, vegetated riprap was installed on multiple benches for habitat enhancement. Pre- and post-project hydraulic modeling showed no impact on flood capacity and indicated that the lower benches would be submerged for specific environmental flows. At these sites reducing beaver pruning (herbivory) of planted trees (in particular cottonwood) and shrubs on the berm face and low berm was the greatest challenge to meeting shaded riparian habitat goals. Older beaver fence became brittle, providing easier access to the site by beavers. During 2010, linear beaver fence maintenance, and cage installation and relocation continued to be an important management action to minimize beaver damage to vegetation. This strategy proved successful and limited further tree losses or damage at these sites, as well as other sites where cages were previously installed.

The observations in this section were taken, primarily, from the field data forms from the site visits performed under Task 6. For more detail and site-specific observations refer to the Compendium that accompanies this report.

Copyright National Academy of Sciences. All rights reserved.

CHAPTER 5

Conclusions and Suggested Research

5.1 Conclusions and Suggested Research

5.1.1 Conclusions

This final report is based on research conducted under NCHRP Project 24-39, "Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures." This research accomplished its basic objectives of evaluating and assessing existing guidelines for the design, installation, monitoring, and maintenance of environmentally sensitive stream bank stabilization and protection measures. In addition, quantitative engineering design guidance was developed for selected treatments. With the guidance available at the outset of this study, there was a reluctance on the part of many engineers to utilize biotechnical approaches to stream bank stabilization techniques. This was due, in part, to a lack of technical training, experience, and definitive hydraulic engineering design guidance. In particular, there was a lack of knowledge about the properties of the vegetative materials being used in relation to the force and stress generated by flowing water, and there was concern regarding the difficulties in obtaining consistent performance from countermeasures that rely on living materials.

While many biotechnical bank-protection measures have been deployed and have survived for a number of years, there remained considerable skepticism within the engineering community regarding the performance of these measures when subjected to flood event magnitudes typical of hydraulic engineering design. The applicability of individual measures to varying stream hydraulic and site conditions, the long-term structural integrity of the measure, and the anticipated maintenance requirements are all critical elements that must be understood in order to support sound engineering decisions. In this regard, the research conducted under this study produced significant advances in the state of practice for the design, installation, monitoring, and maintenance of selected environmentally sensitive treatments. Insights were also gained on the relative benefits and potential risks of several widely used treatments.

Two environmentally sensitive treatments were subjected to detailed testing in a fully instrumented hydraulic flume at prototype scale. Results provided definitive quantitative hydraulic data, including velocity, velocity distribution, shear stress, roughness, and erosion for the following treatments: live siltation and live staking installed with a hard (riprap) toe and vegetated mechanically stabilized soil lifts with brush layering inserted between the lifts but without a hard toe. Resulting hydraulic data are applicable to these particular combinations of environmentally sensitive treatments or to the treatment components, alone. Observations and quantitative analysis of performance were documented in Chapter 3 and were included in the appraisal of results in Chapter 4.

Moreover, the laboratory testing tasks of this study provided proof of concept for an innovative approach to deriving detailed hydraulic data for environmentally sensitive treatments. For the first time, the vegetative components of selected stream bank treatments were installed following

Copyright National Academy of Sciences. All rights reserved.

recommended design criteria, including fabricating the structural component(s), planting the vegetative component(s) and growing them to maturity in a controlled greenhouse setting, and, finally, moving them to a flume for fully instrumented hydraulic testing at prototype scale under a range of flow conditions. As a result of this research, the facility and instrumentation requirements and the procedures necessary to install and test almost any environmentally sensitive bank-protection treatment were identified and testing protocols were established.

While field site investigations generally provide only a synoptic "snapshot" in time of a particular site's condition and may provide mainly anecdotal design and performance data, the site visit program of this study added valuable insights to the growing body of knowledge regarding the installation and performance of environmentally sensitive treatments. Site visits included 16 sites representing a variety of treatment types in three geographic regions (Southeast, upper Midwest, and West Coast). The detailed site visit form which was developed for this study provides a wealth of pertinent design and performance data and is provided as a model for evaluating existing treatment sites or in the reconnaissance and selection phase for sites being considered for environmentally sensitive treatments. For this study additional effort was applied to gathering design and monitoring information, reports and specifications, cost data, and photographic documentation for each site. Hydrologic and hydraulic data that supported design and influenced the level of functionality achieved was also obtained, where available. The resulting compilation of data for the 16 sites was assembled into a Compendium and presented in a searchable database format that will be useful to both the researcher and practitioner considering the investigation and/or utilization of environmentally sensitive treatments for stream bank protection.

The detailed, updated design guidance for three specific treatments, which was presented in Chapter 4, will be of immediate use to the practitioner. This design guidance includes the two treatments tested under this study (live siltation with live staking and a hard toe and VMSE without a hard toe) and an overview and update of guidance for a third widely used treatment, vegetated riprap. General hydrologic, hydraulic, and geomorphic considerations as well as site-specific physical processes that influence the design, installation, and monitoring of any environmentally sensitive treatment are included in this standalone presentation to support the design guidelines. The practitioner will also find two detailed case studies of the application of environmentally sensitive stream bank protection treatments employed in conjunction with stream channel restoration projects that supplement the guidelines. One example deals with the application of environmentally sensitive treatments on an arid region perennial river. The second example deals with a smaller stream in a humid region with significant infrastructure issues. The examples illustrate the integration of hydraulic engineering design with the multidisciplinary approach necessary to achieve project success.

In many cases, stream restoration or biotechnical engineering projects require the seal of a licensed PE. By affixing his or her seal to design documents and drawings the PE assumes the responsibility for the accuracy of the design and affirms that the work is within the engineer's area of expertise and was performed under his or her "responsible charge." While the seal does not "guarantee" the success of a project, it does attest that the design adheres to the "current state of practice" and was performed with a "reasonable standard of care." To support the engineer on a multidisciplinary design team and to acquaint the team with the implications of the engineer's seal, the guidelines include current guidance from FHWA on the use of biotechnical treatments in proximity to transportation infrastructure and discussion of aspects of professional liability in environmentally sensitive design.

As a result of this research, updated quantitative guidance and more detailed documentation and guidelines for design, installation, monitoring, and maintenance of environmentally sensitive stream bank protection measures are now available. The research produced practical, implementable guidance that will enhance the ability of bridge owners and other practitioners

Copyright National Academy of Sciences. All rights reserved.

to utilize environmentally sensitive treatments as an alternative to, or in conjunction with, more traditional "hard engineering" approaches.

5.1.2 Deliverables

As a result of this research, state DOTs now have documentation (photographs and case histories) and guidelines that include selection, design, installation, and maintenance requirements for environmentally sensitive stream bank protection measures including:

- A fully documented literature database related to biotechnical/environmentally sensitive treatments.
- A Compendium of photographs and case histories of existing projects in a searchable database format.
- Application examples illustrating the application of environmentally sensitive treatments for a range of hydrologic and geomorphic settings.
- Detailed standalone design guidelines to facilitate application of the guidance resulting from this study. The guidelines are presented in a format suitable for FHWA's HEC-23 and AASHTO guidance documents.
- A comprehensive final report.

5.2 Implementation Plan

5.2.1 The Product

As described in more detail in preceding sections, the product(s) of this research include guidelines for selection, design, installation, monitoring, and maintenance of environmentally sensitive stream bank protection measures.

5.2.2 The Market

The market or audience for the results of this research includes hydraulic engineers and maintenance and inspection personnel in state, federal, and local agencies with a transportation-related responsibility for selection, design, installation, and maintenance of countermeasures for stream instability at highway facilities, including the implementation of environmentally sensitive protection measures, where appropriate, to satisfy permitting, environmental, and sustainability objectives.

These would include:

- State Highway Agencies
- FHWA
- City/County Bridge Engineers
- National Association of County Engineers (NACE)
- Railroad Bridge Engineers
- USACE
- USFWS
- U.S. Bureau of Land Management
- National Park Service
- U.S. Forest Service
- National Marine Fisheries Service (NMFS)
- Bureau of Indian Affairs
- Any other governmental agency with highway facilities under their jurisdiction

Copyright National Academy of Sciences. All rights reserved.

- Consultants to the agencies above
- American Council of Engineering Companies (ACEC)

5.2.3 Impediments to Implementation

A serious impediment to successful implementation of results of this research will be difficulties involved in reaching a diverse audience scattered among numerous agencies and institutions; however, this can be countered by a well-planned technology transfer program. Because of the complexity and geographic scope of channel instability problems, a major challenge will be to present the results in a format that can be applied by agencies with varying levels of engineering design capabilities and maintenance resources. Presenting the guidelines and methods in a format familiar to bridge and highway owners, who are the target audience, will facilitate their use of the results of this research. Using FHWA's HEC-23 format, which has successfully reached a diverse audience, will help ensure successful implementation.

As with the results of any research, there may be segments of the target audience that may be reluctant to adopt or rely on new approaches. Highway engineers may consider the conditions in their state or region "unique." This concern is addressed by providing illustrative examples at geomorphically diverse sites.

5.2.4 Leadership in Application

FHWA. Because of its broad-based mission to provide guidance to the state highway agencies, the FHWA would ideally take a leading role in disseminating the results of this research. Through the National Highway Institute and its training courses, FHWA has the programs in place to reach a diverse and decentralized target audience.

TRB. The Transportation Research Board through its annual meetings and committee activities, and publications such as the *Transportation Research Record: Journal of the Transportation Research Board*, as well as periodic international bridge conferences can also play a leading role in disseminating the results of this research to the target audience. TRB could also host a webinar sponsored by interested TRB committees or even the Executive Committee for Design and Construction. This would be an excellent forum to roll out the results of this study.

AASHTO. AASHTO is the developer and sanctioning agency for standards, methods, and specifications. Thus, it will be important that the research results be formally adopted through the AASHTO process. The AASHTO Standing Committee on the Environment (SCOE) could also utilize the results of this research. As a collective representation of individual state DOTs, AASHTO can also suggest any needed training to be developed by FHWA or others. The AASHTO Task Committee on Hydrology and Hydraulics could provide centralized leadership through the involvement of all state DOT bridge engineers.

Regional Bridge Conferences. Regional bridge conferences, such as the Western Bridge Engineer Conference or the International Bridge Engineering Conferences, reach a wide audience of bridge engineers, manufacturers, consultants, and contractors. The groups would have an obvious interest in environmentally sensitive stream bank protection measures and their acceptance of the results of this research will be key to implementation by bridge owners.

5.2.5 Activities for Implementation

The activities necessary for successful implementation of the results of this research relate to technology transfer activities, as discussed above, and the activities of appropriate AASHTO committees.

Copyright National Academy of Sciences. All rights reserved.

196 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

5.2.6 Criteria for Success

The best criteria for judging the success of this implementation plan will be acceptance and use of the guidelines and recommendations that result from this research by state highway agency engineers and others with responsibility for design, maintenance, rehabilitation, or inspection of highway facilities. Progress can be gaged by peer reviews of technical presentations and publications and by the reaction of state DOT personnel to updated FHWA guidance documents and NHI training courses.

The desirable consequences of this project, when implemented, will be more efficient planning, design, maintenance, and inspection of highway facilities considering the range of both traditional engineering techniques and environmentally sensitive techniques available to address problems related to stream bank instability at highway facilities. The ultimate result will be a reduction in damage to highway facilities attributable to stream instability and reduced long-term costs and environmental/ecological impacts of countermeasure installations.

5.3 Applicability of Results to Highway Practice

Approximately 82 percent of the 600,000 bridges in the National Bridge Inventory (NBI) are built over waterways. Many, especially those on more active streams, will experience problems with scour, bank erosion, and channel instability during their useful life (Lagasse et al. 2012). The magnitude of these problems is demonstrated by the estimated average annual flood damage repair costs of approximately $50 million for bridges on the Federal-Aid system.

Highway bridge failures caused by scour and stream instability account for most of the bridge failures in this country. A 1973 study for the FHWA (Chang 1973) indicated that about $75 million were expended annually up to 1973 to repair roads and bridges that were damaged by floods. Extrapolating the cost to the present makes this annual expenditure to roads and bridges on the order of $300 to $500 million. This cost does not include the additional indirect costs to highway users for fuel and operating costs resulting from temporary closure and detours and to the public for costs associated with higher tariffs, freight rates, additional labor costs, and time. The indirect costs associated with a bridge failure have been estimated to exceed the direct cost of bridge repair by a factor of five (Rhodes and Trent 1993). Rhodes and Trent (1993) document that $1.2 billion was expended for the restoration of flood-damaged highway facilities during the 1980s.

Although it is difficult to be precise regarding the actual cost to repair damage to the nation's highway system from problems related to stream instability, scour, and erosion the number is obviously very large. The guidelines and recommendations that resulted from this research provide guidance to bridge owners for design, installation, and life-cycle care of a range of environmentally sensitive countermeasure alternatives that provide effective, reliable, and predictable protection while reducing environmental and ecological impacts. The end result will be a more efficient use of highway resources and a reduction in costs associated with the impacts of stream instability on highway facilities.

5.4 Suggested Research

The findings of Chapter 2 and the interpretation and appraisal of testing results in Chapter 3 are reflected in the design guidelines and supporting information in Chapter 4 of this final report. Updated and enhanced guidance for the design, installation, and monitoring of environmentally sensitive stream bank protection measures were developed under NCHRP Project 24-39. Laboratory testing of two environmentally sensitive treatment configurations contributed materially to the quantitative hydraulic engineering guidance available for the design and

Copyright National Academy of Sciences. All rights reserved.

performance of these two treatments and their vegetative components. Compilation of data, documentation, observations, and lessons learned from the site visit program added to the growing body of knowledge on design, installation, and performance for these techniques (see, for example, Goldsmith et al. 2014). Additional research to extend the results of this study could support wider application of environmentally sensitive techniques. The following suggested topics would extend the results of this study.

- The laboratory testing tasks of this study identified the facility and instrumentation requirements and developed testing procedures and protocols for obtaining treatment-specific hydraulic engineering design and performance data. Testing to determine the hydraulic response of additional commonly used environmentally sensitive techniques is warranted. These would include (in order of priority based on reported use by practitioners):
  - **Vegetated riprap**. Generally good performance was reported for this technique. Slope erosion and drought were the most commonly reported causes of substandard behavior. Laboratory testing of the effects of root structure on rock sizing and improved techniques for installing vegetation without disrupting the function of the filter is warranted. Testing of the relative effectiveness and hydraulic response of the methods commonly used to install this treatment (see Section 4.3.3) could contribute to the wider use of this biotechnical technique.
  - **Live fascines**. This treatment consists of bundles of branch cuttings placed in long rows in shallow trenches across a stream bank slope on contour or at an angle. Fascines are intended to grow vegetatively while the terraces formed will trap sediment and detritus, promoting further vegetative establishment. Common reasons for failure include toe erosion and/or flanking. The appropriate spacing between the fascines on a slope, appropriate toe protection, and the performance of fascines relative to coir rolls and straw wattles could be investigated.
  - **Coconut fiber rolls**. Coconut fiber rolls are manufactured, elongated cylindrical structures that are placed at the bottom of stream banks to help prevent scour and erosion. The coconut husk fibers (coir) are generally bound together with a geotextile netting. Common reasons for failure include excessive shear stress leading to scour and undermining, inadequate anchoring conditions, and poor vegetative establishment. Some permissible velocity and shear stress data are available (see McCullah and Gray 2005), but data on optimum configurations and anchoring could improve performance.
  - **TRM**. TRMs are similar to ECBs but are more permanent, designed to resist shear and tractive forces. TRMs are a biotechnical technique intended to work with vegetation (roots and shoots) in a mutually reinforcing manner. While maximum flow velocity for unvegetated TRM has been shown to reach 8 ft/s, data for permissible velocity and shear for mat/vegetation combinations is not currently available (McCullah and Gray 2005).
  - **Customized techniques**. The laboratory testing approach developed and validated under this study could contribute to the design of new/innovative biotechnical designs or customized combinations of various techniques and configurations. Combinations of hard and soft biotechnical components and a variety of vegetation types for high-value, high-risk projects could be tested and optimized with the resulting treatment-specific hydraulic data.
- For NCHRP Project 24-39 both 1-dimensional and 3-dimensional velocity data were acquired for all test runs. Budget constraints limited the analysis of hydraulic data to only the 1-D velocity data. During each flow, 1-D point velocity measurements were taken at each transect at 20%, 60%, and 80% of the total flow depth, and also as close to the bed as possible. During each flow, 3-D acoustic Doppler velocimeter measurements were taken at selected locations where the probe could be positioned within the submerged willow vegetation. This 3-D acoustic Doppler velocimeter data are available for additional analysis and development of appropriate conclusions. However, in acquiring this data some difficulties were encountered,

Copyright National Academy of Sciences. All rights reserved.

particularly in proximity to vegetation clusters. The 3-D measurements were scattered in time and space, and near-bed measurements may be suspect.

- Environmentally sensitive stream bank protection measures are clearly viable on perennial streams of the arid Southwest such as the Rio Grande (see Section 4.4.2). However, additional effort could be allocated to the unique aspects of applying these techniques to ephemeral streams of the arid Southwest. A logical starting point would be publications and guidance from the USDA Plant Materials Centers in this geophysical region, including the Los Lunas Plant Materials Center in New Mexico and the Tucson Plant Materials Center in Arizona. For example, the Los Lunas Center notes that in areas served (the semi-arid and arid Southwest region) environmental conditions in the region, including low precipitation, high-intensity rainfall, wind, extreme topography, and varied land uses, combine to produce a variety of problems needing plant material solutions. Among the Center's major conservation goals are erosion and sediment control and riparian restoration. Similarly, the Tucson Center mission statement includes current conservation needs such as erosion, drought, water quality, wildlife habitat, and wildfire damage. The Center develops and evaluates adapted plant materials and technologies to serve the needs of its service area.

Copyright National Academy of Sciences. All rights reserved.

References

Aberle, J. and Järvelä, J., 2013. Flow Resistance of Emergent Rigid and Flexible Floodplain Vegetation, *Journal of Hydraulic Research* Vol. 51, Issue 1, pp. 33–45.

Adhikari, A. R., Gautam, M. R., Yu, Z., Imada, S., and Acharya, K., 2013. Estimation of root cohesion for desert shrub species in the Lower Colorado riparian ecosystem and its potential for stream bank stabilization, *Ecological Engineering*, Vol. 51, pp. 33–44.

Admiraal, D. M., Schemper, T., and Strahm, B., 2007. Stream Bank Stabilization Using Traditional and Bioengineering Methods: A Literature Review, Nebraska Department of Roads, NDOR Research Project No. SPR-1(2) P549, 93 p.

Allen, H. H. and Leech, J. R., 1997. Bioengineering for Stream Bank Erosion Control: Report 1, Guidelines, U.S. Army Engineers Waterways Experiment Station, Environmental Impact Research Program, Technical Report EL-97-8, 103 p.

Allen, H. H. and Fischenich, C., 2000. Coir Geotextile and Wetland Plants for Stream Bank Erosion Control, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-04), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 8 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr04.pdf

Allen, H. H. and Fischenich, C., 2001. Brush Mattresses for Stream Bank Erosion Control, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-23), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 9 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr23.pdf

Anstead, L. and Boar, R. R., 2010. Willow Spilling: Review of Stream Bank Stabilization Projects in the UK, *Freshwater Reviews*, Vol. 3, No. 1, pp. 33–47.

