United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654
National Engineering Handbook

Stream Restoration Design

(210–VI–NEH, August 2007)

Issued August 2007

Cover photo: Streams and rivers are as complex as they are beautiful. A combination of the principles and analytical tools used in the fields of engineering, landscape architecture, geology, hydraulics, hydrology, ecology, and fluvial geomorphology are necessary to properly analyze and design stream and riverine projects.

Preface

The management of streams is a continuing balance between what people want and what plants and animals need. In an ideal world, a stream can satisfy both—in reality, the balance is ephemeral, at best, as streams evolve and humans continue to imprint their desires on the adjoining or upland landscape. Intervention is often needed when the balance becomes so skewed that the function of streams for either people or nature is at risk.

Just as one would consult a doctor regarding an illness affecting the body's function, one should consult a hydraulic engineer, stream ecologist, geomorphologist, aquatic biologist, or other riparian specialist for the diagnosis or treatment of a stream disorder or problem. An inappropriate or poorly designed restoration project can worsen or broaden the disorder. Site-specific designs based on sound, scientific experience are needed to properly select the size, orientation, and location of stream restoration techniques. Effective designs also need to include appropriate management techniques that remove sources of disturbance, allow the design elements to function well together, and enhance the stream's ability for ecological regeneration.

In planning and designing solutions to some stream problems, simply modifying adjacent land and riparian management practices may be all that is needed to improve degraded stream conditions. Streams are integrators of all upland problems, so some stream conditions are symptomatic of mismanagement of their surrounding watershed(s). In these cases, solutions may lie not only in restoring the stream directly, but in changing land uses and management practices throughout the entire watershed.

In a response to heightened environmental sensitivity, softer approaches are increasingly preferred by permitting agencies and the public. Green or natural engineering is making a strong foothold in the restoration of streams. One green technique, streambank soil bioengineering, has been used for centuries, historically with rock, wood, and native vegetation and now including developed plant materials and geosynthetics. Several large soil bioengineering projects were installed on United States streams (and rivers) in the 1930s, but these labor-intensive methods fell from favor largely until the 1960s. Many of the 1960s projects were not designed and constructed for habitat and landscape enhancement but primarily for structural controls. Przedwojski, Blazejewski, and Pilarczyk (1995) noted that the "application of living materials in civil engineering, including river training, is not as well managed as … earth and concrete structures." In the late 1980s to the present, stream restoration practitioners began to fully embrace green engineering and how-to guides and a one-size-fits-all design approach proliferated. New products and materials emerged, such as geosynthetics, specialized planting equipment, as well as selection and release of improved plant species for riparian areas. Engineers, hydrologists, and biologists also recognized the importance of including other disciplines such as fluvial geomorphologists to achieve comprehensive restoration goals.

Though there has clearly been impressive and needed movement toward green stream restoration, a paucity of supporting design research, engineering principles and scholarship exists. Robinson (2002) found that natural stream techniques had not been proven to the degree that conventional riprap has been, and, thus, often appeared more risky to landowners, permitters, and designers.

The state-of-the-art is still developing, as well as the supporting science and technology. This handbook marks a beginning. It contains tools and guidance to support stream restoration activities—specifically tools to use in designing restoration solutions. The focus of this handbook is on the how-to. It provides the user with specific tools to perform analyses and designs. This handbook presents engineering and ecological assessment and design tools that are applicable to a wide range of stream restoration work. The information contained herein represents both green techniques and structural approaches.

Please note that this handbook makes no endorsement of one particular approach over another and is not intended as a requirement document for purposes of funding or permitting. The guidance provided can be used to design and implement some of the techniques used in stream restorations. It is anticipated that as new methods are validated, they will be added to this guidance document or a supporting Web site.

Acknowledgments

Numerous people have provided source information, as well as expert reviews and comments. Their contributions are acknowledged and very much appreciated. The experience that they have helped document in this handbook will promote the science and art of stream restoration design.

Steering team

Carolyn Adams, director, U.S. Department of Agriculture, Natural Resources Conservation Service, East National Technology Support Center, Greensboro, NC

Jerry Bernard, national geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Charlie Galgowski, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Tolland, CT

Howard Hankin, national aquatic ecologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Bruce Newton, director, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Lamont Robbins, co-director, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX (retired)

David Thackeray, national civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, Washington, DC

Technical editors

Jerry M. Bernard, national geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Jon Fripp, stream mechanics engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Kerry Robinson, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, East National Technology Support Center, Greensboro, NC

Publications staff

Lynn Owens, editor, U.S. Department of Agriculture, Natural Resources Conservation Service, National Cartographic and Geospatial Center, Technical Publications Team, Fort Worth, TX

Wendy Pierce, illustrator, U.S. Department of Agriculture, Natural Resources Conservation Service, National Cartographic and Geospatial Center, Technical Publications Team, Fort Worth, TX

Suzi Self, editorial assistant, U.S. Department of Agriculture, Natural Resources Conservation Service, National Cartographic and Geospatial Center, Technical Publications Team, Fort Worth, TX

Contributing authors

Wade Anderson, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

William Armstrong, senior director of development and marketing, BWR Corporation, Bartlesville, OK

Robert Armstrong, senior project manager, Huitt-Zollars, Inc., Dallas, TX

Peggy Bailey, civil engineer, Tetra Tech, Inc., Breckenridge, CO

Phil Balch, stream restoration specialist, The Watershed Institute, Topeka, KS

Laurie Barnes, environmental generalist, Salix Applied Earthcare, Redding, CA

Frank W. Beaver, assistant professor, University of North Dakota, Department of Geology and Geological Engineering, Grand Forks, ND

Jerry Bernard, national geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

David Biedenharn, research hydraulic engineer, U.S. Army Corps of Engineers, Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS (retired)

Todd Bobowick, biologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Torrington, CT

Ruth Book, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Champaign, IL

Kathryn Boyer, fisheries biologist, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Larry Brannaka, assistant professor, University of New Hampshire, Civil Engineering Department, Durham, NH

Diane Brittle, U.S. Geological Survey, Earth Science Information Center, Reston, VA

Rosanna Brown, landscape architect, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Ghislan Brunet, technical director, Maccaferri, Soil Bioengineering and Ecological Systems, MD

Dave Burgdorf, plant materials specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, East Lansing, MI

Janine Castro, geomorphologist, U.S. Fish and Wildlife Service, Portland, OR

Dave Cline, civil engineer, Tetra Tech, Inc., Seattle, WA

Dennis Clute, construction engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Tracey Cohen, landscape designer, The Bioengineering Group, Inc., Salem, MA

Mark F. Colosimo, senior engineering advisor, Department of State, International Joint Commission, Washington, DC

John B. Conroy, U.S. Geological Survey, Rolla, MO

Ron Copeland, research hydraulic engineer, Mobile Boundary Hydraulics, Vicksburg, MS

Frank Cousins, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, East Lansing, MI

Bradley Cutler, Golden Hills Resource Conservation and Development, Oakland, IA

Kaila Dettman, watershed hydrologist, Salix Applied Earthcare, Redding, CA

Ben Doerge, geotechnical civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Martin Doyle, University of North Carolina, Department of Geography, Chapel Hill, NC

Brock Emmert, geomorphologist, The Watershed Institute, Topeka, KS

Lawrence Fragomeli, structural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Katherine Fontaine, civil engineer, Burgess & Niple, Columbus Ohio

Jon Fripp, stream mechanics civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Bill Fullerton, civil engineer, Tetra Tech, Inc., Lafayette, CA

Tony G. Funderburk, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Central National Technology Support Center, Fort Worth, TX

Charles Galgowski, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Tolland, CT

Thom Garday, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Water Management Center, Little Rock, AR

Fred Gasper, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, East Lansing, MI

Larry Goertz, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX (retired)

Wendi Goldsmith, geologist and soil scientist, The Bioengineering Group, Inc., Salem, MA

Shane Green, area range/riparian specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Salt Lake City, UT

William Hansen, hydrologist, U.S. Department of Agriculture, Forest Service, Francis Marion and Sumter National Forests, Columbia, SC

Roberto “Bobby” Hernandez, community planner, U.S. Envioronmental Protection Agency, Water Quality Protection Division, Region 6, Dallas, TX

Jim Henderson, environmental planner, U.S. Army Corps of Engineers, Research and Development Center, Environmental Laboratory, Vicksburg, MS

Chris Hoag, wetland plant ecologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Interagency Riparian/Wetland Plant Development Project, Plant Materials Center, Aberdeen, ID

Doug Holy, national invasive species specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Mark Johnston, project manager, BWR Corporation, Oklahoma City, OK

Meg Jonas, research hydraulic engineer, U.S. Army Corps of Engineers, Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS

Nancy Kennedy, flood plain administrator, City of Edmond, OK

Alica Ketchem, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Richmond, VA

Mary King, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Altoona, WI

Wayne Kinney, streambank specialist, Midwest Streams Inc., Edwardsville, IL

Dennis Law, soil scientist, U.S. Department of Agriculture, Forest Service, Francis Marion and Sumter National Forests, Columbia, SC

Ming-Han Li, assistant professor, Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX

Morris Lobrecht, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Merri Martz, fisheries biologist, Tetra Tech, Inc., Portland, OR

Kenneth W. Mayben, area civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Weatherford, TX

Dinah McComas, civil engineering technician, U.S. Army Corps of Engineers, Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS

Richard B. McComas, civil engineer, Starkville, MS

Danny McCook, geotechnical engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

John McCullah, watershed geologist, Salix Applied Earthcare, Redding, CA

Dan Mecklenburg, ecological engineer, Ohio Department of Natural Resources, Division of Soil and Water Conservation, Columbus, OH

Chris Miller, plant materials specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Somerset, NJ

David Moore, hydraulic engineer, Burgess & Niple, Inc., Columbus, OH

Daniel Moore, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

L. Jean O'Neil, ecologist, U.S. Army Corps of Engineers, Research and Development Center, Environmental Laboratory, Vicksburg, MS (retired)

Michael A. Pace, cartographer, U.S. Geological Survey, Rolla, MO

Paul Pedone, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Portland, OR

Erick Powell, engineer, Brockway Engineering, Twin Falls, ID

David J. Putnam, biologist, U.S. Fish and Wildlife Service, State College, PA

Dick Quinn, hydraulic engineer, U.S. Fish and Wildlife Service, Newton, MA

Ray Riley, water resources planning specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Water Management Center, Little Rock, AR (retired)

Kerry Robinson, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, East National Technology Support Center, Greensboro, NC

Dave Rosgen, hydrologist, Wildland Hydrology, Fort Collins, CO

David Rush, environmental projects coordinator, Red River Regional Council, Grafton, ND

Leland Saele, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX (retired)

Robert Sampson, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Boise, ID

Lanka Santha, civil engineer and CEO, RoLanka International, Inc., Stockbridge, GA

Patti Sexton, civil engineer, Tetra Tech, Inc., Irvine, CA

Don Shanklin, construction engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX (retired)

Douglas Shields, Jr., research hydraulic engineer, U.S. Department of Agriculture, Agriculture Research Service, National Sedimentation Laboratory, Oxford, MS

Darlene Siegel, fisheries biologist, Tetra Tech, Inc., Portland, OR

Andrew Simon, research geologist, U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS

Robert Snieckus, national landscape architect, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

W. Barry Southerland, fluvial geomorphologist, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Christopher Spaur, ecologist, U.S. Army Corps of Engineers, Baltimore, MD

James Stautzenberger, contract specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, South Central Region, Ft Worth, TX (retired)

Lyle Steffen, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE (retired)

Mitchell Strain, civil engineer, Burgess & Niple, Columbus, OH

James Stribling, biologist, aquatic ecologist, Tetra Tech., Inc., Owings Mills, MD

Donald Stover, engineering equipment operator, U.S. Fish and Wildlife Service, Erie National Wildlife Refuge, Guys Mills, PA

John Thomas, project director, Hungry Canyons Alliance, Oakland, IA

Lyn Townsend, forest ecologist, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Stanley W. Trimble, professor, University of California at Los Angeles, Geography Department, Los Angeles, CA

Ronald Tuttle, national landscape architect, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC (retired)

William A. Wallace, structural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

David Walowsky, civil engineering technician, U.S. Department of Agriculture, Natural Resources Conservation Service, La Fayette, NY

Andrew Ward, professor, The Ohio State University, Department of Food, Agricultural, and Biological Engineering, Columbus, OH

Jason Warne, graduate research assistant, University of North Dakota, Department of Geology and Geological Engineering, Grand Forks, ND

Chester Watson, professor, Colorado State University, Fort Collins, CO

Sean Welch, state hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Portland, OR

Kurt Welke, fisheries manager, Wisconsin Department of Natural Resources, Madison, WI

Monica Wolters, biologist, U.S. Army Corps of Engineers, Research and Development Center, Environmental Laboratory, Vicksburg, MS

Alan Wood, state project engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Harrisburg, PA

Donald Woodward, national hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC (retired)

William Worobec, project director, Big Bear Creek Restoration Project, Dunwoody-Big Bear Hunting and Fishing Club, Williamsport, PA

Ken Worster, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Scott Wright, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Tangent, OR

Steven Yochum, hydrologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Lakewood, CO

Reviewers

Wade Anderson, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Clif Baumer, environmental engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Columbia, MO

Tim Beechie, stream ecologist, National Oeanic and Atmospheric Association, Northwest Fisheries Science Center, Seattle, WA

Jerry Bernard, national geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Kathryn Boyer, fisheries giologist, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Kelsi S. Bracmort, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

Art Brate, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Columbus, OH (retired)

Rosanna Brown, landscape architect, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Dave Burgdorf, plant material specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, East Lansing, MI

Janine Castro, geomorphologist, U.S. Fish and Wildlife Service, Portland, OR

Beth E. Clarizia, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Indianapolis, IN

Ron Copeland, research hydraulic engineer, Mobile Boundary Hydraulics, Vicksburg, MS

Dale Darris, conservation agronomist/Corvallis PMC, U.S. Department of Agriculture, Natural Resources Conservation Service, Corvalis, OR

Dave Dishman, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Portland, OR

Ben Doerge, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Eric Fleming, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Salt Lake City, UT