Anstead, L. Boar, R. R., and Tovey, N. K., 2012. The effectiveness of a soil bioengineering solution for river bank stabilization during flood and drought conditions: two case studies from East Anglia, *Area*, Volume 44, Issue 4, pp. 479–488.

Arlinghaus, D. E. and Arlinghaus, S. L., 2012. Geosocial Networking: A Case from Ann Arbor, Michigan, *Solstice: An Electronic Journal of Geography and Mathematics*, 23(1), http://deepblue.lib.umich.edu/handle/2027.42/58219. (accessed April 14, 2015).

Arizona Department of Environmental Quality, 2005. Stream Bank Stabilization Management Measures, Arizona Department of Environmental Quality, Water Quality Division, Publication Number TM 05-05, 31 p.

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., and Clopper, P. E., 2012. Evaluating Scour at Bridges, Fifth Edition, Report FHWA-HIF-12-003, *Hydraulic Engineering Circular No. 18*, Federal Highway Administration, Washington, D.C.

ASCE, 2008. Sedimentation Engineering: Processes, Measurements, Modeling, and Practice, *ASCE Manuals and Reports on Engineering Practice No. 110* (M. H. García, ed.), Reston, VA.

ASCE Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment, 1998. River width adjustment I: processes and mechanisms, *Journal of Hydraulic Engineering*, 124(9), pp. 881–902.

ASTM International, 2003. Standard Practice for Brushmattressing, American Society for Testing and Materials (ASTM) International, Standard D 6939, 4 p. http://www.astm.org/Standards/D6939.htm

ASTM International, 2013. Standard Practice for Live Staking, American Society for Testing and Materials (ASTM) International, Standard D 6765-13, 3 p. http://www.astm.org/Standards/D6765.htm

ASTM International, 2014. Standard Practice for Construction of Live Fascines on Slopes, American Society for Testing and Materials (ASTM) International, Standard D 6599, 4 p. http://www.astm.org/Standards/D6599.htm

Austin, D. N. and Theisin, M. S., 1994. BMW Extends Vegetation Performance Limits, *Geotechnical Fabrics Report*, 12(3), 8.

Ayres Associates, 2003. *Design Letter Report, Supporting Final Design and Preparation of Construction Plans and Specifications for the GRFs, Bed Sill, and Associated Vegetation Planting, Rio Grande Riparian and Wetland Restoration, Section 1135 Project*, prepared For Pueblo of Santa Ana, New Mexico.

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Ayres Associates, 2006a. Middle Rio Grande Santa Ana Reach Geomorphology, Technical Appendix A, In: *Section 1135 Program, Detailed Project Report and Environmental Assessment for Aquatic Habitat Restoration at Santa Ana Pueblo, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

Ayres Associates, 2006b. *Operation, Maintenance, Repair, Replacement, and Rehabilitation (OMRR&R) Manual for GRF on the Rio Grande, Pueblo of Santa Ana Reservation, New Mexico*, prepared for U.S. Army Corps of Engineers Albuquerque District, Contract No. W912PP-04-C-0003.

Ayres Associates, 2012. *Geomorphic Assessment of the Rio Grande in the Vicinity of the RM 205.8 Nick Point Site*, Prepared for Pueblo of Santa Ana Reservation, New Mexico.

Bache, D. H. and Coppin, N. J., 1989. Vegetation in Civil Engineering Construction: Role and Uses, *Proceedings of the Institution of Civil Engineers*, pp. 247–249.

Baker, K., 2007. Ohio Stream Management Guide No. 10 – Biotechnical Projects in Ohio, Ohio Department of Natural Resources, Division of Soil & Water Resources, Columbus, OH, 4 p. (web page last updated 2/16/07)

Balch, P., 2008. *Instructions for Harvesting, Transporting, and Sorting Live Cuttings for Vegetating and Stabilizing Stream Banks*, Wildhorse Riverworks Inc., Topeka, KS, 7 p. http://wildhorseriverworks.com/publications/lci.pdf

Bankhead, N., Klimetz, L., and Simon, A., 2013. BSTEM-Dynamic User Manual, USDA Forest Service, Pacific Southwest Research Station, Davis, CA.

Barbour, M. T., Gerritsen, J., Snyder, B. D., and Stribling, J. B., 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, Second Edition, EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Barrett, K., Goldsmith, W., and Silva, M., 2006. Integrated bioengineering and geotechnical treatments for stream bank restoration and stabilization along a landfill, *Journal of Soil and Water Conservation*, Vol. 61, No. 3, pp. 144–152.

Bathurst, J. C., Thorne, C. R., and Hey, R. D., 1979, Secondary flow and shear stress at bends, American Society of Civil Engineers, *Journal of Hydraulics (HY10)*, Vol. 105, pp. 1277–1295.

Beasley, J. S., 2011. *Grass root architecture in overtopping simulation trays, tested at CSU and in Hurricane and Storm Damage Risk Reduction (HSDRRS) levees*, with the USACE New Orleans District, USACE Final Report.

Beasley, J. S., Strahan, R. E., and Bush, E. W., 2010. *Soil Capping for Grass Establishment on High-Saline Soils for Levee Embankments*, USACE Report W912P8-07-D-0040 Task 9 Final Report.

Beeson, C. E. and P. F. Doyle, 1995. Comparison of Bank Erosion at Vegetated and Non-vegetated Channel Bends. *Water Resources Bulletin - Journal of the American Water Resources Association.* Vol. 31, No. 6. December 1995. pp. 983–990.

Begin, Z. B., 1981. Stream Curvature and Bank Erosion: A Model Based on the Momentum Equation, *Journal of Geology*, Vol. 89, pp. 497–504.

Bentrup, G. and Hoag, J. C., 1998. *The Practical Stream Bank Bioengineering Guide: User's Guide for Natural Stream Bank Stabilization Techniques in the Arid and Semi-Arid Great Basin and Intermountain West*, Aberdeen (ID): USDA Natural Resources Conservation Service, Aberdeen Plant Materials Center, 67 p. http://www.plantmaterials.nrcs.usda.gov/pubs/idpmcpu116.pdf

Bergdorf, D. W., 2007. *Plant Species with Rooting Ability from Live Hardwood Materials for Use in Soil Bioengineering Techniques*, USDA Natural Resources Conservation Service, Plant Materials Center, Technical Note No. 1, 9 p.

Biedenharn, D. S., Elliott, C. M., and Watson, C. C., 1997. *The WES Stream Investigation and Stream Bank Stabilization Handbook*, U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. http://chl.erdc.usace.army.mil/Media/2/8/7/StreambankManual.pdf

Biedenharn, D. S., Thorne, C. R., Soar, P. J., Hey, R. D., and Watson, C. C., 2001. Effective discharge calculation guide, *International Journal of Sediment Research*, 16(4), 445–459.

Bischetti, G. B., Chiaradia, E. A., Agostino, V. D., Simonato, T., 2009. Quantifying the Effect of Brush Layering on Slope Stability, *Ecological Engineering*, Vol. 36, Issue 3, Elsevier, pp. 258–264. doi:10.1016/j.ecoleng.2009.03.019.

Bishop, J., Smith, K., Hoover, R., and Fulmer, M., 2007. Ohio Stream Management Guide No. 12 – Evergreen Revetments, Ohio Department of Natural Resources, Division of Soil & Water Resources, Columbus, OH, 8 p. (web page last updated 2/16/07)

Bledsoe, B. P., Carney, S. K., and Anderson, R. J., 2011. Scale-Dependent Effects of Bank Vegetation on Channel Processes: Field Data, Computational Dynamics Modeling, and Restoration Design, In *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, American Geophysical Union, Geophysical Monograph Series 194 (Simon, A., Bennett, S. J., and Castro, J. M., eds.), Washington, D.C., pp. 151–165.

Blomberg, J., Borgonovo, A., Bowles, C., Collison, A., and Liquori, M., 2006. Sustainable Creek and River Restoration Using Biotechnical Methods: Engineered Log Structures, *Ecesis*, *The Quarterly Newsletter of the California Society for Ecological Restoration* (SERCAL), Vol. 16, Issue 2, pp. 7–10.

Brewer, L. J., 2001. *Maturity and stability evaluation of composted yard debris*, Thesis in partial fulfillment of M.S. degree, Oregon State University, Corvallis, OR.

Copyright National Academy of Sciences. All rights reserved.

Brice, J. C., 1975. Air Photo Interpretation of the Form and Behavior of Alluvial Rivers, Final report to the U.S. Army Research Office, Washington, D.C.

Brice, 1982. Stream Channel Stability Assessment, Federal Highway Administration, Offices of Research and Development, Report No. FHWA/RD-82/021, Washington, D.C.

Brown, S. A., 1985. Stream Bank Stabilization Measures for Highway Stream Crossings-Executive Summary, FHWA/RD-84/099, Federal Highway Administration, Washington, D.C.

Brown, S. A., McQuivey, R. S., and Keefer, T. N., 1980. Stream Channel Degradation and Aggradation: Analysis of Impacts to Highway Crossings, FHWA/RD-80-159, Federal Highway Administration, Washington, D.C.

Brunet, G. and Shuey, R., 2005. Stream Bank Stabilization with Vegetated Gabions, *Land and Water Magazine*, Vol. 49, Issue 1, pp. 18–22.

Byars, M. and Renfro, J., 2012. Multi-Objective Stream Stabilization in Fort Branch Creek, *Land and Water Magazine*, Vol. 56, No. 5, pp. 15–20.

Caplan, T. R., Cothern, K., Landers, C., and Hummel, O. C., 2012. Growth Response of Coyote Willow (*Salix exigua*) Cuttings in Relation to Alluvial Soil Texture and Water Availability, *Restoration Ecology* (published online 16 October 2012).

Carson, M. A. and Kirkby, M. J., 1972. Hillslope Form and Process, Cambridge University Press, Cambridge.

Chang, F. F. M., 1973. A Statistical Summary of the Cause and Cost of Bridge Failures, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Chen, Y. H. and Cotton, G. K., 1988. Design of Roadside Channels with Flexible Linings, *Hydraulic Engineer Circular No. 15*, FHWA, Publication FHWA-IP:87-7, USDOT/FHWA, McLean, VA.

Chen, Z. Q. R., Kavvas, M. L., Bendeh, H., Tan, E., Carlon, J. T. G., and Lorenzato, S., 2009. *Study of the Roughness Characteristics of Native Plant Species in California Floodplain Wetlanes*, Report to the Department of Water Resources, UC Davis, *J. Amorocho Hydraulics Laboratory*, University of California, Davis.

Cooperman, M. S., Hinch, S. G., Bennett, S., Branton, M. A., Galbraith, R. V., Quigley, J. T., and Heise, B. A., 2007. Stream Bank Restoration Effectiveness: Lessons Learned from a Comparative Study, *Fisheries*, Vol. 32, Issue 6, pp. 278–291.

Copeland, R. R., McComas, D. N., Thorne, C. R., Soar, P. J., Jonas, M. M., and Fripp, J. B., 2001. Hydraulic Design of Stream Restoration Projects, Technical Report ERDC/CHL TR-01-28, U.S. Army Corps of Engineers: Engineer Research and Development Center; Vicksburg, MS.

Coppin, N. J. and Richards, I., 1990. *Use of Vegetation in Civil Engineering*, Butterworths: Sevenoaks, Kent (England).

Cramer, M., Bates, K., Miller, D., Boyd, K., Fotherby, L., Skidmore, P., and Hoitsma, T., 2003. Integrated Stream Bank Protection Guidelines, Washington State Departments of Ecology, Fish and Wildlife, and Transportation, Washington State Aquatic Habitat Guidelines Program, Olympia, WA. http://wdfw.wa.gov/publications/00046/wdfw00046.pdf

Crawford, C. S., Cully, A. C., Leutheuser, R., Sifeuntes, M. S., White, L. H., and Wilbur, J. P., 1993. *Middle Rio Grande Ecosystem: Bosque Biological Management Plan*, U.S. Fish and Wildlife Service, Albuquerque, NM, 291 pp.

Czarnomski, N. M., 2010. Influence of Vegetation on Stream Bank Hydraulics, PhD Dissertation, Oregon State University, 114 p.

Czarnomski, N. M., Tullos, D. D., Thomas, R. E., and Simon, A., 2012. Effects of Vegetation Canopy Density and Bank Angle on Near-Bank Patterns of Turbulence and Reynolds Stresses, *ASCE Journal of Hydraulic Engineering*, Vol. 138, No. 11, pp. 974–978.

Dardeau, E. A., Kilgore, K. J., Jr., and Miller, A. C., 1995. Using Riprap to Create or Improve Riverine Habitat, In *River, Coastal, and Shoreline Protection: Erosion Control Using Riprap and Armourstone* (C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord, and K. W. Pilarczyk, eds.), John Wiley & Sons, New York, pp. 609–620.

Darris, D. C., 2006. *Suggestions for Installing Hardwood Cuttings (Slips, Whips, Live Stakes, Poles, Posts) and Live Fascines (Pacific Northwest Region, West of Cascades)*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 15, 8 p.

Davis, J. C. and Davis, G. A., 2005. *The Inventory and Assessment of Stream Bank Restoration Projects Within the Matanuska-Susitna Borough, Alaska*, U.S. Fish and Wildlife Service, Partners for Fish and Wildlife Program Final Report, Talkeetna, AK.

Davis, J. C. and Davis, G. A., 2007. *Stream Bank Restoration Evaluation – 2007*, Aquatic Restoration & Research Institute, Talkeetna, AK, 40 p.

Denver Urban Drainage and Flood Control District, 2001(a). Chapter 12 – Revegetation, *Drainage Criteria Manual* (Vol. 2), Urban Drainage and Flood Control District, Denver, CO.

Denver Urban Drainage and Flood Control District, 2001(b). Chapter 13 Design Examples - Part 3 (Case Study – Willow Creek), *Drainage Criteria Manual* (Vol. 2), Urban Drainage and Flood Control District, Denver, CO.

Denver Urban Drainage and Flood Control District, 2001(c). Chapter 13 Design Examples - Part 5 (Case Study – Sand Creek), *Drainage Criteria Manual* (Vol. 2), Urban Drainage and Flood Control District, Denver, CO.

Dietrich, W. E. and J. D. Smith, 1983. Influence of the point bar on flow through curved channels, *Water Resources Research*, Vol. 19, pp. 1173–1192.

Copyright National Academy of Sciences. All rights reserved.

Dietrich, W. E., 1987. Mechanics of flow and sediment transport in river bends, In *River Channels: Environment and Process* (K. S. Richards, ed.), Blackwell, Oxford, pp. 179–227.

Donat, M., 1995. *Bioengineering Techniques for Stream Bank Restoration: A Review of Central European Practices*, Province of British Columbia, Ministry of Environment, Lands and Parks and Ministry of Forests, Watershed Restoration Project Report No. 2, 86 p.

Doyle, M. W. and Shields, F. D., Jr., 2012. Compensatory Mitigation for Streams under the Clean Water Act: Reassessing Science and Redirecting Policy, *Journal of the American Water Resources Association*, Vol. 48, Issue 3, pp. 494–509.

Einstein, H. A. and H. W. Shen, 1964. A study of meandering in straight alluvial channels, *Journal of Geophysical Research*, Vol. 69, pp. 5239–5247.

Erosion Control Technology Council (ECTC), 2001. Recommendations on proposed FHWA FP03 Specification.

Ervin, M., 2007. *Ohio Stream Management Guide No. 14 - Live Fascines*, Ohio Department of Natural Resources, Division of Soil & Water Resources, Columbus, OH, 4 p. (web page last updated 2/16/07).

Ervin, M. and Fulmer, M., 2007. *Ohio Stream Management Guide No. 17 - Live Crib Walls*, Ohio Department of Natural Resources, Division of Soil & Water Resources, Columbus, OH.

Eubanks, C. E. and Meadows, D., 2002. *A Soil Bioengineering Guide for Stream Bank and Lakeshore Stabilization*, USDA Forest Service, Technology and Development Program, FS-683, 187 p.

Everaert, G., Pauwels, I. S., Boets, P., Verduin, E., de la Haye, M. A. A., Blom, C., and Goethals, L. M., 2012. Model-based evaluation of ecological bank design and management in the scope of the European Water Framework Directive, *Ecological Engineering*, Vol. 53, pp. 144–152.

Evette, A., Balique, C., Lavaine, C., Rey, F., and Prunier, P., 2012. Using Ecological and Biogeographical Features to Produce a Typology of the Plant Species Used in Bioengineering for Riverbank Protection in Europe, *River Research and Applications*, Vol. 28, Issue 10, pp. 1830–1842.

Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., and Girel, J., 2009. History of Bioengineering Techniques for Erosion Control in Rivers in Western Europe, *Environmental Management*, Vol. 43, Issue 6, pp. 972–984.

Faustini, J. M., Kaufmann, R., and Herlihy, T., 2009. Downstream Variation in Bankfull Width of Wadeable Streams Across the Conterminous United States, *Geomorphology*, Vol. 108, Elsevier, pp. 292–311.

Federal Emergency Management Agency (FEMA), 2011. *Engineering with Nature – Alternative Techniques to Riprap Bank Stabilization*, U.S. Department of Homeland Security, Federal Emergency Management Agency, Washington, D.C., 34 p. http://www.fema.gov/pdf/about/regions/regionx/Engineering_With_Nature_Web.pdf

Federal Highway Administration, 1994a. *Advanced Technology for Soil Slope Stability*, Volume 1, Slope Stability Manual, FHWA-SA-94-005, U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration, 1994b. *Advanced Technology for Soil Slope Stability*, Volume 2, Sample Problems and Case Histories, FHWA-SA-94-006, U.S. Department of Transportation, Washington, D.C.

Fenneman, N. M. and Johnson, D. W., 1946. Physiographic divisions of the counterminous U.S. Geospacial_Data_Presenation_Form: map, U.S. Geological Survey, Reston, VA, available at http://water,usgs.gov/lookup/getspatial?physio.

Ferrari, R. L., 1988. *1986 Lake Powell Survey*, U.S. Bureau of Reclamation Report REC-ERC-88-6, Denver, CO.

FISRWG, 2001. Stream Corridor Restoration: Principles, Processes, and Practices, adopted as *Part 653 of the National Engineering Handbook*, USDA Natural Resources Conservation Service (published October 1998, revised August 2001). http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/?&cid=stelprdb1043244

Fischenich, C., 2000a. *Irrigation Systems for Establishing Riparian Vegetation*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-12), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 6 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr12.pdf

Fischenich, C., 2000b. *Resistance Due to Vegetation*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-07), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 9 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr07.pdf

Fischenich, C., 2001a. *Plant Material Selection and Acquisition*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-33), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 11 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr33.pdf

Fischenich, C., 2001b. *Stability Thresholds for Stream Restoration Materials*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 10 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr29.pdf

Fischenich, J. C. and Allen, H., 2000. *Stream Management*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS, ERDC/EL SR-W-00-1. http://el.erdc.usace.army.mil/elpubs/pdf/srw00-1/srw00-1.pdf

Fischenich, C., and Dudley, S., 2000. *Determining Drag Coefficients and Area for Vegetation*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-08), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 14 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr08.pdf

Copyright National Academy of Sciences. All rights reserved.

Fischer, R. A., 2004. *Using Soil Amendments to Improve Riparian Plant Survival in Arid and Semi-arid Landscapes*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-44), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 5 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr44.pdf

Flikweert, J., Thornton, C., Beasley, J., Kluskens, R. and Hughes, S. A., 2013. Resiliency Against Overtopping – Determining the Need for Armouring on the Levees of New Orleans, In *ICE Breakwater Conf. Proceedings.*

Fongers, D., Manning, K. and Rathbun, J., 2007. *Application of the Richards' Baker Flashiness Index to Gaged Michigan Rivers and Streams*, Michigan Department of Environmental Quality, Lansing, MI.

Forienth, F., 1982. *Begrünungen von Erosionszonen im Bereich über der Waldgrenze*, Zeitschrift für Vegetationstechnik 5, S. 20–24 (In German).

Freeman, G. E., Rahmeyer, W. H., and Copeland, R. R., 2000. *Determination of Resistance Due to Shrubs and Woody Vegetation*, ERDC/CHL TR-00-25, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 62 pp.

Freeman, G., Rahmeyer, W., and Copeland, R., 2004. Development and Application of Methodology for Determination of Hydraulic Roughness for Vegetated Floodplains, *ASCE Proceedings of the Hydraulic Measurements and Experimental Methods Conference*, Reston, VA.

Frothingham, K. M., 2008. Evaluation of stability threshold analysis as a cursory method of screening potential stream bank stabilization techniques, *Applied Geography*, Vol. 28, pp. 124–133.

Gellis, A., Hereford, R., Schumm, S. A., and Hayes, B. R., 1991. Channel evolution and hydrologic variations in the Colorado River basin: Factors influencing sediment and salt loads, *Journal of Hydrology*, Vol. 124, p. 317–344.

Georgia Department of Natural Resources, 2007. *Stream Bank and Shoreline Stabilization Guidance*, Georgia Department of Natural Resources, Environmental Protection Division, Watershed Protection Branch, Atlanta, GA, 10 p.

Georgia Department of Natural Resources, 2011. *Stream Bank and Shoreline Stabilization – Techniques to Control Erosion and Protect Property*, Georgia Department of Natural Resources, Environmental Protection Division, Watershed Protection Branch, Atlanta, GA, 23 p.

Gerstgraser, C., 1998. Bioengineering Methods of Bank Stabilization, *Garten & Landschaft*, Vol. 9, 35–37.

Gerstgraser, C., 1999. The Effect and Resistance of Soil Bioengineering Methods for Stream Bank Protection, *Proceedings of Conference 30, International Erosion Control Association (IECA)*, Nashville TN.

Glath, G., Radsyminski, S. R., Lohse, R., and Freehart, W., 2003. NYSDOT Soil Bioengineering and Biotechnical Engineering Design Guidance and Specifications, *Proceedings of the International Conference on Ecology and Transportation*, August 24–29, 2003, Lake Placid, NY.

Goldsmith, W., Gray, D. H., and McCullah, J., 2014. *Bioengineering Case Studies: Sustainable Stream Bank and Slope Stabilization*, Springer Verlag, New York.

Goldsmith, W., Silva, M., and Fischenich, C., 2001. *Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-26), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 9 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr26.pdf

Grassel, K., 2002. *Taking Out the Jacks – Issues of Jetty Jack Removal in the Bosque and River Restoration Planning*, Water Resources Program, University of New Mexico, Publication No. WRP-6, 46 pp.

Gray, D. H., 2003. Optimizing Soil Compaction and Other Strategies, Balancing Engineering Requirements and Plant-Growth Needs in Slope Protection and Erosion Control Work, *Erosion Control*, Vol. 9, No. 5, September/October.

Gray, D. H. and Barker, D., 2004. Root-Soil Mechanics and Interactions, In *Riparian Vegetation and Fluvial Geomorphology* (Bennett, S. J., and Simon, A., eds.), American Geophysical Union, Water Science and Application 8, Washington, D.C., pp. 113–124.

Gray, D. H. and Leiser, A. T., 1982. *Biotechnical Slope Protection and Erosion Control*, Van Nostrand Reinhold Company Inc., New York, NY, 271 p.

Gray, D. H. and Sotir, R., 1992. Biotechnical stabilization of a highway cut, *Journal of Geotechnical Engineering* (ASCE), Vol. 118, No. GT10.

Gray, D. H. and Sotir, R. B., 1996. *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*, John Wiley & Sons Inc., New York, NY, 378 p.

Greer, E., Pezeshki, S. R., and Shields, F. D., Jr., 2006a. Root Elongation of Black Willow Stakes in Response to Cutting Size and Soil Moisture Regime, *Ecological Restoration*, Vol. 24, pp. 195–197.

Greer, E., Pezeshki, S. R., and Shields, F. D., Jr., 2006b. Influence of Cutting Diameter and Soil Moisture on Growth and Survival of Black Willow (*Salix nigra*), *Journal of Soil and Water Conservation*, Vol. 61, pp. 311–323.

Gu, L., Gao, J., Liu, Y., Wang, Y., and Qian, B., 2012. Experimental research for riverbank restoration by using soil bioengineering, *International Journal of Forest, Soil and Erosion*, Vol. 2, No. 3, pp. 155–157.

Guilfoyle, M. P. and Fischer, R. A., 2006. *Techniques for monitoring success of riparian restoration efforts in arid and semi-arid landscapes.* EMRRP Technical Notes Collection. ERDC TNEMRRP-SR-50. Vicksburg, MS:

Copyright National Academy of Sciences. All rights reserved.

U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/elpubs/pdf/sr50.pdf accessed 17 June 2014.

Gyssels, G., Poesen, J., Bochet, E., and Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review, *Progress in Physical Geography*, Vol. 29, No. 2, pp. 189–217.

Hagen, S., Salisbury, S., Wierenga, M., Xu, G., and Lewis, L., 2002. Soil Bioengineering as an Alternative for Roadside Management: Benefit-Cost Analysis Case Study, *Transportation Research Record: Journal of the Transportation Research Board, No. 1794*, Transportation Research Board of the National Academies, Washington, D.C., pp. 97–104.

Harvey, M. D. and Watson, C. C., 1986. Fluvial processes and morphological thresholds in incised channel restoration, *Water Resources Bulletin*, 22(3), 359–368.

Henderson, J. E., 1986. Environmental Designs for Stream Bank Protection Projects, *Water Resources Bulletin*, 22(4), 549–558.

Henderson, J. E. and Shields, F. D., Jr., 1984. *Environmental Features for Bank Protection Projects*, Technical Report E-84-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 150 pp.

Hicken, E. J. and Nanson, G. C., 1975. The Character of Channel Migration on the Beaton River, Northeast British Columbia, Canada, *Geological Society of America Bulletin*, Vol. 86, pp. 487–494.

Hickin, E. J. and. Nanson, G. C., 1984. Lateral Migration Rates of River Bends, *Journal of Hydraulic Engineering*, Vol. 110, American Society of Civil Engineers, pp. 1557–1567.

Hooke, J. M., 1977. The Distribution and Nature of Changes in River Channel Patterns: The Example of Devon, In *River Channel Changes* (K. J. Gregory ed.), John Wiley & Sons, Chichester, U.K., p. 265–280.

Hoag, J. C., 2007. *How to Plant Willows and Cottonwoods for Riparian Restoration*, USDA Natural Resources Conservation Service, Plant Materials Center, Technical Note No. 23 (revision), 22 p.

Hoag, J. C., 2009a. *Cluster plantings: a way to plant live unrooted cuttings in coarse soils including sands, gravels, and cobbles*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 26, 8 p.

Hoag, J. C., 2009b. *Vertical bundles: a stream bank bioengineering treatment to establish willows and dogwoods on stream banks*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 53, 6 p.

Hoag, J. C., Berg, F. E., Wyman, S. K., and Sampson, R. W., 2001. *Riparian planting zones in the intermountain west*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 16 (revised), 24 p.

Hoag, J. C. and Fripp, J., 2002. *Stream bank soil bioengineering field guide for low precipitation areas*, USDA Natural Resources Conservation Service, Plant Materials Center, Aberdeen, ID, 66 p.

Hoag, J. C. and Fripp, J., 2005. *Stream bank soil bioengineering considerations for semi-arid climates*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 18, 15 p.

Hoag, J. C. and Ogle, D., 2011 (revised). *The Stinger: A Tool to Plant Unrooted Hardwood Cuttings*, USDA Natural Resources Conservation Service, Plant Materials Center, Technical Note No. 6, 10 p.

Hoag, J. C. and Sampson, R. W., 2007. *Planting Willow and Cottonwood Poles Under Rock Riprap*, USDA Natural Resources Conservation Service, Plant Materials Center, Technical Note No. 21, 5 p.

Hoag, J. C., Simonson, B., Cornforth, B., and St. John, L., 2001. *Waterjet Stinge: A Tool to Plant Dormant Unrooted Cuttings of Willow, Cottonwood, Dogwood, and Other Species*, USDA Natural Resources Conservation Service, Plant Materials Center, Technical Note No. 39, 24 p.

Holanda, F. S. R. and da Rocha, I. P., 2011. Stream Bank Soil Bioengineering Approach to Erosion Control, In *Progress in Molecular and Environmental Bioengineering - From Analysis and Modeling to Technology Applications* (Carpi, A. ed.), InTech Europe, Rijeka, Croatia, pp. 553–576.

Hunolt, A. E., 2012. *Survival and Growth of Black Willow (Salix nigra), Silky Willow (Salix sericea), Silky Dogwood (Cornus amomum), and Virginia Sweetspire (Itea virginica) Live Stakes*, MS Thesis, Auburn University, Auburn, AL, 57 p.

Hunolt, A. E., Brantley, E. F., Howe, J. A., Wright, A. N., and Wood, C. W., 2013. Comparison of native woody species for use as live stakes in stream bank stabilization in the southeastern United States, *Journal of Soil and Water Conservation*, Vol. 68, No. 5, pp. 384–391.

Iowa Department of Natural Resources, 2006. *How to Control Stream Bank Erosion*, Iowa Department of Natural Resources, 48 p. http://www.iowadnr.gov/portals/idnr/uploads/water/stormwater/streambankmanual.pdf

Jahra, F., Kawahara, Y., Hasegawa, F., and Yamamoto, H., 2011. Flow – vegetation interaction in a compound open channel with emergent vegetation, *International Journal of River Basin Management*, Vol. 9, Nos. 3–4, pp. 247–256.

Järvelä, J., 2006. Vegetative flow resistance: characterization of woody plants for modeling applications, In *Proceedings of the 2006 World Environmental and Water Resources Congress: Examining the Confluence of Environmental and Water Concerns* (Graham, R. ed.), Omaha, NE, May 21–25, 2006, 10 p.

Copyright National Academy of Sciences. All rights reserved.

Johnson, A. W. and Stypula, J. M., 1993. *Guidelines for Bank Stabilization Projects in the Riverine Environments of King County*, King County Department of Public Works, Surface Management Division, Seattle, WA.

Jones, C. J. and Johnson, P. A., 2015. Describing Damage to Stream Modification Projects in Constrained Settings, *Journal of the American Water Resources Association*, 51(1): 251–262.

Julien, P., 1995. *Erosion and Sedimentation*, Cambridge University Press, NY.

Kancheva, R., Borisova, D., and Georgiev, G., 2014. Chlorophyll assessment and stress detection from vegetation optical properties, *Ecological Engineering and Environmental Protection*, 1, 34–43.

Karle, K. F., 2007. *The Effects of Winter Ice Jam Event on Bioengineered Bank Stabilization Along the Ketnai River*, Report prepared for Alaska Department of Transportation, Statewide Research Office, Juneau, AK, FHWA-AK-RD-07-03, 27 p.

Karle, K. F., Moore, N., and Emmett, W. W., 2003. *Evaluation of Bioengineered Stream Bank Stabilization in Alaska*, Alaska Department of Transportation, Juneau, AK, FHWA-AK-RD-03-03.

Kean, J. W. and Smith, J. D., 2004. Flow and Boundary Shear Stress in Channels with Woody Bank Vegetation, In *Riparian Vegetation and Fluvial Geomorphology* (Bennett, S. J. and Simon, A., eds.), American Geophysical Union, Water Science and Application 8, Washington, D.C., pp. 237–252.

Kilgore, R. T. and Cotton, G. K., 2005. *Design of Roadside Channels with Flexible Linings*, Federal Highway Administration, HEC-15, Third Edition, Publication No. FHWA-NHI-05-114, Washington, D.C.

Knighton, A. D., 1981. Local Variations of Cross-Sectional Form in a Small Gravel-Bed Stream, *Journal of Hydrology (New Zealand)*, Vol. 20, pp. 131–146.

Knighton, D., 1998. *Fluvial Forms and Processes – A New Perspective*, Arnold, London.

Kouwen, N., 1988. Field estimation of the biomechanical properties of grass, *Journal of Hydraulic Research*, 26(5), 559–568.

Kouwen, N., Li, R. M., and Simons, D. B., 1980. A Stability Criteria for Vegetated Waterways, *Proceedings of the International Symposium on Urban Storm Runoff*, University of Kentucky, Lexington, KY, pp. 203–210.

Krymer, V. and Robert, A., 2013. Stream Restoration and Cribwall Performance: A Case Study of Cribwall Monitoring in Southern Ontario, *River Research and Applications* (published online 21 June 2013).

Kush, D., 2007. *Ohio Stream Management Guide No. 07 – Restoring Stream Banks with Vegetation*, Ohio Department of Natural Resources, Division of Soil & Water Resources, Columbus, OH, 2 p. (web page last updated 2/16/07).

Lagasse, P. F., 1980. *An Assessment of the Response of the Rio Grande to Dam Construction, Cochiti to Isleta Reach,* a Technical Report by the Science Research Laboratory, U.S. Military Academy for the U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Lagasse, P. F., 1981. *Geomorphic Response of the Rio Grande to Dam Construction*, New Mexico Geological Society, Special Publication No. 10, pp. 27–46.

Lagasse, P. F., 1999. *NCHRP Research Results Digest 241: 1998 Scanning Review of European Practice for Bridge Scour and Stream Instability Countermeasures*, TRB, National Research Council, Washington, D.C.

Lagasse, P. F., Spitz, W. J., Zevenbergen, L. W., and Zachmann, D. W., 2004. *NCHRP Report 533: Handbook for Predicting Stream Meander Migration*, Transportation Research Board of the National Academies, Washington, D.C.

Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., and Ruff, J. F., 2006. *NCHRP Report 568: Riprap Design Criteria, Recommended Specifications, and Quality Control*, Transportation Research Board of the National Academies, Washington, D.C.

Lagasse, P. F., Zevenbergen, L. W., Spitz, W. J., and Arneson, L. A., 2012. Stream Stability at Highway Structures, *Hydraulic Engineering Circular No. 20*, Fourth Edition, HIF-FHWA-12-004, Federal Highway Administration, Washington, D.C.

Lagasse, P. F., Clopper, P. E., Pagan-Ortiz, J. E., Zevenbergen, L. W., Arneson, L. A., Schall, J. D., and Girard, L. G., 2009. Bridge Scour and Stream Instability Countermeasures - Experience, Selection, and Design Guidelines, *Hydraulic Engineering Circular No. 23*, Volumes 1 and 2, Third Edition, FHWA-NHI-09-112, Federal Highway Administration, Washington, D.C.

Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., Spitz, W. J., and Girard, L. G., 2010. *NCHRP Report 653: Effects of Debris on Bridge Pier Scour*, Transportation Research Board of the National Academies, Washington, D.C.

Landphair, H. C. and Li, M.-H., 2001. *Regional Applications for Biotechnical Methods of Stream Bank Stabilization in Texas: A literature Review*, Report 1836-3, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 46 p.

Landphair, H. C. and Li, M.-H., 2002. *Investigating the Applicability of Biotechnical Stream Bank Stabilization in Texas*, Report 1836-1, Texas Transportation Institute, The Texas A&M University System, College Station, TX, 174 p.

Lane, E. W., and Borland, W. M., 1953. River Bed Scour During Floods, *Transactions of the American Society of Civil Engineers*, Vol. 119, Paper No. 2712, pp. 1069–1080.

Lawson, R., Bouma, D., Olsson, K., Rubin, L., and Powell, E., 2008. *Watershed Management Plan for the Huron River in the Ann Arbor—Ypsilanti Metropolitan Area*, prepared on behalf of and with funding support

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

from Janis A. Bobrin, Washtenaw County Drain Commissioner, Huron River Watershed Council, Ann Arbor, MI.

Lawson, R. and Weiker, D., 2008. *Middle Huron Stream Nutrient Monitoring Program: Analysis of Results: 2002–2007*, Huron River Watershed Council, Ann Arbor, MI.

Leopold, L. B., Emmett, W. W., and Myrick, R. M., 1966. *Channel and Hillslope Processes in a Semi-arid Area, New Mexico*, U.S. Geological Survey Professional Paper 352-G, U.S. Geological Survey, Washington, D.C.

Lewis, L., 2000. *Soil Bioengineering: An Alternative for Roadside Management - A Practical Guide*, Technology & Development Program No. 0077-1801-SDTDC, USDA, Forest Service, San Dimas Technology & Development Center, San Dimas, CA, 43 p.

Li, S., Pezeshki, S. R. Goodwin, S. and Shields, F. D., Jr., 2004. Physiological Responses of Black Willow (*Salix nigra*) Cuttings to a Range of Soil Moisture Regime, *Photosynthetica*, Vol. 42, pp. 585–590.

Li, M.-H., 2006. Learning from stream bank failures at bridge crossings: A biotechnical stream bank stabilization project in warm regions, *Landscape and Urban Planning*, Vol. 77, pp. 343–358.

Li, M.-H. and Eddleman, K. E., 2002. Biotechnical engineering as an alternative to traditional engineering methods: biotechnical stream bank stabilization design approach, *Landscape and Urban Planning*, Vol. 60, pp. 225–242.

Li, M.-H., Landphair, H. C., Arnold, M. A., Mullin, K., and Eddleman, K. E., 2005. A dormancy extension technique for biotechnical stream bank stabilization in warm regions, *Landscape and Urban Planning*, Vol. 71, pp. 223–231.

Lipscomb, C. M., Thorton, C. I., Abt, S. R., and Leech, J., 2001. Performance of Articulated Concrete Blocks in Vegetated and Unvegetated Conditions, *Proceedings of Conference 32, International Erosion Control Association*, Las Vegas, NV.

Lister, D. B., Beniston, R. J., Kellerhals, R., and Miles, M., 1995. Rock Size Affects Juvenile Salmonid Use of Stream-Bank Riprap, In *River, Coastal, and Shoreline Protection: Erosion Control Using Riprap and Armourstone* (C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord, and K. W. Pilarczyk, eds.), John Wiley & Sons, New York, pp. 621–632.

Liu, Y., Gao, J. R., Lou, H. P., Zhang, J. R., and Rauch, H. P., 2010. "Characteristics of Four Plant Species Used for Soil Bioengineering Techniques in River Bank Stabilization," European Geosciences Union General Assembly 2010, Geophysical Research Abstracts, Vol. 12, EGU2010-7981-1.

Lohnes, R. and Handy, R. L., 1968. Slope Angles in Friable Loess, *Journal of Geology*, Vol. 76, pp. 247–258.