Darcie Frantila, scientific technical editor, Wildland Hydrology, Fort Collins, CO

Jon Fripp, stream mechanics civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

William Fullerton, hydraulic engineer, P.E., Tetra Tech, Inc., Lafayette, CA

Tony G. Funderburk, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Central National Technology Support Center, Fort Worth, TX

Charlie Galgowski, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Tolland, CT

Marie Garsjo, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Larry Goertz, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX (retired)

Craig Goodwin, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Lincoln, NE

Johnny J. Green, director, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Shane Green, state range management specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Salt Lake City, UT

Angela Greene, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Canaan Valley Institute, Davis, WV

Kale Gullett, fisheries biologist, U.S. Department of Agriculture, Natural Resources Conservation Service, East National Technology Support Center, Greensboro, NC

Howard Hankin, national aquatic ecologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC

William Hansen, hydrologist, U.S. Department of Agriculture, Forest Service, Francis Marion and Sumter National Forests, Columbia, SC

Presley Hatcher, chief, Permits Section, U.S. Army Corps of Engineers, Regulatory Branch, Fort Worth, TX

Roberto "Bobby" Hernandez, community planner, U.S. Environmental Protection Agency, Region 6, Water Quality Protection Division, Dallas, TX

Chris Hoag, wetland plant ecologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Interagency Riparian/Wetland Plant Development Project, Plant Materials Center, Aberdeen, ID

Sonia Maassel Jacobsen, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, St. Paul, MN

Robert Joy, plant materials specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, HI

Harold L. Klaege, state conservationist, U.S. Department of Agriculture, Natural Resources Conservation Service, Salinas, KS

John Leif, manager, U.S. Department of Agriculture, Natural Resources Conservation Service, Plant Materials Center, East Lansing, MI

Barb Lensch, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Madison, WI

Ming-Han Li, assistant professor, Texas A&M University, Department of Landscape Architecture and Urban Planning, College Station, TX

Morris Lobrecht, design engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Sharla B. Lovern, agricultural engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Stillwater, OK

Edwin Mas, tropical technology specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Mayagüez, PR

Danny McCook, geotechnical engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Peter D. McKone, wildlife biologist, director of Environmental Services, Dunaway Associates, Fort Worth, TX

Chris Miller, plant materials specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Somerset, NJ

Daniel Moore, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Carlos Morganti, plant material/grazing land specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Mayagüez, PR

Scott Mueller, assistant state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Madison, WI

George Pess, stream ecologist, National Oeanic and Atmospheric Association, Northwest Fisheries Science Center, Seattle, WA

Frank Reckendorf, fluvial geomorphologist, Reckendorf and Associates, Salem, OR

Dean M. Renner, stream mechanics engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Olympia, WA

Kerry Robinson, hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, East National Technology Support Center, Greensboro, NC

Phil Roni, watershed program manager, National Oeanic and Atmospheric Association, Northwest Fisheries Science Center, Seattle, WA

Dave Rosgen, hydrologist, Wildland Hydrology, Fort Collins, CO

Kae Rosgen, Wildland Hydrology, Fort Collins, CO

Glenn Sakamoto, manager, U.S. Department of Agriculture, Natural Resources Conservation Service, Plant Materials Center, Honolulu, HI

Rob Sampson, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Boise, ID

Roy Schiff, Yale University, Ph.D. candidate

Mark Schuller, fisheries biologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Spokane, WA (retired)

Patti Sexton, civil engineer, P.E., Tetra Tech, Inc., CA

Louise O. Slate, civil engineer, project manager, H.W. Lochner, Inc., Raleigh, NC

Marty Soffran, agricultural engineer, SCC Streambank Protection Technical Liaison, U.S. Department of Agriculture, Natural Resources Conservation Service, Salina, KS

Robbin B. Sotir, soil bioengineer, Robbin B. Sotir and Associates, Inc., Marietta, GA

W. Barry Southerland, fluvial geomorphologist, U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center, Portland, OR

Chris Spaur, ecologist, U.S. Army Corps of Engineers, Baltimore, MD

Allan Stahl, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Annapolis, MD

Paul Starkey, civil engineering technician, U.S. Department of Agriculture, Natural Resources Conservation Service, Buffalo, WY

James Stautzenberger, contract specialist, U.S. Department of Agriculture, Natural Resources Conservation Service, Ft Worth, TX (retired)

Ashley Steel, quantitative ecologist, National Oeanic and Atmospheric Association, Northwest Fisheries Science Center, Seattle, WA

Tony Stevenson, state conservation engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Little Rock, AR

Darrel M. Temple, research hydraulic engineer, U.S. Departement of Agriculture, Agriculture Research Service, Stillwater, OK (retired)

Larry Tennity, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Dover, DE

John Thomas, project director, Hungry Canyons Alliance, Oakland, IA

Hans O. Tiefel, professor, Religion and Ethics, College of William and Mary, Williamsburg, VA (retired)

Ron Tuttle, national landscape architect, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC (retired)

Brandon Viers, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Columbia, MO

Andrew Ward, professor, Ohio State University, Department of Food, Agriculture, and Biological Engineering, Columbus, OH

Sean Welch, state hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Portland, OR

Robin White, geologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Albuquerque, NM

Peter Wilcock, professor, Johns Hopkins University, Department of Geography and Environmental Engineering, Baltimore, MD

Alan D. Wood, state project engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Harrisburg, PA

Donald Woodward, national hydraulic engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC (retired)

Ken Worster, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, TX

Scott Wright, civil engineer, U.S. Department of Agriculture, Natural Resources Conservation Service, Tangent, OR

Steven Yochum, hydrologist, U.S. Department of Agriculture, Natural Resources Conservation Service, Lakewood, CO

Executive Summary

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) has worked with private landowners since the 1930s to implement conservation plans that address their farm or ranch natural resource needs. Those plans often include voluntary measures to address problems associated with streams and, increasingly, to enhance habitat functions important to aquatic species of concern. In short, the agency works with the public in managing streams to meet their ecological needs and the needs of people who work and live nearby. NRCS technical assistance is based on science-based solutions that result in installed projects that range from relatively simple streambank protection to more complex plans covering watershed-scale stream and riparian restoration efforts involving multiple partners and agencies. There is a recognized need for the agency's technical guidance documents to be consistent, accurate, available, and current with stream-related innovations and improvements.

In 1998, an NRCS-led effort resulted in 15 Federal agencies producing the document entitled "Stream Corridor Restoration: Principles, Processes, and Practices" (NEH 653). Diverse groups of users, both nationally and internationally, are using this interagency document to plan stream corridor restoration projects. However, this document stopped short of providing specific design guidance tools that are required as the NRCS increasingly becomes involved in stream restoration projects that cover the full range of treatments, from natural to management to structural. These stream restoration projects require designs that can best be developed from a balance of skills in both engineering and ecology. This extensive document was assembled to ensure NRCS specialists and field personnel have the best design tools available.

The primary emphasis of this handbook is on how-to techniques; theory is only briefly discussed. Concise outlines, tables, and formulas are presented. While primarily an NRCS effort, stream and aquatic ecology experts from a variety of Federal, state, and local agencies, as well as private consultants and universities, contributed to the content.