López, F. and García, M. H., 2001. Mean flow and turbulence structure of open-channel flow through non-emergent vegetation, *Journal of Hydraulic Engineering*, 127(5), 392–402.

Luna, T., Dumbrose, R. K., Landis, T. D., 2006. *Collecting Dormant Hardwood Cuttings for Western Riparian Restoration Projects*, USDA Forest Service, Missoula Technology and Development Program, Tech Tips 0624-2334-MTDC, 8 p.

Lutenegger, A. J., 1987. Suggested Method for Performing the Borehole Shear Test, *Geotechnical Testing Journal*, 10(1), ASTM, 19–25.

Mabey, M. A., 2009. *Monitoring of Bioengineering Stabilization Projects*, Final Report, SPR 353, Oregon Department of Transportation Research Section and Federal Highways Administration, FHWA-OR-RD-10-06, 71 p.

Maniaci, C. and Nolen, A., 2005. *Vegetated Riprap Survey of Highways in Southcentral and Interior Alaska*, Report prepared for Alaska Department of Transportation, Statewide Research Office, Juneau, AK, FHWA-AK-RD-05-08.

Manners, R. B., Schmidth, A., and Wheaton, J. M., 2013. Multiscalar Model for the Determination of Spatially Explicit Riparian Vegetation Roughness, *Journal of Geophysical Research: Earth Surface*, Vol. 118, pp. 1–19.

Markham, A. J. and Thorne, C. R., 1992. Geomorphology of Gravel-bed River Bends, In *Dynamics of Gravel-Bed Rivers* (P. Billi, R. D. Hey, C. R. Thorne, and P. Tacconi, eds.), John Wiley & Sons, Chichester, UK, pp. 433–450.

Martin, L. T., Pezeshki, S. R., and Shields, F. D., Jr., 2004. High Oxygen Level in a Soaking Treatment Improves Root and Shoot Development of Black Willow (*Salix nigra*) Cuttings, *The Scientific World Journal*, Vol. 4, pp. 899–907.

Maryland Department of the Environment, 2000. *Maryland Waterways Construction Guidelines* (revised), Maryland Department of the Environment, Water Management Administration, Baltimore, MD. http://www.mde.state.md.us/programs/Water/WetlandsandWaterways/DocumentsandInformation/Documents/www.mde.state.md.us/assets/document/WetlandsWaterways/mgwc.pdf

Maynord, S. T., 1990. Riprap Stability Results from Large Test Channel, *Hydraulic Engineering, Proceedings of the 1990 ASCE National Conference*, Vol. 1, Chang, H. H. and Hill, J. C., (eds.), San Diego, CA, July 30–August 3.

Maynord, S. T., 1994. Toe Scour Protection Methods, In *Hydraulic Engineering '94* (G. V. Controneo and R. R. Rumer, eds.), American Society of Civil Engineers, New York, NY 1025–1029.

Maynord, S. T., 1995. 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. Maynord, and K. W. Pilarczyk, eds.), John Wiley & Sons, Ltd., Chichester, U.K.

Copyright National Academy of Sciences. All rights reserved.

Maynord, S. T., 1996. Toe-Scour Estimation in Stabilized Bendways, *Journal of Hydraulic Engineering*, Vol. 122, No. 8, pp. 460–464.

Maynord, S. T., Ruff, J. F., and Abt, S. R., 1989. Riprap Design, *ASCE, Journal of Hydraulic Engineering*, Vol. 115, No. 7, pp. 937–939.

McBride, M., Hession, W. C., Rizzon, D. M., and Thompson, D. M., 2007. The influence of riparian vegetation on near-bank turbulence: a flume experiment, *Earth Surface Processes and Landforms*, Vol. 32, Issue 13, pp. 2019–2037.

McCuen, R. H., Johnson, P. A., and Ragan, R. M., 2002. *Hydrologic Design of Highways*, Hydraulic Design Series No. 2, Federal Highway Administration, Washington, D.C.

McCullah, J., 2006. *Environmentally-Sensitive Stream Bank Stabilization (E-SenSS)*, Course Manual, Salix Applied Earthcare, Redding, CA, 88 p.

McCullah, J., 2015. Environmentally Sensitive Stream Bank Stabilization Techniques: Geyserville Bridge and the Russian River - 5 Years Later, *Land and Water Magazine*, March/April 2015, Fort Dodge, IA.

McCullah, J. and Dettman, K., 2004. *Guadalupe River Restoration Project: Biotechnical Channel Stabilization Solutions*, Salix Applied Earthcare, Redding, CA.

McCullah, J. and Gray, D., 2005. *NCHRP Report 544: Environmentally Sensitive Channel- and Bank-Protection Measures*, Transportation Research Board of the National Academies, Washington, D.C., 50 p. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_544.pdf

Mckay, S. K. and Fischenich, J. C., 2011. *Robust Prediction of Hydraulic Roughness*, ERDC/CHL CHETN-VII-11, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Merritt, A., Burns, D. A., and Huff, H., 2010. Bioengineering and Reinforced Vegetation, *Erosion Control Magazine*, Vol. 17, No. 5, pp. 20–25.

Michigan Department of Environmental Quality (MDEQ), 1999. *Pollutants Controlled Calculation and Documentation for Section 319 Watershed Training Manual*, Lansing, MI.

Middle Huron Partners and Stormwater Advisory Group, 2012. *Total Suspended Solids Reduction Implementation Plan for Malletts Creek, October 2011 – September 2016, For the Purpose of Achieving the Total Maximum Daily Load (TMDL) and Removing the Biota Impairment of Malletts Creek*, Huron River Watershed Council, Ann Arbor, MI.

Millar, R. G. and Eaton, B. C., 2011. Bank Vegetation, Bank Strength, and Application of the University of British Columbia Regime Model to Stream Restoration, In *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools* (Simon, A., Bennett, S. J., and Castro, J. M., eds.), American Geophysical Union, Geophysical Monograph Series 194, Washington, D.C., pp. 475–485.

Miller, S. J., Fischenich, J. C., and Thornton, C. I., 2012. *Stability Thresholds and Performance Standards for Flexible Lining Materials in Channel and Slope Restoration Applications*, EBA Technical Notes Collection, ERDC TN-EMRRPEBA-13, Vicksburg, MS; U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Nanson, G. C. and Hickin, E. J., 1986. A statistical analysis of bank erosion and channel migration in western Canada, *Geological Society of America Bulletin*, Vol. 97, p. 497–504.

Neil, C. R., 1984. Bank erosion versus bedload transport in a gravel river, In *River Meandering* (C. M. Elliot, ed.), *Proceedings of the Conference Rivers '83*, American Society of Civil Engineers, New York, p. 204–211.

New Jersey Department of Agriculture, 2012. 2012 Revised Erosion Control Standards: 26, *Standard for Soil Bioengineering*, 18 p. http://www.nj.gov/agriculture/divisions/anr/pdf/26_Soil%20Bioengineering%202011.pdf

Niezgoda, S. L. and Johnson, P. A., 2012. Applying Risk-Benefit Analysis to Select an Appropriate Stream Bank Stabilization Measure, *Journal of Hydraulic Engineering*, Vol. 138, No. 5, pp. 449–461.

Nordin, C. F., and Beverage, J. P., 1965. *Sediment Transport in the Rio Grande, New Mexico*, USGS Professional Paper 462-F.

Norman, J. N., 1975. *Design of Stable Channels with Flexible Linings*, HEC-15, US DOT, Federal Highway Administration, Washington, D.C.

Norris, J. E. and Greenwood, J. R., 2006. Assessing the role of vegetation on soil slopes in urban areas, *Proceedings*, IAEG 2006.

NRCS, 1996. Chapter 16 - Stream Bank and Shoreline Protection, *Part 650 Engineering Field Handbook*, U.S. Department of Agriculture, Natural Resources Conservation Service, 210-vi-EFH (December 1996). http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17553.wba

NRCS, 2007a. *Stream Restoration Design*, *Part 654 - National Engineering Handbook*, USDA, Natural Resources Conservation Service, 210-VI-NEH (August 2007). http://directives.sc.egov.usda.gov/RollupViewer.aspx?hid=17092

NRCS, 2007b. Technical Supplement 14I – Stream Bank Soil Bioengineering, *Stream Restoration Design, Part 654 - National Engineering Handbook*, USDA, Natural Resources Conservation Service, 210-VI-NEH (August 2007). http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17818.wba

NRCS, 2007c. Technical Supplement 14J – Use of Large Woody Material for Habitat and Bank Protection, *Stream Restoration Design, Part 654 - National Engineering Handbook*, USDA, Natural Resources Conservation

Copyright National Academy of Sciences. All rights reserved.

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

Service, 210-VI-NEH (August 2007). http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17819.wba

NRCS, 2008. Erosion. Section 3, Sedimentation, *National Engineering Handbook Part 632, Sedimentation Geology.* US Department of Agriculture, Natural Resources Conservation Service, Washington, D.C., Accessed 17 June 2014. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=18375.wba

Nunnally, N. R. and Sotir, R. B., 1997. Criteria for Selection and Placement of Woody Vegetation in Stream Bank Protection, *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, University, MS, pp. 816–821.

Orchard, Hiltz, and McCliment, Inc., 2011. Malletts Creek Stream-Bank Stabilization Project, Washtenaw Water Resources Commissioner's Office, City of Ann Arbor, MI.

Oregon Department of Transportation, 2011. *Hydraulics Manual - Part 1*, Oregon Department of Transportation, Highway – Geo-Environmental Section, Salem, OR.

Ortiz, R. M., 2004. *A River In Transition: Geomorphic and Bed Sediment Response to Cochiti Dam on the Middle Rio Grande, Bernalillo to Albuquerque, New Mexico*, Master's Thesis, University of New Mexico, Albuquerque, NM.

Osman, A. M. and Thorne, C. R., 1988. Riverbank Stability Analysis I: Theory, *Journal of Hydraulic Engineering*, Vol. 114, No. 2, New York.

Parsons, D. A., 1963. *Vegetative Control of Streambank Erosion*, Federal Interagency Sedimentation Conference, USDA Misc. Publication 970:130–136, Washington, D.C.

Petrone, A. and Preti, F., 2008. Suitability of soil bioengineering techniques in Central America: a case study in Nicaragua, *Hydrology and Earth System Sciences*, Vol. 12, pp. 1241–1248.

Petryk, S. and Bosmajian, G., 1975. Analysis of flow through vegetation, *Journal of the Hydraulics Division*, 101(7), 871–884.

Pezeshki, S. R., Anderson, P. H., and Shields, F. D., Jr., 1998. Effects of soil moisture regimes on growth and survival of black willow (*Salix nigra*) posts (cuttings), *Wetlands*, 18(3), 460–470.

Pezeshki, S. R. and Shields, F. D., Jr., 2006. Black Willow Cutting Survival in Stream Bank Plantings, Southeastern United States, *Journal of American Water Resources Association*, Vol. 42, No. 1, pp. 191–200.

Pezeshki, S. R., Li, S. Shields, F. D., Jr., and Martin, L. T., 2007. Factors Governing Survival of Black Willow (*Salix nigra*) Cuttings in a Stream Bank Restoration Project, *Ecological Engineering*, Vol. 29, pp. 56–65.

Pezeshki, S. R., Brown, C. E., Elcan, J. M., and Shields, F. D., Jr., 2005. Responses of Nondormant Black Willow (*Salix nigra*) Cuttings to Preplanting Soaking and Soil Moisture, *Restoration Ecology*, Vol. 13, No. 1, pp. 1–7.

Pollen, N., 2007. Temporal and spatial variability in root reinforcement of stream banks: accounting for soil shear strength and moisture, *Catena*, Vol. 69, pp. 197–205.

Pollen, N. and Simon, A., 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, *Water Resources Research*, Vol. 41, Paper W07025, 11 p.

Pollen-Bankhead, N. and Simon, A., 2010. Hydrologic and hydraulic effects of riparian root networks on stream bank stability: Is mechanical root-reinforcement the whole story? *Geomorphology*, 116(3), 353–362.

Pollen-Bankhead, N., Simon, A., Jaeger, K., and Wohl, E., 2009. Destabilization of stream banks by removal of invasive species in Canyon de Chelly National Monument, Arizona, *Geomorphology*, 103, 363–374.

Pollen, N., Simon, A., and Collison, A., 2004. Advances in Assessing the Mechanical and Hydrologic Effects of Riparian Vegetation on Stream Bank Stability, In *Riparian Vegetation and Fluvial Geomorphology* (Bennett, S. J., and Simon, A., eds.), American Geophysical Union, Water Science and Application 8, Washington, D.C., pp. 125–139.

Rahmeyer, W. and Werth, D., 1996. *The Study of the Resistance and Stability of Vegetation Ecosystem Plant Groupings in Flood Control Channels Vol. 1* Reports. 148 p.

Rathburn, J., 2006. *Standard Operating Procedure: Assessing Bank Erosion Potential Using Rosgen's BEHI*, Michigan Department of Natural Resources and Environment, Nonpoint Source Pollution Unit, Lansing. Available: www.michigan.gov/deq/1, 1607, 7–135.

Rhoads, B., García, M., Rodriguez, J., Bombardelli, F., Abad, J. and Daniels, M., 2008. Methods for Evaluating the Geomorphical Performance of Naturalized Rivers: Examples from the Chicago Metropolitan Area, In *River Restoration: Managing the Uncertainty in Restoring Physical Habitat* (S. Darby and D. Sear, eds.). John Wiley and Sons, Ltd., Chichester, West Sussex, England, pp. 209–228.

Rhodes, J. and Trent, R., 1993. Economics of Floods, Scour, and Bridge Failures, Hydraulic Engineering, *Proceedings of the 1993 National Conference*, v. 1, ASCE, pp. 928–933.

Richard, G. A., 2001. *Quantification and Prediction of Lateral Channel Adjustments Downstream from Cochiti Dam, Rio Grande, NM*, Ph.D. Dissertation, CSU, Fort Collins, CO.

Richards, K. S., 1982. *Rivers: Form and Process in Alluvial Channels*, Methuen, London.

Richards, P. L. and Brenner, A. J., 2004. Delineating source areas for runoff in depressional landscapes: Implications for hydrologic modeling, *Journal of Great Lakes Research*, 30(1), 9–21.

Copyright National Academy of Sciences. All rights reserved.

Richardson, E. V., Simons, D. B., and Lagasse, P. F., 2001. *River Engineering for Highway Encroachments - Highways in the River Environment*, FHWA-NHI 01-004, Federal Highway Administration, Hydraulic Design Series No. 6, Washington, D.C.

Roni, P. and Beechie, T., 2013. *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitat*, Wiley-Blackwell, Hoboken, NJ.

Roni, P., Hanson, K., and Beechie, T., 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques, *North American Journal of Fisheries Management*, Vol. 28, Issue 3, pp. 856–890.

Rosgen, D. L., 1996. *Applied River Morphology*, Wildland Hydrology Publications, Pagosa Springs, CO.

Rosgen, D. L., 2001a. A Practical Method of Computing Streambank Erosion Rate, In *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Vol. 2, No. 2, pp. 9–15.

Rosgen, D. L., 2001b. *Watershed Assessment of River Stability and Sediment Supply (WARSSS)*, Wildland Hydrology, Fort Collins, CO.

Salazar, C. L., 1998. *Morphology of the Middle Rio Grande from Cochiti to Bernalillo Bridge, New Mexico*, Master's Thesis, CSU, Fort Collins, CO.

Schaff, S. D., Pezeshki, R. R., and Shields, F. D., Jr., 2002. Effects of Pre-Planting Soaking on Growth and Survival of Black Willow Cuttings, *Restoration Ecology*, Vol. 10, No. 2, pp. 267–274.

Schaff, S. D., Pezeshki, S. R., and Shields, F. D., Jr., 2003. Effects of Soil Conditions on Survival and Growth of Black Willow Cuttings, *Environmental Management*, Vol. 3, No. 1 pp. 748–763.

Schiechtl, H., 1980. *Bioengineering for Land Reclamation and Conservation*, University of Alberta Press, Edmonton, Alberta, Canada, 404 p.

Schiechtl, H. M. and Stern, R., 1996. *Ground Bioengineering Techniques for Slope Protection and Erosion Control*, Blackwell Science, London, England.

Schiechtl, H. and Stern, R., 1997. *Water Bioengineering Techniques for Watercourse Bank and Shoreline Protection*, Blackwell Science, London.

Schoklitsch, A., 1937. *Hydraulic Structures, A Text and Handbook, Vol. I*, American Society of Mechanical Engineers, NY, NY 1937.

Schueler, T. and Brown, K., 2004. *Urban Stream Repair Practices Version 1.0*, Urban Subwatershed Restoration Manual No. 4, Center for Watershed Protection, Ellicott City, MD.

Schumm, S. A., Harvey, M. D., and Watson, C. C., 1984. *Incised Channels: Morphology, Dynamics and Control*, Water Resources Publications, Littleton, CO.

Scottish Environment Protection Agency (SEPA), 2008. *Engineering in the Water Environment Good Practice Guide - Bank Protection: Rivers and Locks*, Scottish Environment Protection Agency, WAT-SG-23, 37 p. http://www.sepa.org.uk/water/water_regulation/guidance/engineering.aspx

Seville, S. and MacKay, K., 2006. Bioengineered Structure Performance in Riverine Systems: Review of the Guadalupe Creek Restoration Project Five Years After Construction, *Ecesis – The Quarterly Newsletter of the California Society for Ecological Restoration (SERCAL)*, Vol. 16, Issue 2, pp. 4–6.

Shafer, D. and Lee, A., 2003. *Willow Stake Installation: Example Contract Specifications*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-ER-02), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 12 p. http://el.erdc.usace.army.mil/elpubs/pdf/er02.pdf

Shen, H. W. and Komura, S., 1968. Meandering Tendencies in Straight Alluvial Channels, *Journal of Hydraulics* (HY4), Vol. 94, pp. 997–1016.

Shen, H. W., Schumm, S. A., Nelson, J. D., Doehring, D. O., and Skinner, M. M., 1981. "Methods for Assessment of Stream-Related Hazards to Highways and Bridges," FHWA/RD-80/160, Federal Highway Administration, Washington, D.C.

Shields, F. D., Jr., 2007. Scour calculations, Technical Supplement 14B in Stream Restoration Design, *National Engineering Handbook Part 654*, USDA-NRCS, Washington, D.C., CD-ROM. 2007.

Shields, F. D., Cooper, C. M., and Testa, S., 1995. Towards Greener Riprap: Environmental Microscale to Macroscale, In *River, Coastal, and Shoreline Protection: Erosion Control Using Riprap and Armourstone* (C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord, and K. W. Pilarczyk, eds.), John Wiley & Sons, New York, pp. 557–574.

Shields, F. D., Jr., Pezeshki, S. R., Wilson, G. V., Weiming, W., and Dabney, S. M., 2008. Rehabilitation of an Incised Stream Using Plant Materials: The Dominance of Geomorphic Processes, *Ecology and Society*, Vol. 13, No. 2, p. 20.

Shields, F. D., Jr., Simon, A. and Dabney, S., 2009. Stream bank dewatering for increased stability, *Hydrological Processes*, 23:1537–1547.

Simon, A., 1989. A Model of Channel Response in Disturbed Alluvial Channels, *Earth Surface Processes and Landforms*, Vol. 14, p. 11–26.

Simon, A. and Collison, A. J. C., 2002. Quantifying the Mechanical and Hydrologic Effects of Riparian Vegetation on Stream Bank Stability, *Earth Surface Processes and Landforms*, Vol. 27, pp. 527–546.

Copyright National Academy of Sciences. All rights reserved.

Simon, A., Pollen-Bankhead, N., and Thomas, R. E., 2011. Development and Application of a Deterministic Bank Stability and Toe-Erosion Model for Stream Restoration, In *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools* (Simon, A., Bennett, S. J., and Castro, J. M., eds.), American Geophysical Union, Geophysical Monograph Series 194, Washington, D.C., pp. 453–474.

Simon, A., Derrick, D., Alonso, C., and Pollen-Bankhead, N., 2008. *Application of a Deterministic Bank-Stability Model to Design a Reach-Scale Restoration Project*, ASCE, World Environmental and Water Resources Congress, Honolulu, HI.

Simons, Li & Associates, 1982. *Engineering Analysis of Fluvial Systems*, Fort Collins, CO.

Sixta, M. J., 2004. *Hydraulic Modeling and Meander Migration of the Middle Rio Grande, New Mexico*, Master's Thesis, CSU, Fort Collins, CO.

Slate, L. O., Shields, F. D., Jr., Schwartz, J. S., Carpenter, D.O., and Freeman, G. E., 2005. Engineering Design Standards and Liability for Stream Channel Restoration, *Journal of Hydraulic Engineering*, Vol. 133, No. 10, pp. 1099–1102.

Soar, P. J. and Thorne, C. R., 2001. *Channel Restoration Design for Meandering Rivers*, ERDC/CHL CR-01-1, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Sotir, R. B. and Nunnally, N. R., 1995. Use of Riprap in Soil Bioengineering Streambank 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. Maynord, and K. W. Pilarczyk, eds.), John Wiley & Sons, New York.

Sotir, R. B. and Fischenich, C., 2001. *Live and Inert Fascine Streambank Erosion Control*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-31), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 8 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr30.pdf

Sotir, R. B. and Fischenich, C., 2003. *Vegetated Reinforced Soil Slope for Stream Bank Erosion Control*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-30), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 10 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr30.pdf

Sotir, R. B. and Fischenich, C., 2007. *Live Stake and Joint Planting for Stream Bank Erosion Control*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-35), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 8 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr35.pdf

Steen, P., 2014. *The State of the Huron's River and Tributaries*, The State of the Huron Conference. Huron River Watershed Council, Ann Arbor, MI. http://www.hrwc.org/wp-content/uploads/2014/05/Steen_StateofAffairs.pdf (accessed April 13, 2015).

Stone, M. C., Chen, L., Mckay, S. K., Goreham, J., Acharya, K., Fishennich, C., and Stone, A. B., 2011. Bending of submerged woody riparian vegetation as a function of hydraulic flow conditions, *River Research and Applications*, 29(2):195–205.

Strahler, A. N., 1965. *Physical Geography*, John Wiley & Sons, New York, 442 p.

Sylte, T. and Fischenich, C., 2000. *Rootwad Composites for Stream Bank Erosion Control and Fish Habitat Enhancement*, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-21), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 10 p. http://el.erdc.usace.army.mil/elpubs/pdf/sr21.pdf

Temple, D., 1980. Tractive Force Design of Vegetated Channels, *Transactions*, A28 Vol. 23, No 4.

Texas Department of Transportation (TXDOT), 1999. *Field Performance Testing of Selected Erosion Control Products*, TXDOT/TTI Hydraulics and Erosion Control Laboratory, Bryan, TX.

The River Restoration Centre, 2002. *Manual of River Restoration Techniques*, The River Restoration Centre, Cranfield, Bedfordshire, U.K. http://www.therrc.co.uk/rrc_manual.php

Theisen, M. S., 1992. Evaluation of Biotechnical Composites under High Velocity and Shear Conditions, *Proceedings of the XXIII Annual International Erosion Control Association Conference*, Orlando, FL, pp 285–305.

Thompson, A., 1986. Secondary Flows and the Pool-Riffle Unit: A Case Study of the Processes of Meander Development, *Earth Surface Processes and Landforms*, Vol. 11, pp. 631–641.

Thorne, C. R., 1981. Field Measurements of Rates of Bank Erosion and Bank Material Strength, In *Erosion and Sediment Transport Measurement*, IAHS Publication No. 133, pp. 503–512.

Thorne, C. R., 1998. *Stream Reconnaissance Handbook*, John Wiley & Sons, Chichester, U.K.

Thorne, C. R. and Abt, S. R., 1993. *Velocity and Scour Prediction in River Bends*, Contract Rep. HL-93-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Thorne, C. R. and Osman, A. M.,1988. Riverbank Stability Analysis. II: Applications, *Journal of Hydraulic Engineering*, Vol. 114, No. 2, New York.

Tilley, D. and Hoag, J. C., 2008. *Evaluation of fall versus spring planting of dormant hardwood willow cuttings with and without soaking treatment*, USDA Natural Resources Conservation Service, Plant Materials Center, Riparian/Wetland Project Information Series No. 25, 9 p.

Torre, A., 2001. *Stream Stabilization*, Western Australia Water and Rivers Commission, River Restoration Report No. RR 10, East Perth, Western Australia, 32 p. http://www.water.wa.gov.au/PublicationStore/first/11792.pdf

Copyright National Academy of Sciences. All rights reserved.

Trimble, S. W., 2004. Effects of Riparian Vegetation on Stream Channel Stability and Sediment Budgets, In *Riparian Vegetation and Fluvial Geomorphology* (Bennett, S. J., and Simon, A., eds.), American Geophysical Union, Water Science and Application 8, Washington, D.C., pp. 153–169.

USACE, 1981. *Final Report to Congress, The Stream Bank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251*, Main Report, Supplemented by Appendices A-H in separate volumes. U.S. Army Corps of Engineers, Washington, D.C.

USACE, 1991. *Hydraulic Design of Flood Control Channels*, Engineering Manual No. 1110-2-1601 (revised), Washington, D.C.

USACE, 1994. *Channel Stability Assessment for Flood Control Projects*, Engineer Manual 110-2-1418, Headquarters, USACE, Washington, D.C.

USACE, 2002a. *Middle Rio Grande Santa Ana Reach Geomorphology, Section 1135 Program, Detailed Project Report and Environmental Assessment for Riparian and Wetland Restoration, Pueblo of Santa Ana Reservation, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

USACE, 2002b. *Value Engineering Study Summary Report, Riparian/Wetland Restoration Project, Pueblo of Santa Ana Reservation, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

USACE, 2006. *Lessons Learned: Stream Bank Stabilization on Army Training Lands*, U.S. Army Corps of Engineers, Public Works Technical Bulletin 200-3-41.

USACE, 2008. *Section 1135 Program, Draft Detailed Project Report and Environmental Assessment for Aquatic Habitat Restoration at Santa Ana Pueblo, New Mexico*, U.S. Army Corps of Engineers Albuquerque District.

USACE, 2010. *River Analysis System*, HEC-RAS, User's Manual, Version 4.1, Hydrologic Engineering Center, Davis, CA.

USDA, 1947 (revised 1954). *SCS Handbook of Channel Design for Soil and Water Conservation*, SCS TP-61, U.S. Department of Agriculture, Washington, D.C.

USDA, 2007. Sandbar Willow—Plant Fact Sheet, USDA NRCS Plant Materials Program, Washington, D.C.

Walter, J., Hughes, D., and Moore, J. N., 2005 (revised). *Stream Bank Revegetation and Protection: A Guide for Alaska*, Alaska Department of Fish and Game, Division of Sport Fish, Anchorage, AK, 91 p.

Washington Dept. of Fish & Wildlife, 2003. *Integrated Streambank Protection Guidelines*, published in cooperation with Washington Dept. of Transportation and Washington Dept. of Ecology.

Water Resources Commissioner, Undated. *Malletts Creek Restoration Project*, Final Report, Washtenaw County Water Resources Commissioner, Washtenaw County, MI. http://www.ewashtenaw.org/government/drain_commissioner/project-status/malletts_creek/dc_mc_mcrp.html (accessed October 8, 2014).

Water Resources Council, Hydrology Committee, 1981. *Guidelines for Determining Flood Frequency*, Bulletin 17B, U.S. Water Resources Council, Washington, D.C.

Wells, G. W., 2002a. *Biotechnical Stream Bank Protection: The Use of Plants to Stabilize Stream Banks*, USDA Forest Service — National Agroforestry Center, Agroforestry Notes (USDA-NAC), AF Note 23, 4 p.

Wells, G. W., 2002b. *Planning Biotechnical Stream Bank Protection*, USDA Forest Service, National Agroforestry Center, Agroforestry Notes (USDA-NAC), AF Note 24, 4 p.

WET, 1990. *Re-evaluation of the Stream Bank Erosion Control Evaluation and Demonstration Project*, Report to U.S. Army Corps of Engineers, Vicksburg District, Contract No. DACW38-88-D-0099.

White, R. J., Carreiro, M. M., and Zipperer, W. C., 2014. Woody plant communities along urban, suburban, and rural streams in Louisville, Kentucky, USA, *Urban Ecosystem*, Published online.

Wilson, C. A. M. E., Yagci, O., Rauch, H. P., and Olsen, N. R. B., 2006. 3D Numerical Modeling of a Willow Vegetated River/Floodplain System, *Journal of Hydrology*, Vol. 327, pp. 13–21.

Wisconsin Department of Transportation (WSDOT), 2013. *Roadside Design, Chapter 740 Soil Bioengineering.* http://www.wsdot.wa.gov/publications/manuals/fulltext/M25-30/Roadside.pdf#page=221

Wood, D. A. and Jarrett, A. R., 2004. Design Tool for Rootwads in Stream Bank Restoration, 2004 American Society of Agricultural and Biological Engineers Annual Meeting, Paper No. 042047.

Woodson, R. C., 1961. Stabilization of the Middle Rio Grande in New Mexico, *Journal of the Waterways and Harbors Division: Proceedings American Society of Civil Engineers*, Vol. 87, No. WW4, Paper 2980, pp. 1–15.

Woodson, R. C. and Martin, T. J., 1963. The Rio Grande Comprehensive Plan in New Mexico and Its Effects on the River Regimen Through the Middle Valley, *Proceedings of the 2nd Federal Interagency Sedimentation Conference*, Jackson, MS.

Wunder, S., Lehmann, B. and Nestmann, F., 2011. Determining of the drag coefficients of emergent and just submerged willows, *International Journal of River Basin Management*, Vol. 9, Nos. 3–4, pp. 231–236.

Wuycheck, J., 2004. *Total Maximum Daily Load for Biota for Malletts Creek, Washtenaw County*, Michigan Department of Environmental Quality, Water Division, Lansing.

Yalin, M. S., 1971. On the formation of dunes and meanders, *Proceedings of the 14th International Congress of the International Association for Hydraulic Research*, Vol. 3, Paper C13, pp. 1–8.

Yalin, M. S., 1992. *River Mechanics*, Pergamon, Oxford.

Copyright National Academy of Sciences. All rights reserved.

Ying, W., Jiarong, G., Lan, G., and Bintian, Q., 2011. Slope Protection Effect Contrastive Studies on Soil Bioengineering Measures for Natural Stream Bank and Artificial Slope, *Proceedings 2011 International Conference on Asia Agriculture and Animal*, IPCBEE Vol. 13, IACSIT Press, Singapore, pp. 192–196.

Yochum, S., 2013. *Guidance for Stream Restoration*, USDA, Natural Resources Conservation Service - Colorado, Technical Notes, Engineering - No. 27.2, 69 p.

Zevenbergen, L. W., Arneson, L. A., Hunt, J. H., and Miller, A. C., 2012. *Hydraulic Design of Safe Bridges*, Report FHWA-HIF-12-018, Hydraulic Design Series No. 7, Federal Highway Administration, Washington, D.C.

Zuazo, V. and Pleguezuelo, C., 2008. Soil erosion and runoff prevention by plant covers. A review, *Agronomy for Sustainable Development*, 28, 65–86.

Copyright National Academy of Sciences. All rights reserved.

APPENDIX A

NCHRP Report 544 Findings on Selected Treatments

Copyright National Academy of Sciences. All rights reserved.

McCullah and Gray (*NCHRP Report 544*) – Summary of Hydraulic Loading, Reasons for Failure, and Research Opportunities

DATA AVAILABILITY AND RESEARCH OPPORTUNITIES

McCullah and Gray found that availability of design data in terms of sustainable hydraulic loads varied considerably among the 44 techniques included in *NCHRP Report 544*. Their findings represent the state of practice in the 2003–2005 time frame and provide a baseline for developing more definitive design data for selected treatments under NCHRP Project 24-39. The McCullah and Gray findings for the 16 treatments that were included in the NCHRP Project 24-39 Task 2 survey of relevant agencies (see Appendix B) are summarized below.

NCHRP Report 544 also found that 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 for *NCHRP Report 544*, and expert input and testimonials, research opportunities where identified in the descriptions of many techniques. These are also summarized below.

1. COCONUT FIBER ROLLS

HYDRAULIC LOADING

Only limited data has been collected for shear stress or velocity tolerances of coir or coconut fiber rolls. In general, fiber rolls should only be used under relatively low to moderate shear stress and velocity conditions. Available data shown in Table 1 comes largely from empirical information or from vendors' design criteria (Allen and Fischenich 2000). Failure of coconut fiber rolls has been attributed to several mechanisms, i.e., flanking, undercutting, and anchor failure.

TABLE 1: Limiting Shear Stress And Velocity Levels For Fiber Geotextile Rolls ***(after Allen and Fischenich 2000).***

FIBER ROLL TYPE	LIMITING VELOCITY m/sec (ft/sec)	LIMITING SHEAR STRESS Kg/m^2 (lbs/ft^2)
Roll with coir rope mesh (staked only, without rock bolster)	<1.5 (<5)	1.0 – 3.9 (0.2 – 0.8)
Roll with polypropylene rope mesh (staked only, without rock bolster)	<2.4 (< 8)	3.9 – 14.6 (0.8 – 3.0)
Roll with polypropylene rope mesh (staked, with rock bolster)	<3.7 (< 12)	> 14.6 (> 3.0)

Copyright National Academy of Sciences. All rights reserved.

COMMON REASONS/CIRCUMSTANCES FOR FAILURE

Reasons for failure include excessive shear stress leading to scour and undermining, inadequate anchoring conditions, a poor vegetative establishment environment (e.g., shade, toxic soil/water chemistry, etc), and poor construction methods. If the substrate beneath the fiber roll is noncohesive material, such as sand or silt, anchoring may be problematic because of the lack of sufficient skin friction to hold the anchors (stakes) in place (Allen and Fischenich 2000). Conversely, a substrate laden with interspersed rocks may make it difficult to drive the stakes in place.

An example of a Coconut Fiber Roll failure can be found in Racin and Hoover (2001), pages 88 through 93.

RESEARCH OPPORTUNITIES

The combined use of coconut fiber rolls with discontinuous, redirective techniques, e.g., Bank Barbs, Vanes, and Bendway Weirs, merits additional investigation. The potential value of fiber rolls for improving near shore aquatic habitat also deserves some attention.

2. LARGE WOODY DEBRIS (LWD) STRUCTURES

HYDRAULIC LOADING

LWD structures are suitable for velocities up to 3 m/s (10 ft/s).

Allen and Leech (1997) reported various local velocities measured with a flowmeter. Roaring Fork River, CO, log revetments cabled to bank measured 3 m/s (10 ft/s), Snowmass Creek, CO rootwads measured 2.6 m/s (8.7 ft/s), Upper Truckee River, rootwads, 1.2 m/s (4.0 ft/s).

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Failures of LWD structures are attributed mainly to inadequate anchoring and orientation, and unsuccessful vegetation establishment. The improper installation and orientation of LWD when imbedded in structural armor can result in undercutting, structural damage, and subsequent loss of the armor and the woody debris. When anchoring to bedrock or boulders, improper quantity, placement, gluing, or drilling of anchor points can lead to excessive movement and instability of the structure (Washington State 2003). Projects with under-ballasted box groins and no bank armoring adjacent to the structure in particular streams have been known to fail (Slaney, et al. 2001). If vegetation does not establish properly, the habitat benefits of the structure may be somewhat limited and the integrity of the structure and adjacent banks could be compromised. Vegetation may fail to establish due to a variety of circumstances such as: improper orientation of the rootwad that accelerates local scour or negatively alters scour patterns; lack of access to water during periods of drought; lack of seed recruitment; or inappropriate installation timing (e.g., planting live willow stakes during the dry season).

RESEARCH OPPORTUNITIES

Allowable velocities or hydraulic loading for redirective structures.

Copyright National Academy of Sciences. All rights reserved.

3. LIVE BRUSH MATTRESS

HYDRAULIC LOADING

Studies have shown that brush mattresses have stabilized a bank in a test flume against velocities exceeding 7 m/s (20 ft/s) (Gerstgrasser 1999).

Allen and Fischenich (2000) report the following velocity and shear stress data:

Brush Mattress Type	Velocity	Shear
Mattress without rock toe, initial	<2.7 m/sec (<4 ft/sec)	2.0 – 14.6 kg/m^2 (0.4 – 3.0 lb/ft^2)
Mattress without rock toe, grown	<3.4 m/sec (<5 ft/sec)	19.5 – 34.2 kg/m^2 (4.0 – 7.0 lb/ft^2)
Mattress with rock toe, initial	3.4 m/sec (<5 ft/sec)	3.9 – 20.0 kg/m^2 (0.8 – 4.1 lb/ft^2)
Mattress with rock toe, grown	8.2 m/sec (<12 ft/sec)	19.5 – 39.0 kg/m^2 (4.0 – 8.0 lb/ft^2)

Florineth (1982) provided additional shear force tolerances for brush mattresses without a rock toe: 20.5 kg/m^2 (4.2 lb/ft^2) just after construction, 30.8 kg/m^2 (6.3 lb/ft^2) after 15 months, and 41.0 kg/m^2 (8.4 lb/ft^2) after the third year.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Flanking or undermining of the revetment due to a lack of toe protection, or lack of upstream and downstream keys.

RESEARCH OPPORTUNITIES

Additional information regarding the required soil moisture and depth of soil fill for successful vegetation establishment would be valuable to obtain. A study of the effects of slope steepness on brush mattress growth and establishment would be useful as well.

4. LIVE BRUSH LAYERING

HYDRAULIC LOADING:

Allowable velocity for brush layering is 3.7 m/s (12.1 ft/s), and allowable shear stress is 19 to 300 N/m^2 (0.4 to 6.25 lb/ft^2) depending on how long the brush layers have had to establish (Fischenich 2001). Schiechtl and Stern (1996) suggest an allowable shear stress of 140 N/m^2 (2.92 lb/ft^2).

Copyright National Academy of Sciences. All rights reserved.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

The most likely causes of failure are the following:

1. Inadequate reinforcement from the brush layer inclusions, i.e., too large a vertical spacing or lift thickness for the given soil and site conditions, i.e., slope height, slope angle, and soil shear strength properties,
2. Inadequate tensile resistance in the brush layers as a result of too small an average stem diameter and/or too few stems per unit width,
3. Failure to properly consider seepage conditions and install adequate drainage measures, e.g., chimney drain, behind brush layer fill, and conversely,
4. Inadequate moisture applied during installation, and
5. Inadequate attention to construction procedures and details.