Much of the information herein is not new; it is compiled from a rich system of existing guides used to treat or restore streams. Many of these legacy guides, however, consist of narrowly focused technologies primarily for engineered solutions, constructed earth channels, or bank armor, and do not fully integrate ecological, biological, or geomorphic criteria. NRCS developed guidance in the late 1980s and early 1990s for soil bioengineering practices, but these documents are dated and do not provide a system-based or holistic approach to analysis and design. Other information written and published by others, both inside and outside NRCS, provides guidance for balancing ecological goals with appropriate combinations of management and engineering designs. Guidance, tools, and procedures contained in this design handbook are those currently available for use—no additional research or development was specifically fostered for this effort. As appropriate, information was updated, reformatted, and edited to fit within the handbook's structure.

This handbook does not prescribe specific design procedures, nor does it assume that all stream restorations or rehabilitations will require structural treatments. Successful and sustainable stream work requires a thorough, contextual understanding of dynamic physical, chemical, and biological processes; risks and limitations; and range of applications for appropriate tools. It also involves weighing the wide array of management and intervention options that can be used to attain the desired and achievable condition. The overall stream restoration planning process should result in clear and obtainable goals, which should be implemented through appropriate designs. The best-designed treatment cannot make up for rushed, cookie-cut, or poorly defined plans.

In summary, this assembly of tools will help designers achieve a balance of management and engineering techniques. It does this by providing NRCS and other stream practitioners with principles and methods to restore functions in ways that enhance the natural abilities of streams and stream corridors to self-repair and adjust to variations in sediment and water loads without substantially compromising the needs and goals of the adjacent landowners.

Part 654 Stream Restoration Design

Contents:

Technical Supplements

Introduction

Case Studies

Terminology

This section provides a ready reference for some of the words and phrases used in the field of stream restoration design to the section or sections of the handbook where it is most thoroughly addressed. Other institutional and legal definitions exist for these terms, and many other definitions may exist in published sources. The definitions provided here are in the context of the scope and content of this handbook.

Adaptive management	An approach to management that addresses changing site and project conditions, as well as taking into affect new knowledge; a management approach that incorporates monitoring of project outcomes and uses the monitoring results to make revisions and refinements to ongoing management and operations actions.	Ch. 16
Adfluvial fish	Species that hatch in rivers or streams, migrate to lakes as juveniles to grow, and return to rivers or streams to spawn.	TS 14N
Aggradation	Long-term sediment deposition occurs on the bed of a channel; opposite is degradation or bed erosion.	Ch. 13
Alaska Steeppass Fishway	See Denil Fishway.	TS 14N
Alignment	Planform of a channel.	Ch. 12
Allowable shear stress design method	A threshold channel design technique whereby channel dimensions are selected so that the average applied grain bed shear stress is less than the allowable shear stress for the boundary material.	Ch. 8
Allowable velocity	The greatest mean velocity that will not cause the channel boundary to erode.	Ch. 8
Allowable velocity design method	A threshold channel design technique whereby channel dimensions are selected so that the applied velocity during design conditions is less than the limiting velocity of the channel boundary.	Ch. 8
Alluvial channel	Streams and channels that have bed and banks formed of material transported by the stream under present flow conditions. There is an exchange of material between the inflowing sediment load and the bed and banks of an alluvial channel.	Ch. 7
Alluvial channel design	A design approach whereby a channel configuration is selected so that it is in balance with the inflowing sediment and water discharges.	Ch. 9
Amphidromous fish	Species that move between fresh and salt water during some part of their life cycle, but not for breeding.	TS 14N
Anadromous fish	Species that incubate and hatch in freshwater, migrate to saltwater as juveniles to grow, and return to freshwater as adults to spawn.	TS 14N

Analogy design method	A design approach that is based on the premise that conditions in a reference reach with similar characteristics and watershed conditions can be copied or adapted to the project reach.	Ch. 7 Ch. 9
Analytical design method	The use of bed resistance and sediment transport equations to calculate channel design variables.	Ch. 7
Anastomosed channels	Multiple-thread streams. The multiple channels tend to be narrow and deep because their banks are typically cohesive sediments; often found on alluvial fans.	Ch. 1
Anthroprogenic constraints	Constraints on a stream or river that are caused by human activities or constructed projects.	Ch. 2
Annual duration gage analysis	The analysis of the recorded peak flow values that have occurred for each year in the duration of interest; typically used for the estimate of flows with return intervals in excess of 2 years.	Ch. 5
Annual flood	The highest peak discharge that can be expected to occur on average in a given year.	Ch. 5
Areal sediment sampling	See Surface sediment sampling.	TS 13A
Arid	An area which generally has insufficient rainfall to support conventional agriculture without supplemental irrigation.	TS 14I
Armor layer	A streambed containing at least some sediment that is too large to be transported by the hydraulic flow conditions, finer particles are selectively removed, leaving a layer of coarser materials.	Ch. 7, TS 13A
Armor layer (sampling)	Technique used to sample the upper layer of coarse surface layer material.	TS 13A
Articulating concrete block (ACB)	A matrix of interconnected concrete block units installed to provide an erosion resistant revetment for streams and rivers.	TS 14L
Attenuation	The subsidence or flattening of a floodwave as it moves down the channel.	Ch. 6
Avulsions	Occur when bank erosion and longitudinal adjustment occur at a large scale and is typically characterized by rapid changes in channel planform.	Ch. 1
Barb	See Stream barb.	
Baseflow	See Low flow.	
Band-aid solution	Treatment techniques used to address small, local issues.	Ch. 14
Bank zone	The area above the toe zone, located between the average water level and the bankfull discharge elevation.	Ch. 4, TS 14I

Bankfull depth	The distance from the deepest part of the channel to the bankfull elevation line, typically measured across a straight section (riffle) of a channel.	Ch. 3
Bankfull discharge	Used as a surrogate for channel-forming discharge, defined, in part, by the visual identification of morphological bankfull indices.	Ch. 5
Bankfull indices	Field indicators of bankfull discharge.	CH. 5, TS 5
Bankfull width	The width of channel at bankfull elevation.	CH. 3
Bankline migration	The adjustment of planform in natural meandering channels.	Ch. 12
Bat	A flying mammal (*Chiroptera*). TS13D	Ch. 3
Bed control structure	A type of grade control structure that is designed to provide a hard point in the streambed that is capable of resisting the erosive forces of the stream.	TS 14G
Bed zone	The bottom of the channel.	Ch. 4, TS 14I
Bedding layer	See Filter layer.	TS 14K
Bedform scour	Vertical channel bed movement that results from the troughs between crests of the bedforms.	TS 14B
Bedrock	A solid rock on the face or beneath the Earth's surface.	Ch. 3
Bend scour	Bed erosion along the outside of a river or stream bend.	TS 14B
Bendway weirs	A flow-changing bank stabilization technique used to protect and stabilize stream and river banks. Flows are directed over the weir perpendicular to the angle of the weir.	TS 14H
Biota	The plants and animals of a region.	Ch. 1
Braided streams	Multiple-thread streams formed in response to erodible banks, high bed-material sediment load, and rapid and frequent variations in stream discharge. The multiple channels of braided streams tend to be shallow and wide.	Ch. 1
Branch packing	A soil bioengineering technique used to fill localized slumps and gullies. It involves the use of alternating layers of live cuttings and soil.	TS 14I
Bridge pier scour	Erosion of a streambed around the piers of bridges.	TS 14B
Brush layering	A soil bioengineering technique that provides protection against surface erosion and shallow-seated slope failure. It involves the use of alternating layers of live cuttings and soil.	TS 14I