As with all resistive streambank structures, flanking is always a potential problem. If frozen soil is employed in constructing the soil lifts between brush layers, some settlement may occur when the soil thaws. This settlement may falsely signal a slope failure.

RESEARCH OPPORTUNITIES

A need exists to study carefully the performance of brush layer protected streambanks that are subjected to stream ice.

5. LIVE FASCINES

HYDRAULIC LOADING

Escarameia (1998) suggests that all bioengineering treatments be limited to situations where mean flow velocity is less than 1 m/s (3.3 ft/s). Fischenich (2001) presents data from a variety of published sources that suggests live fascines will withstand shear stresses up to 60 N/m^2 (and velocities of 1.8 to 2.4 m/s (5.9 to 7.9 ft/s)). Fripp (personal communication, 2002) presents data from Gerstgrasser (1999) that show fascines may withstand up to 100 N/m^2 and 3 m/s (9.8 ft/s), data from Schiechtl and Stern (1996) for live fascines of 60 N/m^2 (right after construction) and 80 N/m^2 (after 3 to 4 seasons of growth), and data from Schoklitsch (1937) indicating fascines may be used in situations with shear stresses ranging from 10 to 50 N/m^2.

Dr. Gerstgrasser reported that while the fascines themselves could withstand high velocities, the unprotected, horizontal soil areas between the fascines showed accelerated erosion (personal communication, 2000).

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Toe erosion and/or flanking can cause loss of the structure, if not combined with a toe protection in areas where shear stresses and velocities exceed limits for the soils underlying the structure. Flanking can be caused by insufficient keying-in of the structure (Sotir and Fischenich 2001).

Copyright National Academy of Sciences. All rights reserved.

RESEARCH OPPORTUNITIES

Studies could be conducted to further investigate the spacing between fascines on a slope that provides the optimum stability while minimizing costs, and how they perform relative to coir rolls and straw wattles.

6. LIVE SILTATION

HYDRAULIC LOADING

This technique may be used for velocities up to 2 m/sec (6.6 ft/sec), but velocities should be at least 0.25 m/sec (0.8 ft/sec) for the system to function properly.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Cuttings will not promote siltation as well if not located at the water's edge. If located further up the bank, cuttings may dry out, and will only trap sediments and slow velocities during high flows. Cuttings may not grow well if not handled properly prior to installation.

RESEARCH OPPORTUNITIES

Research into velocities that this technique can withstand would be helpful.

7. LIVE STAKING

HYDRAULIC LOADING

Allowable shear stress for this technique is approximately 120 N/m^2 (2.5 lb/ft^2) (Schiechtl and Stern 1996), and allowable velocity is about 0.9 m/s (3 ft/s) (Gray and Sotir 1996).

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Live staking can fail if vegetation is not handled properly prior to installation, is installed incorrectly (less than 80% of the cutting in the ground, bud scars facing down, poor soil contact, etc.) or not irrigated or "watered in" when installed in arid areas.

RESEARCH OPPORTUNITIES

Studies would be valuable regarding the effect live staking has on increasing the ability of other measures to withstand higher velocities and shear stresses.

8. ROOTWAD REVETMENTS

HYDRAULIC LOADING

Allen and Leach (1997) report allowable velocities for rootwad revetments of 2.7 m/sec (8.9 ft/sec).

Copyright National Academy of Sciences. All rights reserved.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

The most frequent reasons for failure of rootwad revetments are flanking and undercutting of the structure. Flanking may occur if upstream or downstream meanders are unstable, causing changing flow directions, the footer log does not extend far enough to protect the entire structure, or the trunk is not keyed in to a sufficiently stable substrate. Undercutting may result if the rootwad is not set at an appropriate elevation, or the trunk is not embedded far enough.

RESEARCH OPPORTUNITIES

Thresholds for allowable shear stress have not been developed, and would greatly assist in specification of these structures (Sylte and Fischenich 2000).

9. SOIL AND GRASS COVERED RIPRAP

HYDRAULIC LOADING

Soil-covered riprap with vegetative cover performs well in situations where flow velocities in the vicinity of the bank do not exceed 1 to 2 m/sec (4 to 6 ft/sec). Critical velocities vary with the variety of vegetation used and soil conditions.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Flanking, overtopping or undermining of the revetment due to improperly installed or insufficient keyways is one of the primary reasons for failure of riprap. Improperly graded granular material can also cause undermining and failure of the installation. Undersized stones can be carried away by strong currents, and sections of the revetment may settle due to poorly consolidated substrate. Vegetation may require irrigation if seeded or installed during the late spring or summer, or in extremely droughty soils. Also, only particular grass species can tolerate excess soil moisture when the banks are inundated.

RESEARCH OPPORTUNITIES

Information Unavailable

10. TURF REINFORCEMENT MATS

HYDRAULIC LOADING

The maximum flow velocity for unvegetated TRM has been shown to reach 2.4 m/sec (8 ft/sec) under long-term flow conditions (50-days) in a laboratory test (Austin and Theisen 1994).

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Critical points in conveyance system applications where mats can lose support include points of overlap between mats, projected water surface boundaries and channel bottoms.

Copyright National Academy of Sciences. All rights reserved.

A-8 Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

RESEARCH OPPORTUNITIES

None identified.

11. VEGETATED GABION BASKET

HYDRAULIC LOADING

Fischenich (2001) reported a maximum allowable velocity of 4.3 m/s (14.1 ft/s) for gabion baskets.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

- Baskets not adequately filled, allowing stones to shift and cause abrasion and fatigue failures of wire.
- Baskets damaged by floating debris, wear, corrosion, or vandalism.
- Flanking or undermining of the structure due to insufficient keying, or unstable banks on upstream or downstream end.

RESEARCH OPPORTUNITIES

Long-term (more than 15 years) performance of vegetated gabions.

12. VEGETATED GABION MATTRESS

HYDRAULIC LOADING

Limit velocities for vegetated gabion mattresses range from 4.2 m/sec (13.8 ft/sec) for a 15 cm (6 in.) thick mattress to 6.4 m/sec (21 ft/sec) for a 30 cm (12 in.) thick mattress (Freeman and Fischenich 2000).

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

- Mattresses not adequately filled, allowing stones to shift and cause abrasion and fatigue failures of wire.
- Baskets damaged by floating debris, wear, corrosion, or vandalism.
- Flanking or undermining of the structure due to insufficient keying, or unstable banks on upstream or downstream end.
- Omission of a filter layer below the installation.
- Attempts to vegetate the mattress after construction is complete.

RESEARCH OPPORTUNITIES

None identified.

Copyright National Academy of Sciences. All rights reserved.

13. VEGETATED MECHANICALLY STABILIZED EARTH

HYDRAULIC LOADING

There appears to be little or no published test data for permissible hydraulic loading of VMSE structures. There does exist, however, published data on vegetated coir mats and live brushlayers, respectively, as shown in Table 1. These data can be used to approximate permissible shear stresses and velocities for VMSE. In the case of vegetated coir mats or fabric, the cuttings are inserted through the fabric into the underlying soil, whereas in the case of VMSE, the cuttings are inserted between successive lifts of wrapped earth. In either case, the presence of the vegetation acts to either help anchor the netting in place or to slow velocities adjacent to the netting interface.

Accordingly, upper bound values in Table 2 can be used to estimate allowable shear stresses and velocities for VMSE, particularly when the vegetation is fully established.

TABLE 2: Limiting shear stress and velocity levels for selected soil bioengineering treatments *(adapted from Fischenich 2001).*

Treatment Type	Limiting Velocity m/sec (ft/sec)	Limiting Shear Stress Kg/m^2 (lbs/ft^2)
Live fascines	0.37 – 0.94 (1.2 – 3.1)	29 – 39 (6 – 8)
Coir roll	0.9 – 1.5 (3 – 5)	39 (8)
Vegetated coir mat	1.2 – 2.4 (4 – 8)	46.4 (9.5)
Live brush mattress (initial)	0.1 – 1.2 (0.4 – 4.1)	19.5 (4)
Live brush mattress (established)	1.2 – 2.5 (3.9 – 8.2)	58.6 (12)
Brush layering (initial/established)	0.1 – 2.0 (0.4 – 6.5)	58.6 (12)
Live willow stakes	0.64 – 0.94 (2.1 – 3.1)	14.6 – 48.8 (3 – 10)

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

No known instances of failure have been published. The most likely causes of a hypothetical failure, however, would be the following:

1. Inadequate primary reinforcement from the inert tensile inclusions (fabric or geotextile), i.e., improper vertical spacing or lift thickness, insufficient allowable unit tensile resistance in the selected fabric or geotextile, too short an embedment length, etc., for the given soil and site conditions, viz., slope height, slope angle, and soil shear strength properties.
2. Failure to properly consider seepage conditions and install adequate drainage measures, e.g., chimney drain behind VMSE structure.
3. Inadequate attention to construction procedures and details.
4. As with all resistive, shoreline protective structures, flanking is always a potential problem.

Copyright National Academy of Sciences. All rights reserved.

RESEARCH OPPORTUNITIES

Some uncertainty exists at present as to the exact permissible shear stresses and velocities for VMSE interfaces. Performance results during high water conditions indicate that VMSE can withstand hydraulic loadings at least equal to those listed in Table 2 for either vegetated coir mats or live brush layers alone. Additional research would also be helpful on the nature of the interaction between roots and fabric and root architecture/distribution in VMSE structures.

14. VEGETATED RIPRAP

HYDRAULIC LOADING

The riprap blanket should be keyed into the streambed below the expected depth of scour. Toe depth should be based on potential scour, which is not directly related to stream discharge. More stone can be placed as a skirt at the base of the revetment or be used to increase the width of the key, the purpose of this stone being to fall into scour holes should they be deeper than expected.

Permissible shear and velocity for vegetated riprap is related to the size of rock used in construction. Other factors, such as the angularity of the stone, the thickness of the layers of stone, and the angle at which the faces of the stone structure are constructed also come into play. Detailed guidance for sizing stone for bed and bank stabilization structures is beyond the scope of this guideline, and many approaches are available. However, the Maynord (1995) equation gives a D_{50} stone size for an angular stone riprap revetment of 0.875 m (2.87 ft) if the near-bank vertically averaged velocity is 3.5 m/s (11.5 ft/s), and flow depth = 1 m (3.3 ft), and stone is placed on a bank slope of 1V:1.5H. Use of riprap larger than this is unusual.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Flanking, overtopping or undermining of the revetment due to improperly installed or insufficient keyways is one of the biggest reasons for failure of riprap. Improperly designed or installed filter material can also cause undermining and failure of the installation. Undersized stones can be carried away by strong currents, and sections of the revetment may settle due to poorly consolidated substrate. Vegetation may require irrigation if planted in a nondormant state, or in extremely droughty soils. Also, vegetation may be limited by excess soil moisture (Pezeshki et al. 1998).

RESEARCH OPPORTUNITIES

Investigate the performance of this technique under conditions where banks are subjected to scour forces, bank overriding, or plucking action by ice. Does the presence/use of vegetation play a useful role? How does the vegetation or vegetative component respond to ice damage? What appears to enhance, or conversely, detract from the ability of vegetation to perform well under icing conditions?

Copyright National Academy of Sciences. All rights reserved.

15. VEGETATED ARTICULATED CONCRETE BLOCKS

HYDRAULIC LOADING

The critical velocity and failure shear stress for ACBs are on the order of 4.3 m/s (14 ft/s) and 226 Pascals (4.7 psf), respectively. Performance studies (Lipscomb et al. 2001) of articulated concrete blocks (Corps block) under vegetated and unvegetated conditions have shown that vegetation increases the critical failure shear stress by about 40%. Failure of an ACB system is defined as excessive loss of subgrade beneath the block mat resulting in vertical discontinuities between adjacent blocks.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Flanking or loss of blocks at the edges can be a problem with block systems; therefore, the system must be well keyed in at the edges. The loss of blocks from the center of the mat may lead to loss of articulation/interlocking and compromise the effectiveness of the system. Cabling armor units together and encapsulation (e.g., wire cages used with gabion (Reno) mattresses) minimize this problem. Improper placement and sizing of filter fabric beneath an ACB mat can lead to washout of fines beneath the mat and collapse or settlement problems. The filter fabric layer can sometimes act as a sliding surface. This problem is gradually ameliorated as vegetation becomes established in the mat.

RESEARCH OPPORTUNITIES

Determine the extent to which geotextile filter fabrics placed beneath ACB mats impede the growth, development, and penetration of roots through the filter cloth into the native soil beneath.

16. WILLOW POSTS AND POLES

HYDRAULIC LOADING

Allen and Leach (1997) report velocities of 2 m/sec (6.6 ft/sec) sustained by willow cuttings.

COMMON REASONS / CIRCUMSTANCES FOR FAILURE

Dessication and browsing are the two biggest reasons for failure. Often, willow post installations need to be fenced for a year or so, especially in agricultural areas, to allow the Willows to get established. Willows that are not planted deeply enough, have too much of their stem exposed, or do not have good stem to soil contact can dry out and die before getting established.

RESEARCH OPPORTUNITIES

None identified.

Copyright National Academy of Sciences. All rights reserved.

References Cited Above

Allen, H. and Leech, J.R. (1997). "Bioengineering for Streambank Erosion Control," Report 1, Guidelines, Technical Report EL-97-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Allen, H.H. and Fischenich, J.C. (2000). "Coir Geotextile Roll and Wetland Plants for Streambank Erosion Control," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-04), U.S. Army Engineer Research Development Center, Vicksburg, MS.

Austin D.N. and Theisen, M.S. (1994). "BMW Extends Vegetation Performance Limits," Geotechnical Fabrics Report, April/May.

Escarameia, M. (1998). "River and Channel Revetments," Thomas Telford, Ltd., London.

Fischenich, J.C. (2001a). "Impacts of Stabilization Measures," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-32), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fischenich, J.C. (2001b). "Stability Thresholds for Stream Restoration Materials," EMRRP Technical Notes Collection (ERDC-TN-EMRRP-SR-29), U.S. Army Engineering Research and Development Center, Vicksburg, MS.

Florineth, F. (1982). "Experiences with Bioengineered Measures for Watercourses in Mountains," Landschaftswasserbau, TU Wien, Vol. 3.

Freeman, G.E. and Fischenich J.C. (2000). "Gabions for Streambank Erosion Control," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-22), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Gerstgraser, C. (1999). "The Effect and Resistance of Soil Bioengineering Methods for Streambank Protection," Proceedings of Conference 30, International Erosion Control Association.

Gray, D.H. and Sotir, R. (1996). "Biotechnical and Soil Bioengineering Slope Stabilization," John Wiley & Sons, New York, NY.

Lipscomb, C.M., Thorton, C.I., Abt, S.R., and Leech, J.R. (2001). "Performance of Articulated Concrete Blocks in Vegetated and Un-Vegetated Conditions," *Land and Water*, Vol. 45, No. 4.

Maynord, S.T. (1995). "Corps Riprap Design Guidance for Channel Protection," C.R. Thorne, S.R. Abt, F.B.J. Barends, S.T. Maynord, and K.W. Pilarczyk. (eds.), In *River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone*, John Wiley & Sons, Ltd., Chichester, U.K.

Pezeshki, S.R., Anderson, P.H. and Shields, F.D., Jr. (1998). "Effects of Soil Moisture Regimes on Growth and Survival of Black Willow (Salix nigra) posts (cuttings)," *Wetlands* Vol. 18, No. 3, 460-470.

Copyright National Academy of Sciences. All rights reserved.

Racin, J.A., Hoover, T.P., and Crossett Avila, C.M. (2000). "California Bank and Shore Rock Slope Protection Design - Practitioner's Guide and Field Evaluations of Riprap Methods," Report FHWA-CA-TL-95-10, California Department of Transportation., Sacramento, CA.

Schiechtl, H.M. and Stern, R. (1996). "Ground Bioengineering Techniques for Slope Protection and Erosion Control," Blackwell Science. London, England.

Schiechtl, H.M. and Stern, R. (1998). "Water Bioengineering Techniques for Riverbank and Shore Stabilization," Blackwell Science, London, England.

Schoklitsch, A. (1937). "Hydraulic Structures; a Text and Handbook," Translated by Samuel Shulits, The American Society of Mechanical Engineers, New York, NY.

Slaney, P.A., Koning, D'Aoust, S.G., and R.G. Millar (2001). "Increased Abundance of Rainbow Trout in Response to Large Woody Debris Rehabilitation at the West Kettle River," *Streamline: Watershed Restoration Technical Bulletin*, Vol. 5, No. 4.

Sotir, R.B. and Fischenich, J.C. (2001). "Live and Inert Fascine Streambank Erosion Control," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-31), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Sytle, T.L. and Fishenich, J.C. (2000). "Rootwad Composites for Streambank Stabilization and Habitat Enhancement," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-21), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Washington Department of Fish and Wildlife (2003). "Integrated Streambank Protection Guidelines," published in co-operation with Washington Dept. of Transportation and Washington Dept. of Ecology, Olympia, WA.

Copyright National Academy of Sciences. All rights reserved.

APPENDIX B

Survey Form

Copyright National Academy of Sciences. All rights reserved.

National Cooperative Highway Research Program

NCHRP Project 24-39

Evaluation and assessment of environmentally sensitive stream bank protection measures

Contact Information:

Your name: ______________________________

Your agency: ______________________________

Address: ______________________________

____

____

Phone: ______________________________

Fax: ______________________________

Email: ______________________________

This questionnaire is NOT designed for interactive email reply. Please respond within 30 days of receipt if possible, using one of the following methods:

1. **Print out questionnaire, fill out by hand, and fax or mail to the address below.**
2. **Save questionnaire to a file, fill out responses and email as an attachment.**

Please return completed questionnaire to:

Mr. Paul E. Clopper, P.E.
Co-Principal Investigator, NCHRP Project 24-39
Ayres Associates Inc
3665 JFK Pky., Bldg. 2, Suite 200
Fort Collins, Colorado 80525

Phone: (970) 223-5556
Fax: (970) 223-5578
Email: clopperp@AyresAssociates.com

☐ *Please check here if you do not have the time to fully complete the enclosed questionnaire, but would like to receive a call from the research team to discuss any items further. Thank you.*

Copyright National Academy of Sciences. All rights reserved.

Problem Statement

Vegetation is the most natural method for protecting streambanks, and it provides ecosystem services in the form of habitat, water quality and aesthetic benefits. Stream bank protection measures that incorporate vegetation are referred to as biotechnical or bioengineered measures. However, there is a reluctance on the part of designers to employ biotechnical measures due to a lack of quantitative guidance.