Brush mattress	A streambank soil bioengineering technique that includes a layer of live cuttings placed flat against the sloped face of the bank.	TS 14I
Brush revetments	A soil bioengineering technique used to stabilize streambanks. Brush and tree revetments are nonsprouting shrubs or trees installed along the toe of the streambank to provide bank erosion protection and to capture sediments.	TS 14I
Brush spur	A long, box-like structure of brush that extends from within the bank into the streambed. They function very similarly to stone stream barbs.	TSs 14I, 14J
Brush trench	A soil bioengineering technique that is a row of live cuttings that is inserted into a trench along the top of an eroding streambank, parallel to the stream. The live cuttings form a fence that filters runoff and reduces the likelihood of rilling.	TS 14I
Brush wattle fence	See Wattle.	
Bulk sediment sampling	See Volumetric sediment sampling.	TS 13A
Burst swimming speed	Refers to the highest swimming speeds of a fish; generally lasts less than 20 seconds and ends in extreme fatigue.	TS 14N
Catadromous fish	Species that hatch in saltwater, migrate to freshwater as juveniles to grow, and return to saltwater to spawn.	TS 14N
Catchment	See Drainage area.	
Celerity	The speed that a floodwave moves down the channel.	Ch. 6
Channel alignment design	Techniques used to establish a stable channel planform.	Ch. 12
Channel classification	See Classification.	
Channel evolution	Systematic changes of a stream channel to a perturbation.	Ch. 3
Channel evolution model (CEM)	A model that illustrates the stages through which a stream progresses when subjected to destabilizing influences.	Ch. 3
Channel evolution model classification	A classification system that provides a predictable sequence of change in a disturbed channel system.	Ch. 3
Channel-forming discharge	Concept based on the idea that for a given alluvial stream, there exists a single discharge that, given enough time, would produce the width, depth, and slope equivalent to those produced by the natural flow in the stream. This discharge, therefore, dominates channel form and process.	Ch. 5
Channel slope	The average slope of the longitudinal thalweg profile.	Ch. 1
Channel stage classification	A stream classification system based on the channel evolution model.	Ch. 3
Channel stages	See Channel evolution model.	

Channel storage	Water that is temporarily stored in a natural or constructed channel while en route to an outlet.	Ch. 5
Channelization	The alteration of an existing river or stream for a specific physical, biologic, or aesthetic purpose.	Ch. 1
Check dam	A small dam constructed to slow stream velocity and/or prevent degradation.	TS 14P
Classification	The categorization of a stream reach into a specific class based on factors and measurements such as dominant mode of sediment transport, entrenchment ratio, and sinuosity. Streams can also be classified by their biota, habitat conditions, baseflow levels, and direct measures of water quality.	Ch. 3
Clear water scour	Occurs when there is insignificant transport of bed-material sediment from the upstream into the contracted section.	TS 14B
Coefficient of determination	Usually expressed as R^2, this commonly used measure of the goodness of fit is a dimensionless ratio of the explained variation in the dependent variable over the total variation of the dependent variable.	Ch. 5 Ch. 9
Coir fascine	A soil bioengineering technique used to stabilize streambanks. A manufactured product consisting of coconut husk fibers bound together in a cylindrical bundle held by natural or synthetic netting.	TS 14I
Compaction	The process of densifying soil so that air is expelled and the pore space is reduced.	TS 14I
Conditional letter of map amendment (CLOMA)	Provides Federal Emergency Management Agency's comment on whether a proposed project would be excluded from the Special Flood Hazard Area.	Ch. 17
Conditional letter of map revision (CLOMR)	Provides for a review of whether a proposed project within the Special Flood Hazard Area meets the minimum flood plain management criteria of the National Flood Insurance Program.	Ch. 17
Confidence limits	Provide a measure of the uncertainty or spread in an estimate. In hydrologic gage analysis, they are a measure of the uncertainty of the discharge at a selected exceedance probability.	Ch. 5
Confluence	The point where two streams or rivers merge. If they are of approximate equal size, this point may be called a fork.	Ch. 2
Conservation management unit (CMU)	An area having similar land use and treatment needs and management plan.	Ch. 4
Constraints	Limitations on the physical or biologic behavior and characteristics of a stream.	Ch. 2
Constructed channel	A ditch or reconstructed natural channel.	Ch. 2

Construction inspector	The person responsible for the day-to-day quality control inspection required to ensure that the work is installed according to the design, industry standards, and contract requirements.	Ch. 15
Contour fascines	See Fascines.	
Contract types	The many methods used to direct and pay for the installation of stream restoration or stabilization. The contract types vary primarily by administrative burden, construction oversight, and incentive for the contractor to control cost.	Ch. 15
Contracting officer (CO)	The person responsible for administering the contract including ensuring that the proper type of contract is being used and funds are spent according to regulations.	Ch. 15
Contracting officer's representative (COR)	The person responsible to the state engineer and the contracting officer to see that the work is carried out as designed and in accordance with the contract requirements.	Ch. 15
Contraction scour	Erosion of a streambed that occurs when the flow cross section is reduced by natural features, such as stone outcrops, ice jams, or debris accumulations, or by constructed features such as bridge abutments.	TS 14B
Conveyance	A measure of the flow-carrying capacity of a cross section.	Ch. 6
Cost reimbursement contract	A contract type whereby the contractor is paid for identified costs that are defined as reimbursable. See Contract types.	Ch. 15
Crib wall	A soil bioengineering technique used to stabilize streambanks. The crib is a hollow, box-like structure of interlocking logs or timbers. The structure is filled with rock, soil, and live cuttings or rooted plants.	TS 14K
Crimping and seeding	A soil bioengineering surface roughening treatment that secures straw to the surface. It is a temporary surface treatment that protects and promotes the establishment of permanent grasses and vegetation.	TS 14I
Critical shear stress	The shear stress at the initiation of particle motion.	Ch. 8
Cross-section area	See Flow area.	
Cross vane structure	A structure that provides grade control and a pool for fish habitat.	Ch. 11, TS 14G
Crumb test	A common field test for dispersive clays.	TS 14A
Darting speed	See Burst swimming speed.	
Dead stout stakes	Diagonally cut 2- by 4-inch lumber used to secure soil bioengineering practices.	TS 14I
Deflector	A structure that forms a physical barrier to protect the bank, and forces the flow to change direction either by direct impact or deflection.	TS 14H

Degradation	Long-term sediment removal occurring through increased erosion from the channel bed.	Ch. 13
Denil fishway	A rectangular channel fitted with a series of symmetrical, closely spaced baffles that redirect flowing water and allow fish to swim around or over a barrier.	TS 14N
Denil ladder	See Denil fishway.	
Depth	The distance between the channel bottom and the water surface.	Ch. 6
Design flows	Stream restoration design should consider a variety of flow conditions. These flows should be considered from both an ecological, as well as a physical, perspective.	Ch. 5
Design layout	The physical location of design elements in a stream restoration project; the most common methods used to locate features on a drawing include referencing to a baseline or centerline, creating a grid, or using a global positioning system (GPS).	Ch. 15
Design storm	A prescribed precipitation distribution and associated recurrence interval.	Ch. 5
Dimensionless shear stress	The ratio of the critical shear stress and the product of the grain diameter and the submerged specific weight of the particle, also referred to as the Shields parameter.	Ch. 8
Discharge	The rate of flow, often expressed in cubic feet per second, or ft^3/s.	Ch. 5
Disturbances	Changes to the physical or ecologic condition that are outside of the normal range of natural variations. Disturbances can be natural or anthropogenic.	Ch. 1
Ditch	A long, relatively narrow, constructed channel.	Ch. 10
Do Nothing option	See Future without action alternative.	
Dominant channel processes	Dominant channel processes are the forces at work in the watershed, which cause and limit channel change.	Ch. 13
Dominant discharge	See Channel-forming discharge.	
Dormant post planting	A soil bioengineering technique involving the use of large dormant stems, branches, or trunks of live woody plant material, that are planted for bank erosion control and creation of riparian vegetation.	TS 14I
Drag	The fluid force component acting on a sediment particle, which is parallel to the mean flow.	TS 14J
Drainage area	The area from which surface rainfall runoff is contributed to a specific point.	Ch. 5

Drained soil conditions	This is not a description of the water level in the soils, but rather a description of the pore pressure condition in the soil when it is loaded. A drained condition implies that either no significant pore pressures are generated from the applied load or that the load is applied so slowly that the pressure dissipates during the slowly applied loading. See Undrained soil conditions.	TS 14A
Duration	The length of time that water flows at a given discharge or a given depth.	Ch. 6
Effective discharge	The mean of the arithmetic discharge increment that transports the largest fraction of the annual sediment load over a period of years; often used as a surrogate for channel-forming discharge.	Ch. 5
Embankment bench	A technique used to stabilize steep banks with little or no disturbance at the top of the slope and minimal disturbance to the streambed. A gravel bench is constructed along the toe and protected with riprap.	TS 14K
Endangered Species Act (ESA)	A 1973 Act of Congress instructing Federal agencies to carry out programs to conserve endangered and threatened species and to conserve the ecosystems on which these species depend.	Ch. 17
Energy	A property of a body or physical system which enables it to move against a force. It is the amount of work required to move a mass through a distance.	Ch. 6
Engineer	The person responsible for the technical requirements of project installation and represents the owner.	Ch. 15
Entrenchment	The extent of vertical containment of a channel relative to its adjacent flood plain.	Ch. 3
Entrenchment ratio	The flood-prone width divided by the bankfull width.	Ch. 3
Ephemeral stream	A stream or reach of a stream that flows only in direct response to precipitation, and whose channel is above the water table at all times. The term may be arbitrarily restricted to a stream that does not flow continuously during periods of as much as a month.	Ch. 7
Ephemeroptera, Plecoptera, and Trichoptera Index (EPT)	A biologic assessment technique that is used to assess land use and water quality within a watershed. It uses benthic macroinvertebrates, such as stoneflies, mayflies, and caddis flies as indicators.	Ch. 3
Equilibrium bed slope	The slope at which the sediment transport capacity of the reach is in balance with the sediment transported into it.	Ch. 13, TS 14B
Equipment rental contracts	A contract type used in instances where a fixed-price construction contract would be impractical because of the nature of the work and when it would not be feasible to prepare detailed drawings and specifications. It requires substantial construction oversight. See Contract types.	Ch. 15

Equilibrium slope	The slope of a channel at which the sediment transport capacity of the reach is in balance with the sediment transported into it.	Ch. 13, TS 14G
Erosion	The wearing away of soil by running water, wind, or ice.	Ch. 1
Erosion control blankets (ECB)	A temporary protective blanket laid on top of bare soil vulnerable to erosion; commonly made of mulch, wood fiber, or synthetics.	TSs 14D, 14I
Erosion control fabric	See Erosion control blankets.	TSs 14D, 14I
Erosion stop wattle fence	See Wattle.	
Excavated bench	A technique used to stabilize steep banks with little or no disturbance at the top of the slope and minimal disturbance to the streambed. It involves shaping the upper half or more of the high bank to allow the formation of a bench to stabilize the toe of the slope.	TS 14K
Extremal hypothesis	A hypothesis that assumes a channel will adjust its geometry so that the time rate of energy expenditure is minimized.	Ch. 9
Facet	A distinct morphological segment of a longitudinal profile; riffle, pool, run, or glide (tail-out).	TS 3E
Fascine	A soil bioengineering technique used to provide stabilization to the toe of streambanks. A long bundle of live cuttings bound together into a rope or sausage-like bundles.	TS 14I
Federal Acquisition Regulations (FAR)	Regulations that govern Federal contracts.	Ch. 15
Filter layer	A layer that prevents the smaller grained particles from being lost through the interstitial spaces of the riprap material, while allowing seepage from the banks to pass. This layer typically consists of a geosynthetic layer or sand, gravel, or quarry spalls.	TS 14K
First-order stream	An unbranched tributary.	Ch. 3
Fish ladders	The broad category of techniques used to provide migrating fish with upstream passage around or through fish passage barriers.	TS 14N
Fish screens	The broad category of devices used to preclude adult and juvenile fish from entering flow diversion structures, pump intakes, diversion channels, pipes, or penstocks.	TS 14N
Fishways	See Fish ladders.	
Fixed-price contract	In most cases, considered to be the preferable type of construction contract. However, it requires an accurate cost estimate and construction details. See Contract types.	Ch. 15

Flood	A general term given to a relatively high flow measured in height or discharge quantity.	Ch. 5
Flood frequency	The anticipated period in years before a given flood will reoccur.	Ch. 5
Flood insurance rate map (FIRM)	The official map of a community on which the Federal Emergency Management Agency has delineated both the special hazard areas and the risk premium zones applicable to the community.	Ch. 17
Flood plain maps	Maps developed by the National Flood Insurance Program to reduce damages and loss of life caused by floods. The basis for flood management, regulation, and insurance requirements by identifying areas subject to flooding are provided.	Ch. 17
Flood-prone width	The width of the active flood plain at the flood plain elevation (twice the maximum bankfull depth); composed of the active channel (bankfull width) and left and right flood plain (flood-prone) widths.	Ch. 3
Floodway	The channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation by more than designated height.	Ch. 17
Flow area	The area of the cross section between ground and water surface.	Ch. 6
Flow-changing devices	A broad category of structures which can be used to divert flows away from eroding banks.	TS 14H
Flow depth	See Depth.	
Flow duration	The percentage of time that a flow level is equaled or exceeded in a stream or river, typically represented with a flow-duration curve.	Ch. 5
Flow-frequency analysis	A consistent, statistical method for denoting the probability of occurrence of flows at a specific point in a stream system.	Ch. 5
Fluvial	Streams and rivers, in geography and Earth science, it is used to refer to all topics related to flowing water.	Ch. 1
Fluvial fish	Species that live in the flowing waters of rivers or streams, but migrate between rivers and tributaries for breeding, feeding, or sheltering.	TS 14N
Fluvial geomorphology	The study of the origin and evolution of landforms shaped by river processes.	Ch. 1
Force account agreements	Used when the sponsor performs the work using its own equipment and personnel.	Ch. 15