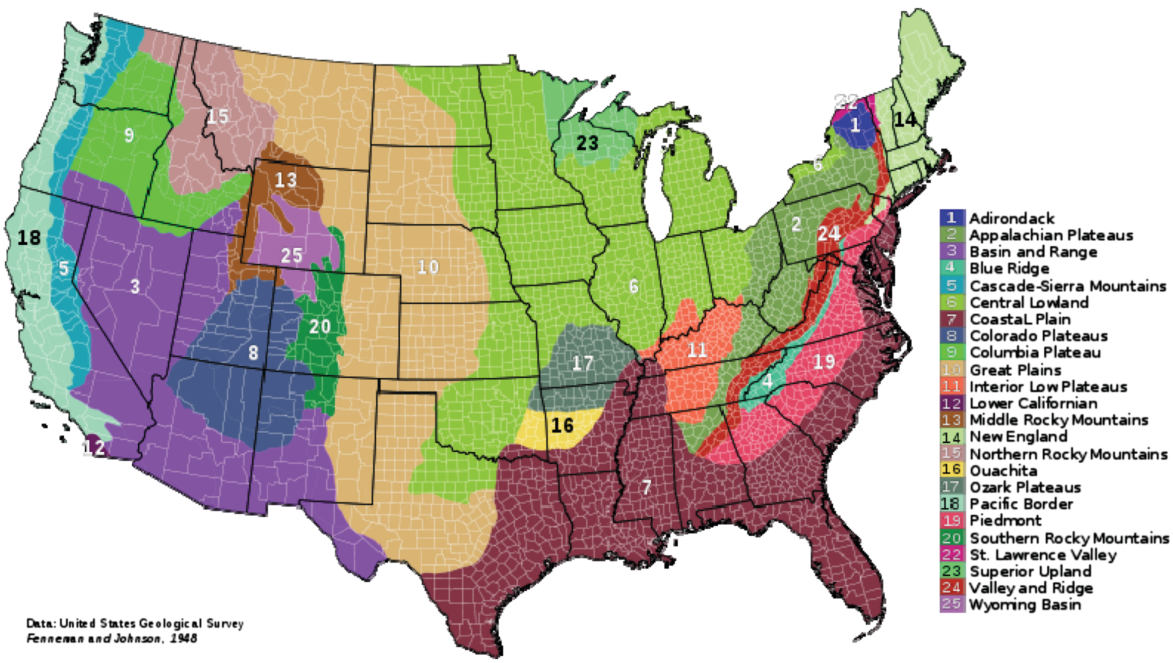
The objectives of NCHRP Project 24-39 are to produce guidelines for appropriate selection, design, installation, and maintenance of environmentally sensitive stream bank stabilization and protection measures.

Your response

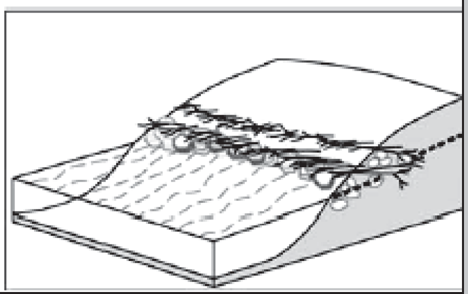
Please complete the forms on the following pages for each of the major physiographic provinces in which you have streambank protection projects featuring biotechnical measures.

This form is for physiographic province number _______.

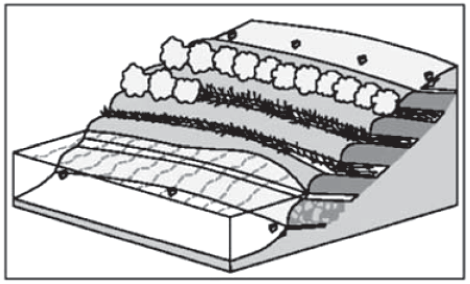
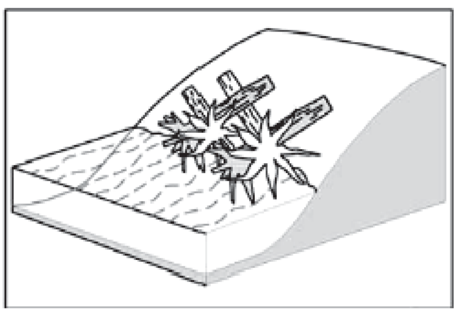
Geophysical Provinces of the Conterminous United States



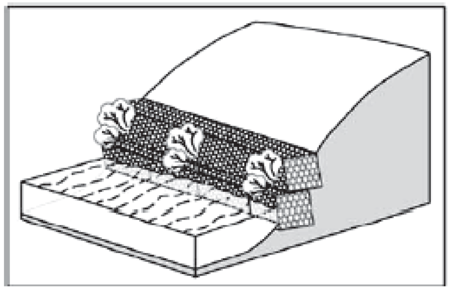
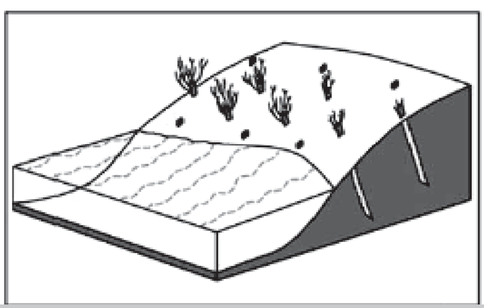
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
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. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ __________________

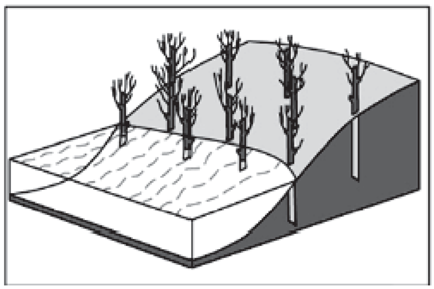
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
VEGETATED MECHANICALLY STABILIZED EARTH  Vegetated mechanically stabilized earth consists of live cut branches interspersed between lifts of soil wrapped in natural fabric, for example, coir, synthetic geotextiles (turf reinforcement mats, erosion control blankets, or geogrids). **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________
LARGE WOODY DEBRIS STRUCTURES  Large wood (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. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events?	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________

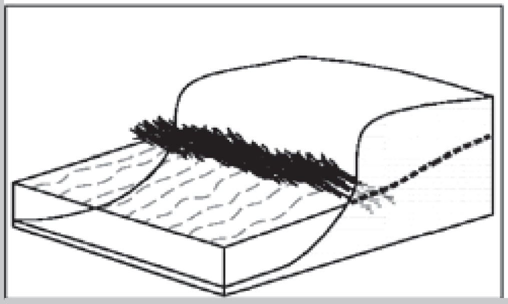
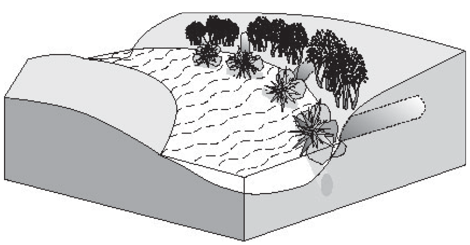
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
		☐ Yes ☐ No If yes, approx. number ___	☐ Model simulations	___________________
VEGETATED GABION BASKET  Gabions are rectangular baskets of twisted or welded wire mesh that are filled with rock. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other _______________ ___________________
LIVE STAKING  Live stakes are very useful as a revegetation technique, a soil reinforcement technique, and as a way to anchor erosion control materials.	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion

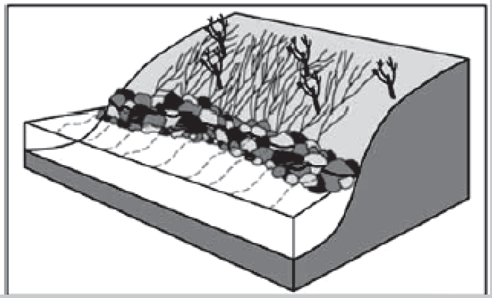
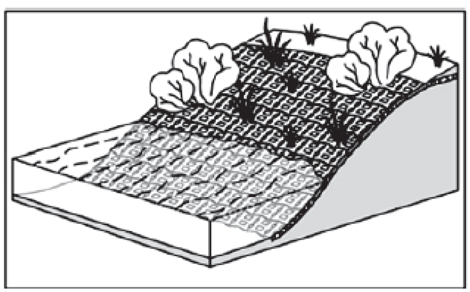
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
Remarks:	☐ 2-5 ☐ > 5	Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	○ Drought ☐ Other ______________ __________________
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 control blankets or geogrids. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ __________________

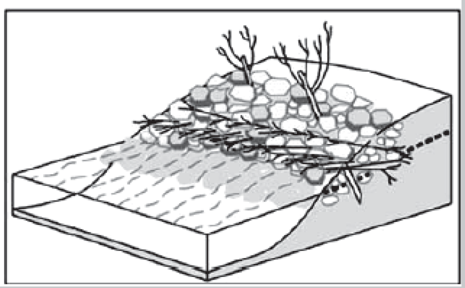
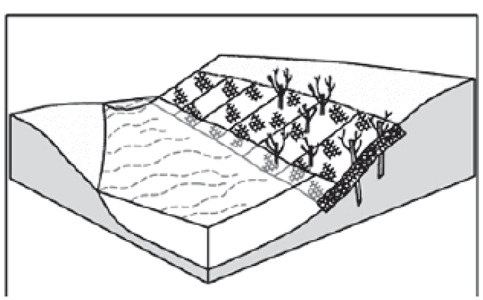
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
LIVE SILTATION  Live siltation is a bioengineering technique involving the installation of a living or a nonliving brushy system at the water's edge. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ____ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ____	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________
ROOTWAD REVETMENT  Rootwad revetments are constructed by burying tree trunks in banks perpendicular to the flow direction with rootwads protruding into the channel. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ____ yr event Have any installations experienced multiple flood events?	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________

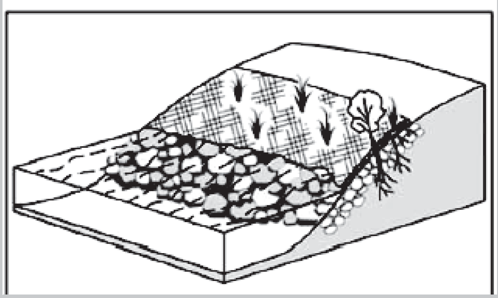
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
		☐ Yes ☐ No If yes, approx. number ___	☐ Model simulations	___________________
LIVE BRUSH MATTRESS  A live brush mattress is a blanket of live brushy cuttings and soil fill 6 to12 in. thick. The mattresses are usually constructed from live willow branches or other species that easily root from cuttings. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other _______________ ___________________
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	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion

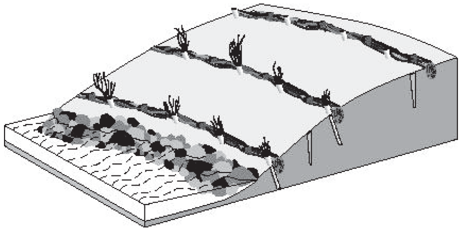
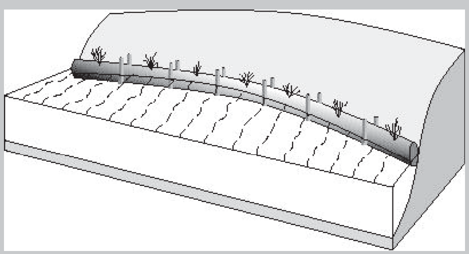
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
can conform to slight irregularities in slope topography caused by settlement. **Remarks:**	☐ 2-5 ☐ > 5	Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	○ Drought ☐ Other ______________ ___________________
VEGETATED RIPRAP  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. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________
VEGETATED GABION MATTRESS 	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event?	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation

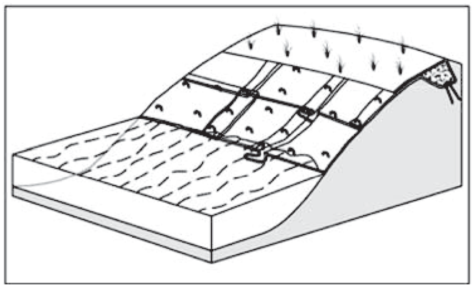
Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
Gabion mattresses differ from gabion baskets as they are shallow (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. **Remarks:**	Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________
SOIL AND GRASS COVERED RIPRAP  Soil and grass covered riprap refers to either: (1) an ordinary riprap blanket covered with a layer of soil or (2) a crown cap of soil and plant material placed over a riprap toe running along the base of a steep bank, effectively reducing the bank angle. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________

Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
LIVE FASCINES  Dormant branch cuttings bound together into long sausage-like, cylindrical bundles and placed in shallow trenches on slopes to reduce erosion and shallow sliding. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________
COCONUT FIBER ROLL  Coconut fiber rolls are cylindrical structures composed of coconut husk fibers bound together with twine. Rolls are placed along lower slopes for erosion control while trapping sediment which encourages plant growth within the fiber roll. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other ______________ ___________________

Copyright National Academy of Sciences. All rights reserved.

Measure	No. of sites	Overall performance	Monitoring Information	Failure mode(s)
TURF REINFORCEMENT MATS  Turf reinforcement mats (TRMs) are relatively permanent blankets, usually specified for banks subjected to flowing water. TRMs are intended to work with vegetation (roots and shoots) in a mutually reinforcing manner. As such, vegetated TRMs can resist higher tractive forces than either vegetation or TRMs can alone. **Remarks:**	☐ None ☐ One ☐ 2-5 ☐ 6-20 ☐ >20 Number of years in service (typical): ☐ < 2 ☐ 2-5 ☐ > 5	Typical performance: ☐ Unknown ☐ Complete failure ☐ Partial success ☐ Satisfactory ☐ Excellent Have any installations experienced a flood event? ☐ Yes ☐ No If yes, approx. ___ yr event Have any installations experienced multiple flood events? ☐ Yes ☐ No If yes, approx. number ___	☐ None ☐ Anecdotal ☐ Sequential photos ☐ Plans and specs ☐ Reports ☐ Publications ☐ Survey data ☐ Stage data ☐ Discharge data ☐ Velocity data ☐ Sediment data ☐ Biological data ☐ Cost data ☐ Model simulations	☐ Unknown ☐ Scour of bank face ☐ Toe scour, undermining ☐ Piping, subsurface erosion ☐ Geotechnical slope failure ☐ Ice ☐ Flanking ☐ Failure of u/s or d/s key Plant mortality due to: ○ Beaver damage ○ Large animal depredation ○ Insects ○ Disease ○ Vandalism ○ Erosion ○ Drought ☐ Other _______________ ____________________

Copyright National Academy of Sciences. All rights reserved.

KNOWN BIOTECHNICAL STREAMBANK PROTECTION SITES:

Please specifically identify two or three biotechnical streambank protection sites in your region that have a strong base of documentation. Please include photos, plans and specifications, monitoring reports, or other information if available.

(Example: State Route 601, Bridge #6126 over Blackwood Creek, approx. 1.5 miles north of the Town of Wheaton, Sansone County, Nebraska)

Site No.	Location/technique	Additional information provided? (Y/N)
1		
2		
3		

Would you recommend that any of the above-listed sites be considered as a potential field study site for NCHRP Project 24-39? If you answer yes, you or your designated representative will be contacted for further information by a member of the project team.

I recommend one or more sites listed above as a potential field study site:

______ YES

______ NO

If "Yes," designated representative: ______________________________
Name

____
Telephone Number

OTHER TYPES OF TREATMENTS:

Please feel free to attach information and/or design guidance for other types of bank protection treatments that are not represented in previous sections of this survey.

Thank you for your assistance.

Copyright National Academy of Sciences. All rights reserved.

APPENDIX C

Field Data Form

Copyright National Academy of Sciences. All rights reserved.

FIELD DATA FORMS

NCHRP PROJECT 24-39

Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures

FIELD DATA COLLECTION FORM

1. SCOPE AND PURPOSE

RIVER:	LOCATION:	DATE(S):

PROJECT: NCHRP 24-39, "Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures"	STUDY REACH:
COMPLETED BY:	GPS COORDINATES:

BANK PROTECTION TREATMENT (check all that apply):

Live brush layering ____	Live brush mattress ____
VMSE ____	Vegetated ACBs ____
Large woody debris ____	Vegetated riprap ____
Vegetated gabions ____	Vegetated gabion mattress ____
Live staking ____	Soil and grass covered riprap ____
Willow posts and poles ____	Live fascines ____
Live siltation ____	Coconut fiber roll ____
Rootwad revetment ____	Turf Reinforcement Mats (TRMs)____
	Other (describe):

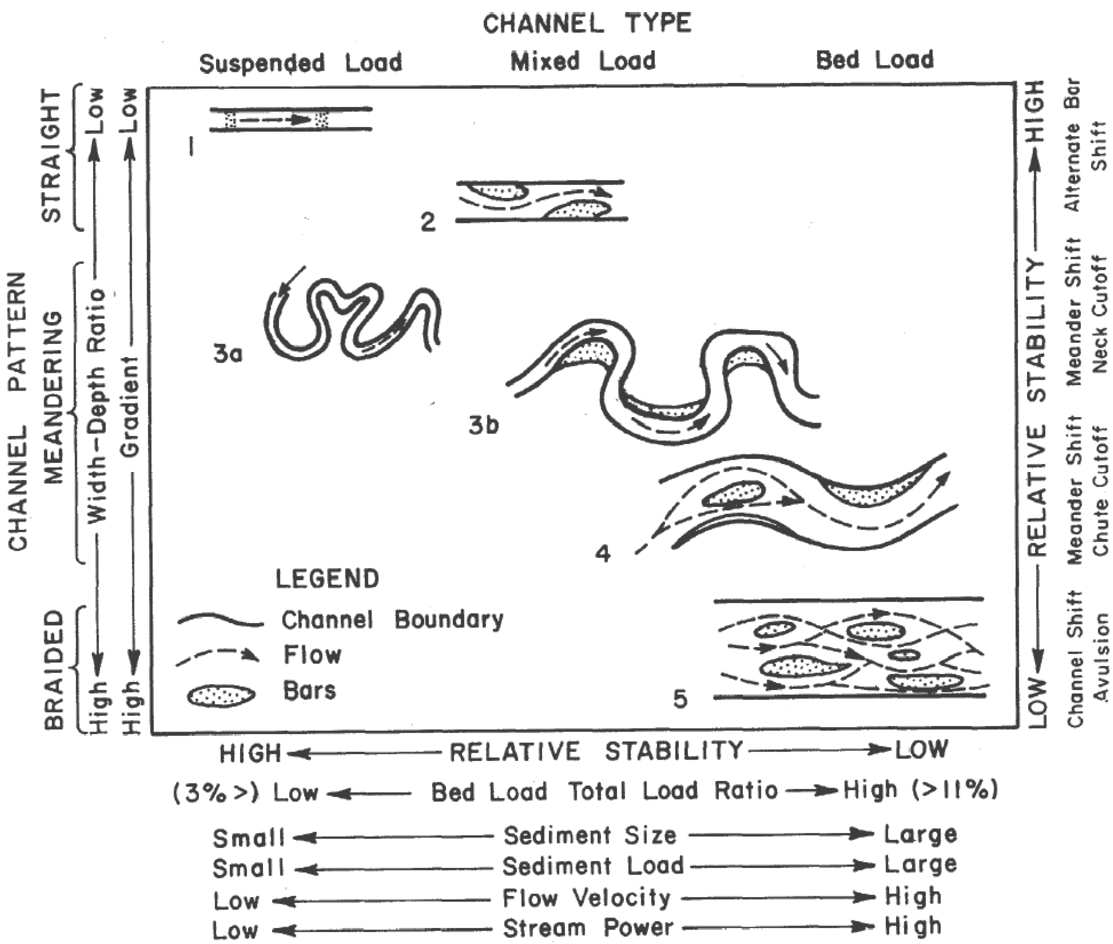
GENERAL NOTES AND COMMENTS: (Include site history; maintenance, if any; major floods and droughts, i.e., a timeline of performance):

Copyright National Academy of Sciences. All rights reserved.