Formal contract	Under the Federal Acquisition Regulations as of 2005, formal contracts must be used for projects with a value greater than $100,000.	Ch. 15
Friction factor (*f*)	The roughness coefficient in the Darcy-Weisbach velocity equation.	Ch. 6
Froude number	A dimensionless ratio, relating inertial forces to gravitational forces, and representing the effect of gravity on the state of flow in a stream.	Ch. 6
Future without Action alternative	The option that involves allowing the site to progress without a project. The resources, both physical and ecological, that may be lost by not implementing the project are assessed as part of this alternative.	Chs. 2, 14
Gabion	A rock-filled wire mesh basket used to stabilize streambanks and slopes.	TS 14K
Gabion grade control	Grade control structures built with rock-filled wire mesh baskets.	TS 14G
Gage analysis	The use of statistical techniques to estimate probable frequency of flow events from recorded stream or river gage records.	Ch. 5
General permits	Issued Nationwide or regionally for categories of activities that are either similar in nature and cause only minimal individual and cumulative adverse impacts.	Ch. 17
General scour	Streambed erosion affecting the entire channel cross section.	TS 14B
Geocell	A product composed of polyethylene strips, connected by a series of offset, full-depth welds to form a three-dimensional honeycomb system.	TS 14D
Geogrid	A geosynthetic formed by a regular network of integrally connected elements with apertures greater than a quarter inch to allow interlocking with surrounding soil, rock, earth, and other surrounding materials to function primarily as reinforcement.	TS 14D
Geologic assessment	The review of both the surface and subsurface features of geology and their possible impacts on a stream or river.	Ch. 3
Geomorphic analog	The use of a stable stream reach as a template for restoration design.	Ch. 2
Geomorphic goals	Goals or objectives based on concepts of landscape position, landforms, and ongoing processes that change them.	Ch. 2
Geomorphology	The study of the origin and evolution of landforms.	Ch. 1
Geonet	A geosynthetic consisting of integrally connected parallel sets of ribs overlying similar sets at various angles for planar drainage of liquids and gases.	TS 14D

Geosynthetic	A planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as part of a manmade project structure, or system.	TS 14D
Geotechnical analysis	The evaluation of the forces involved in bank instability problems including gravity acting on the soils in the slope, the internal resistance of soils in the slope, and the seepage forces in the soils in the bank.	TS 14A
Geotextile	A permeable geosynthetic comprised solely of textiles.	TS 14D
Glide	The downstream end of pools, just upstream of the next riffle, where the channel slope becomes adverse as the deeper section is intercepted by the tailing off point bar.	Ch. 11
Goals	The overall desired outcome, such as restore channel to preflood conditions.	Chs. 2, 16
Grade control	See Grade stabilization techniques.	
Grade stabilization techniques	Techniques used to stop channel degradation, typically accomplished by the construction of inchannel structures.	TS 14G
Grain Reynolds number	The ratio of the product of shear velocity and grain diameter to kinematic viscosity.	Ch. 8
Grass-lined channel design method	A threshold channel design technique used where climate and soils can support permanent vegetation, and baseflow does not exist. The approach is similar to the allowable velocity channel design method.	Ch. 8
Gravelometer	Device used to assist with the measurement of particles sampled as part of a pebble count.	TS 13A
Ground water	Water in a saturated zone or stratum beneath the land surface.	Ch. 1
Grout	See Grouted riprap.	
Grouted riprap	A riprap bed where the voids have been filled with concrete; often used where the required stone size cannot be obtained or at sites where a significant and damaging debris load is expected.	TSs 14K, 14G
Gully/gullies	Entrenched channels extending into areas with previously undefined or weakly defined channel conditions.	TS 14P
Gully plug	A small earthen dam constructed at one or more locations along the gully.	TS 14P
Habitat	A specific environment in which a particular plant or animal lives.	Ch. 1
Hybrid design methods	The use of a combination of analytical, as well as analogy and hydraulic geometry design methods, to calculate design variables.	Ch. 7

Hydraulic control structure	A type of grade control structure designed to reduce the energy slope along the degradational zone to the degree that the stream can no longer scour the bed.	TS 14G
Hydraulic depth	The ratio of the cross-section area of flow to the free surface or top width.	Ch. 6
Hydraulic geometry design method	Design approach based on the concept that a river system tends to develop in a predictable way, producing an approximate equilibrium between the channel and the inflowing water and sediment.	Chs. 7, 9
Hydraulic radius	The ratio of the cross-sectional area of flow to the wetted perimeter or flow boundary.	Ch. 6
Hydrodrill	See Waterjet stinger.	
Hydrodrill stinger	See Waterjet stinger.	
Hydro-physiographic area	A drainage basin where the combination of the mean annual precipitation, lithology, and land use produces similar discharge for a given drainage basin.	Ch. 3
Incentive contracts	A contract type that links the contractor's profit to performance by establishing reasonable and attainable targets that are clearly communicated to the contractor. See Contract types.	Ch. 15
Incipient motion design	See Threshold channel design.	
Index of Biotic Integrity (IBI)	A biological assessment technique that uses fish surveys to assess human effects on a stream and its watershed.	Ch. 3
Individual permit	A type of permit that involves the evaluation of a specific project.	Ch. 17
Infiltration	The downward movement of water into the surface of soil.	Ch. 1
Informal contract	Under the Federal Acquisition Regulations as of 2005, informal contracts and contracting procedures can be used for projects with a value of $100,000 or less. Informal contracts are those put in place using simplified acquisition procedures.	Ch. 15
Intermittent stream	A stream that flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas. The term may be arbitrarily restricted to a stream that flows continuously during periods of at least 1 month; also may be a stream that does not flow continuously, as when water losses from evaporation or seepage exceed the available streamflow.	Ch. 7
Irrigation ditch	A long, narrow constructed channel used to convey irrigation water from its source to place of use.	Ch. 1

Jetties	A flow-changing technique used to stabilize and protect stream and river banks. Fence-like structures extending from the bank and into the stream.	TS 14H
J-hook	A rock structure used to provide bank stabilization.	Ch. 11, TS 14G
Joint planting	A streambank soil bioengineering technique that includes cuttings of live woody plant material inserted in the voids of riprap, and into the ground below the rock.	TSs 14I, 14K
Jumping height	The maximum height obtained by a specific species and age of fish. Older and larger fish have greater maximum jumping heights, although some species have no jumping abilities at any age.	TS 14N
Labor-hour contracts	A variation of the time-and-materials contract, differing only in that materials are not supplied by the contractor. See Contract types.	Ch. 15
Lane's relationship	A qualitative conceptual model, also known as a stream balance used as an aid to visually assess stream responses to changes in flow, slope, and sediment load.	Ch. 13
Lane's tractive force design method	See Allowable shear stress design method.	
Large woody materials (LWM)	Habitat and bank stabilization provided until woody riparian vegetation and stable bank slopes can be established. Trees, branches, and rootwads are considered large woody materials. Also called large woody debris.	TS 14J
Letter contracts	Written preliminary contractual instruments that authorize the contractor to begin work immediately.	Ch. 15
Letter of map amendment (LOMA)	An amendment to the currently effective Federal Emergency Management Agency map establishing that a property is not located in a Special Flood Hazard Area.	Ch. 17
Letter of map revision (LOMR)	An official amendment to the currently effective Federal Emergency Management Agency map.	Ch. 17
Letter of permission (LOP)	A type of permit issued through an abbreviated processing procedure.	Ch. 17
Lift	The fluid force component on sediment particles perpendicular to the mean flow direction.	TS 14C
Live bed conditions	May be assumed at a site if the mean velocity upstream exceeds the critical velocity for the beginning of motion for the median size of bed material available for transport.	TS 14B