2. RELATION OF CHANNEL TO VALLEY

Planform	Planform Data	Lateral Activity	Floodplain Features
Straight	Bend Radius ______	None	None
Sinuous	Meander belt width ______	Meander progression	Meander scars
Irregular	Wavelength ______	Increasing amplitude	Scroll bars+sloughs
Regular meanders	Meander Sinuosity ______	Progression+cutoffs	Oxbow lakes
Irregular meanders	**Location in Valley**	Irregular erosion	Irregular terrain
Tortuous meanders	Left	Avulsion	Abandoned channel
Braided	Middle	Brading	Braided deposits
Anastomosed	Right		

Circle the representative channel type:



For details on the use of this figure see FHWA Hydraulic Engineering Circular No. 20 (2012) Section 4.5.3 and/or Hydraulic Design Series No. 6 (2001) Section 5.4.1.

Copyright National Academy of Sciences. All rights reserved.

Circle the representative stage of channel evolution:

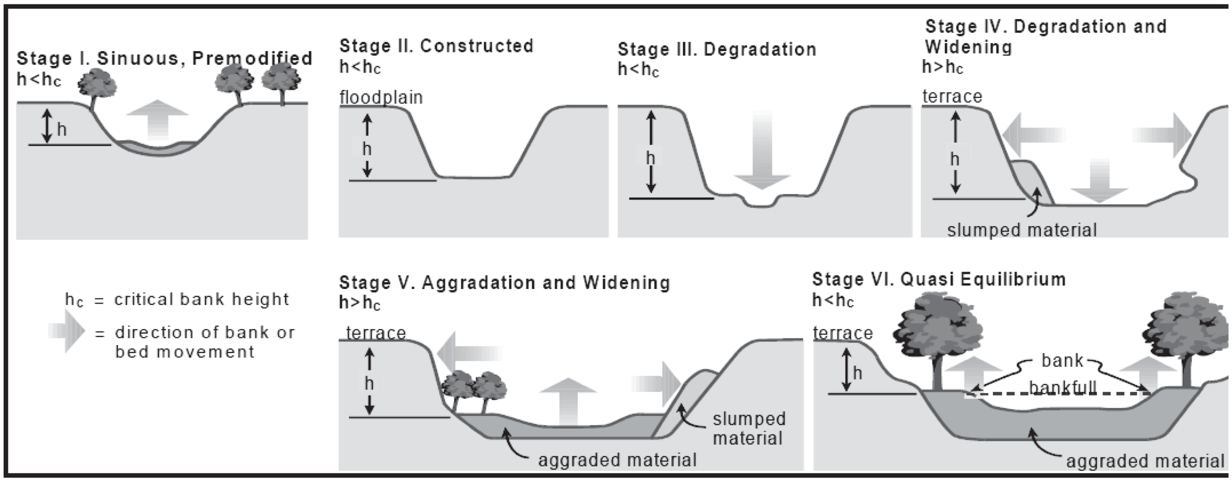


Figure 2 – Six stages of channel evolution from Simon and Hupp (1986) and Simon (1989b) identifying Stages I and VI as 'reference' channel conditions.

Table 1 – Summary of conditions to be expected at each stage of channel evolution.

Stage	Descriptive Summary
I	*Pre-modified* – Stable bank conditions, no mass wasting, small, low angle bank slopes. Established woody vegetation, convex upper bank, concave lower bank.
II	*Constructed* – Artificial reshaping of existing banks. Vegetation often removed, banks steepened, heightened and made linear.
III	*Degradation* – Lowering of channel bed and consequent increase of bank heights. Incision without widening. Bank toe material removed causing an increase in bank angle.
IV	*Threshold* – Degradation and basal erosion. Incision and active channel widening. Mass wasting from banks and excessive undercutting. Leaning and fallen vegetation. Vertical face may be present.
V	*Aggradation* – Deposition of material on bed, often sand. Widening of channel through bank retreat; no incision. Concave bank profile. Filed material re-worked and deposited. May see floodplain terraces. Channel follows a meandering course.
VI	*Restabilization* – Reduction in bank heights, aggradation of the channel bed. Deposition on the upper bank therefore visibly buried vegetation. Convex shape. May see floodplain terraces.

Evolution of incised channel from initial incision (A, B) and widening (C, D) to aggradation (D, E) and eventual relative stability; h is bank height. For details on the use of this figure, see FHWA Hydraulic Engineering Circular No. 20 (2012) Section 2.2.

Copyright National Academy of Sciences. All rights reserved.

3. Stability Indicators, Descriptions, and Ratings. Range of Values in Ratings Columns Provide Possible Rating Values for Each Factor.				
Stability Indicator	Ratings			
	Excellent (1-3)	Good (4-6)	Fair (7-9)	Poor (10-12)
1. Watershed and floodplain activity and characteristics	Stable, forested, undisturbed watershed	Occasional minor disturbances in the watershed, including cattle activity (grazing and/or access to stream), construction, logging, or other minor deforestation. Limited agricultural activities.	Frequent disturbances in the watershed, including cattle activity, landsliding, channel sand or gravel mining, logging, farming, or construction of buildings, roads, or other infrastructure. Urbanization over significant portion of watershed.	Continual disturbances in the watershed. Significant cattle activity, landsliding, channel sand or gravel mining, logging, farming, or construction of buildings, roads, or other infrastructure. Highly urbanized or rapidly urbanizing watershed.
2. Flow habit	Perennial stream with no flashy behavior	Perennial stream or ephemeral 1st order stream with slightly increased rate of flooding	Perennial or intermittent stream with flashy behavior	Extremely flashy; flash floods prevalent mode of discharge; ephemeral stream other than 1st order stream
3. Channel pattern	Straight to meandering with low radius of curvature; primarily suspended load	Meandering moderate radius of curvature; mix of suspended and bed loads; well maintained engineered channel	Meandering with some braiding; tortuous meandering; primarily bed load; poorly maintained engineered channel	Braided; primarily bed load; unmaintained engineered channel
4. Entrenchment / channel confinement	Active floodplain exists at top of banks; no sign of undercutting infrastructure; no levees	Active floodplain abandoned, but is currently rebuilding; minimal channel confinement; infrastructure not exposed; levees are low and set well back from the river	Moderate confinement in valley or channel walls; some exposure of infrastructure; terraces exist; floodplain abandoned; levees are moderate in size and have minimal setback from the river	Knickpoints visible downstream; exposed water lines or other infrastructure; channel width to top of banks ratio small; deeply confined; no active floodplain; levees are high and along the channel edge
5. Bed material Fs = approximate portion of sand in the bed	Assorted sizes tightly packed, overlapping, and possibly imbricated. Most material > 4 mm. Fs < 20%	Moderately packed with some overlapping. Very small amounts of material < 4 mm. 20 < Fs < 50%	Loose assortment with no apparent overlap. Small to medium amounts of material < 4 mm. 50 < Fs < 70%	Very loose assortment with no packing. Large amounts of material < 4 mm. Fs > 70%
6. Bar development S = Slope W/Y = Width-to-Depth ratio	For S < 0.02 and W/Y > 12, bars are mature, narrow relative to stream width at low flow, well vegetated, and composed of coarse gravel to cobbles. For S > 0.02 and W/Y < 12, no bars are evident	For S < 0.02 and W/Y > 12, bars may have vegetation and/or be composed of coarse gravel to cobbles, but minimal recent growth of bar evident by lack of vegetation on portions of the bar. For S > 0.02 and W/Y < 12, no bars are evident.	For S < 0.02 and W/Y > 12, bar widths tend to be wide and composed of newly deposited coarse sand to small cobbles and/or may be sparsely vegetated. Bars forming for S > 0.02 and W/Y < 12.	Bar widths are generally greater than 1/2 the stream width at low flow. Bars are composed of extensive deposits of fine particles up to coarse gravel with little to no vegetation. No bars for S < 0.02 and W/Y > 12.
7. Obstructions, including bedrock outcrops, armor layer, large woody debris jams, grade control, bridge bed paving, revetments, dikes or vanes, riprap	Rare or not present	Occasional, causing cross currents and minor bank and bottom erosion.	Moderately frequent and occasionally unstable obstructions, cause noticeable erosion of the channel. Considerable sediment accumulation behind obstructions.	Frequent and often unstable causing a continual shift of sediment and flow. Traps are easily filled causing channel to migrate and/or widen.

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

3. Stability Indicators, Descriptions, and Ratings (continued).

Stability Indicator	Ratings			
	Excellent (1-3)	Good (4-6)	Fair (7-9)	Poor (10-12)
8. Bank soil texture and coherence	Clay and silty clay; cohesive material	Clay loam to sandy clay loam; minor amounts of noncohesive or unconsolidated mixtures; layers may exist, but are cohesive materials.	Sandy clay to sandy loam; unconsolidated mixtures of glacial or other materials; small layers and lenses of noncohesive or unconsolidated mixtures	Loamy sand to sand; noncohesive material; unconsolidated mixtures of glacial or other materials; layers or lenses that include noncohesive sands and gravels
9. Average bank slope angle (where 90° is a vertical bank) V = Vertical H = Horizontal	Bank slopes < 3H:1V (18°) for noncohesive or unconsolidated materials to < 1:1 (45°) in clays on both sides	Bank slopes up to 2H:1V (27°) in noncohesive or unconsolidated materials to 0.8:1 (50°) in clays on one or occasionally both banks	Bank slopes to 1H:1V (45°) in noncohesive or unconsolidated materials to 0.6:1 (60°) in clays common on one or both banks.	Bank slopes over 45° in noncohesive or unconsolidated materials or over (60°) in clays common on one or both banks
10. Vegetative or engineered bank protection	Wide band of woody vegetation with at least 90% density and cover. Primarily hard wood, leafy, deciduous trees with mature, healthy, and diverse vegetation located on the bank. Woody vegetation oriented vertically. In absence of vegetation, both banks are lined or heavily armored.	Medium band of woody vegetation with 70-90% plant density and cover. A majority of hard wood, leafy, deciduous trees with maturing, diverse vegetation located on the blank. Woody vegetation oriented 80-90° from horizontal with minimal root exposure. Partial lining or armoring of one or more banks.	Small band of woody vegetation with 50-70% plant density and cover. A majority of soft wood, piney, coniferous trees with young or old vegetation lacking in diversity located on or near the top of bank. Woody vegetation oriented at 70-80° from horizontal often with evident root exposure. No lining of banks, but some armoring may be in place on one bank.	Woody vegetation band may vary depending on age and health with less than 50% plant density and cover. Primarily soft wood, piney, coniferous trees with very young, old and dying, and/or monostand vegetation located off of the bank. Woody vegetation oriented at less than 70° from horizontal with extensive root exposure. No lining or armoring of banks.
11. Bank Cutting	Little or none evident. Infrequent raw banks, insignificant percentage of total bank.	Some intermittently along channel bends and at prominent constrictions. Raw banks comprise minor portion of bank in vertical direction.	Significant and frequent on both banks. Raw banks comprise large portion of bank in vertical direction. Root mat overhangs.	Almost continuous cuts on both banks, some extending over most of the banks. Undercutting and sod-root overhangs.
12. Mass wasting or bank failure	No or little evidence of potential or very small amounts of mass wasting. Uniform channel width over the entire reach.	Evidence of infrequent and/or minor mass wasting. Mostly healed over with vegetation. Relatively constant channel width and minimal scalloping of banks.	Evidence of frequent and/or significant occurrences of mass wasting that can be aggravated by higher flows, which may cause undercutting and mass wasting of unstable banks. Channel width quite irregular and scalloping of banks is evident.	Frequent and extensive mass wasting. The potential for bank failure, as evidenced by tension cracks, massive undercuttings, and bank slumping, is considerable. Channel width is highly irregular and banks are scalloped.
13. Upstream distance to bridge from meander impact point and alignment	More than 115 ft (35 m); bridge is well aligned with river flow	66-115 ft (20 - 35 m); bridge is aligned with flow	33 - 66 ft (10 - 20 m); bridge is skewed to flow or flow alignment is otherwise not centered beneath bridge	Less than 33 ft (10 m); bridge is poorly aligned with flow

For background information and examples of the use of this table, see FHWA Hydraulic Engineering Circular No. 20 (2012) Section 5.4.

4. Assessment Monitoring Protocol for Environmentally Sensitive Bank Protection Measures (adapted from Jones and Johnson)

Category	Excellent (1-3)	Good (4-6)	Poor (7-9)	Failed (10-12)
Streambank vegetation	Streambank vegetation is in good condition[1] and showing progress along all streambank surfaces.	50-70% of the bank is covered by vegetation in good condition or showing progress.	50-70% of the bank is covered by stressed or dying plants.	Less than 50% of the bank is covered by vegetation or disruption due to grazing and mowing is evident.
Bank stability and migration	Banks are stable and vegetated	Isolated instances of bank failures (mass wasting, undercut, etc.) or raw banks, affecting 5-30% of treated bank	Bank failures or raw banks frequent, describing 30-60% of treated bank segment. Channel migration is evident anywhere in reach, but thalweg is within design channel limits.	Bank failures or raw banks prevalent, describing >60% of treated bank segment. Thalweg has migrated outside design channel limits anywhere in reach.
Infrastructure protection	Infrastructure is not in immediate danger	Erosion has left infrastructure (1) nearer stream flow or (2) with more surface exposed to stream flow than as-built condition	Infrastructure shows unexpected signs of vulnerability that has the potential to impact the integrity or functioning of the infrastructure. Infrastructure is exposed to stream flow.	The structural integrity of infrastructure is compromised or infrastructure has failed as a result of stream flow.
Structural integrity[2]	Structure and structure components have not been displaced and there is no visible erosion.	At least 10% of the structure is displaced from the as-built location and/or structure is attached to bank but erosion is visible everywhere structure is in contact with bank.	25-75% of the structure is displaced from as-built location and/or structure is partially detached from bank.	More than 75% of structure is displaced from as-built location and/or structure is detached from bank.
Flow obstruction and sedimentation	Less than half of the bottom is affected by sediment deposition. Pools are not filling in and there are few to no unintended obstructions.	Occasional unintended obstructions are present; minor local scour at these obstructions.	Sediment deposition is affecting 50-80% of the channel bottom or pool depths have measurably decreased. Moderately frequent unintended obstructions.	Unintended obstructions are frequent or have significantly altered the design capacity of the channel. Aggradation is evident or sediment deposition affects >80% of the channel bottom.

NOTES: [1]Key indicators of condition include leaf color and evidence of insects, herbivory, disease, trampling, competition from undesirable species, and vandalism.

[2]Score each structure in the reach and use the median score for the overall site score.

For background information on the use of this table, see Jones, C.J. and Johnson, P.A., 2015. "Describing damage to stream modification projects in constrained settings," In *Journal of the American Water Resources Association*.

Copyright National Academy of Sciences. All rights reserved.

5. FUNCTIONALITY

YES	NO	N/A	HYDROLOGY
			1) Floodplain above bankfull is inundated in "relatively frequent" events
			2) Where beaver dams are present they are active and stable
			3) Sinuosity, width/depth ratio, and gradient are in balance with the landscape setting (i.e., landform, geology, and bioclimatic region)
			4) Riparian-wetland area is widening or has achieved potential extent
			5) Upland watershed is not contributing to riparian-wetland degradation

YES	NO	N/A	VEGETATION
			6) There is diverse age-class distribution of riparian-wetland vegetation (recruitment for maintenance/recovery)
			7) There is diverse composition of riparian-wetland vegetation (for maintenance/recovery)
			8) Species present indicate maintenance of riparian-wetland soil moisture characteristics
			9) Streambank vegetation is comprised of those plants or plant communities that have root masses capable of withstanding high-streamflow events
			10) Riparian-wetland plants exhibit high vigor
			11) Vegetation growing within or on bank protection measures exhibits no sign of drought stress
			12) Vegetation growing within or on bank protection measures exhibits no sign of significant herbivory
			13) Vegetation growing within or on bank protection measures exhibits no sign of trampling by humans or animals
			14) Vegetation growing within or on bank protection measures exhibits no sign of competition from undesirable species
			15) Vegetation growing within or on bank protection measures exhibits no sign of damage due to vandalism
			16) Adequate riparian-wetland vegetative cover is present to protect banks and dissipate energy during high flows
			17) Vegetation growing within or on bank protection measures is dense and flexible enough to shield the bank from erosional stresses during high flows
			18) Vegetation growing within or on bank protection measures likely provides root reinforcement to slopes for failure planes at least 3 feet below the surface
			19) Plant communities are an adequate source of coarse and/or large woody material (for maintenance/recovery)

Copyright National Academy of Sciences. All rights reserved.

YES	NO	N/A	EROSION/DEPOSITION
			20) Floodplain and channel characteristics (i.e., rocks, overflow channels, coarse and/or large woody material) are adequate to dissipate energy
			21) Point bars are revegetating with riparian-wetland vegetation
			22) Lateral stream movement is associated with natural sinuosity
			23) System is vertically stable
			24) Stream is in balance with the water and sediment being supplied by the watershed (i.e., no excessive erosion or deposition)
			25) Structural components of the bank protection measure do not exhibit signs of flanking erosion
			26) Evidence of local bed scour adjacent to the bank protection measure is absent or insignificant

Remarks on Functionality:

____

____

____

____

____

____

Summary Functional Determination:

Functional Rating:
Functional ________
Functional-At Risk ________
Nonfunctional ________
Unknown ________

Trend for Functional-At Risk:
Upward ________
Downward ________
Not Apparent ________

Are factors contributing to unacceptable conditions outside the control of the manager?
Yes _____
No _____

If yes, what are those factors?
Flow regulations ___ Mining activities ___ Upstream channel conditions ___
Channelization ___ Road encroachment ___ Oil field water discharge ___
Augmented flows ___ Other (specify)______________________________

Copyright National Academy of Sciences. All rights reserved.

6. TREATMENT/CHANNEL SKETCH MAP (PLAN VIEW)

Map Symbols
(to be determined by field crew)

Study Reach Limits Cross-Section Bank Profile	North Point Flow Direction Impinging Flow	Cut Bank Exposed Island/Bar Structure	Photo Point Treatment Type and Location

7. REPRESENTATIVE CROSS-SECTION

8. VEGETATIVE COVER ON BANK (%)

Turf grass _______	Notes:
Herbaceous Cover _______	
Willow/Brush _______	
Trees _______	

Copyright National Academy of Sciences. All rights reserved.

9. BANK PROFILE SKETCHES

Profile Symbols
(to be determined by field crew)

Bank Top Edge Bank Toe Water's Edge	Failed Debris Attached Bar Undercutting	Engineered Structure Significant Vegetation Vegetation Limit

Copyright National Academy of Sciences. All rights reserved.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
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
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

Copyright National Academy of Sciences. All rights reserved.

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

NON-PROFIT ORG.
U.S. POSTAGE
PAID
COLUMBIA, MD
PERMIT NO. 88

ISBN 978-0-309-37540-5
90000
9 780309 375405

Copyright National Academy of Sciences. All rights reserved.