Live brush sills	A soil bioengineering technique that involves rows of live cuttings inserted into an excavated trench. This treatment is intended to promote sediment deposition and can function as erosion stops.	TS 14I
Live pole cuttings	A soil bioengineering technique that involves the use of dormant stems, branches or trunks of live woody plant material inserted into the ground that are planted for bank erosion control and creation of riparian vegetation.	TS 14I
Live post planting	See Dormant post planting.	
Live siltation	See Live brush sills.	
Live stakes	See Live pole cuttings.	
Local scour	Erosion of the streambed immediately adjacent to some obstruction to flow.	TS 14B
Log crib	See Crib wall.	
Log-Pearson type III distribution	The most commonly used frequency distribution for peak flows in the United States. It applies to nearly all series of natural floods; commonly used for stream gage analysis.	Ch. 5
Longitudinal peak stone toe (LPST)	A type of bank protection involving the placement of a windrow of stone in a peak ridge along the toe of an eroding bank.	TS 14K
Loose rock grade control structure	A simple type of a grade control structure consisting of placing natural stone or other nonerodible elements across the channel to form a hard point.	TS 14G
Low flow	A general term that refers to the average low flows in a stream. It is typically due to soil moisture and ground water. Critical habitat conditions often occur during low flows.	Ch. 5
Low-flow channel	A portion of a channel that conveys low or baseflows.	Ch. 10
LUNKERS	Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids—a technique providing both streambank stability and edge cover aquatic habitat.	TS 14O
Maintenance	Actions taken to ensure that the stream restoration project performs as designed and attaining project objectives.	Ch. 16
Manning's *n*	An empirical factor in Manning's equation which accounts for frictional resistance of the flow boundary.	Ch. 6
Meander	Deviation of the stream direction from the shortest possible path down a stream valley.	Ch. 12
Meander geometry	The five parameters commonly used in the description of meander patterns, including wavelength, radius of curvature, arc length, amplitude, and beltwidth.	Ch. 12

Meander length	The product of the meander wavelength and the valley slope divided by the channel slope.	Ch. 12
Meander ratio	The length of the stream divided by the length of the valley.	Ch. 12
Mobile boundary stability	The rate at which sediment enters the channel reach from upstream equal to the capacity of the reach to transport sediment of the same composition on downstream.	Ch. 7
Model (1–D)	One-dimensional models only consider forces that occur in one direction (usually the streamwise). Velocity and other stream properties may vary upstream and downstream, but not from bank to bank and not from the bed to the water surface.	Chs. 1, 5
Model (2–D)	Models are usually depth-averaged. They simulate variation in the horizontal plane, but assume no variation in the vertical.	Chs. 1, 5
Model–conceptual	Describes the objects and relationships either with words or diagrams.	Ch. 1
Model–empirical	Contains any empirical relationship, one based on data. An empirical model is based, at least in part, on observed data, rather than a thorough understanding of the underlying physical principles.	Ch. 1
Model–lumped	Describes processes on a scale larger than a point, while a distributed model describes all processes at a point, then integrates processes over space and time to produce a total system response.	Ch. 1
Model–mathematical	Formal mathematical models representing objects and interactions quantitatively with equations.	Ch. 1
Model–parametric	Has parameters that must be estimated in some fashion.	Ch. 1
Model–physical	Three-dimensional representations, usually at some relevant scale.	Ch. 1
Model–steady	Predict conditions that occur for a given set of boundary conditions. For example, a flow model might predict the water surface elevation, given a fixed channel geometry and a constant flow.	Ch. 1
Model–stochastic	Outputs are predictable only in a statistical sense. Repeated use of a given set of model inputs produces outputs that are not the same, but follow certain statistical patterns.	Ch. 1
Model–unsteady	Predicted variations that occur with time, such as during the passage of a storm hydrograph, by dividing such an event into a series of steady-state time steps. Complex, unsteady models have feedback loops that allow channel boundaries or other key variables to respond to inputs and change between time steps.	Chs. 1, 5
Momentum	The mass of a body times its velocity.	Ch. 6

Monitoring	The process of measuring or assessing specific physical, chemical, and/or biological parameters of a project.	Ch. 16
Montgomery and Buffington classification	A classification system based on defining channel processes. It is a geomorphic process-based system.	Ch. 3
Muddying-in	The practice of pouring a slurry mix of water and soil into the hole around the cutting stem of a plant to achieve good soil to stem contact.	TS 14I
National Environmental Policy Act (NEPA)	The Federal law establishing a national policy for the environment and requires specific actions by Federal agencies.	Ch. 17
National Flood Insurance Program (NFIP)	A program administered by the Federal Emergency Management Agency providing for flood insurance, flood plain hazard mapping, and flood plain management.	Ch. 17
Nationwide General Permit (NWP)	A type of general permit issued nationally by the U.S. Army Corps of Engineers for specific dredge or fill activities.	Ch. 17
National Pollutant Discharge Elimination System (NPDES)	A provision of the Clean water Act regulating point discharges into waters of the United States.	Ch. 17
Natural channel	A river, stream, creek, or swale that has existed long enough and without significant alteration to establish a dynamically stable route.	Ch. 2
Navigable waters	Defined for U.S. Army Corps of Engineers regulatory purposes as those waters that are subject to the ebb and flow of the tide and/or are presently used, or have been used in the past, or may be susceptible for use to transport interstate or foreign commerce.	Ch. 17
Newbury riffle	A type of constructed loose rock grade control structure.	TS 14G
No Action alternative	See Future without action alternative.	
NRCS Conservation Practice Standards	Guidance provided for applying conservation technology and set the minimum criteria for acceptable application of the technology. State variations on these standards may be more restrictive.	Ch. 4
NRCS contract specialist	The person who assists the administrative officer in contract matters for contracts and agreements.	Ch. 15
NRCS Planning Process	Steps used to develop an appropriate plan for natural resource protection or improvement.	Chs. 2, 4
NRCS State Conservation Practice Standards	Each state determines which NRCS National Conservation Practice Standards are applicable in their state. States add the technical detail needed to effectively use the standards at the field office level, and issue them as state conservation practice standards. Minimum criteria may be more restrictive than the national standards.	Ch. 4

Objectives	The detailed, focused outputs or outcomes that achieve the project goals.	Chs. 2, 16
Open channel flow	Flow where one surface is open to the atmosphere.	Ch. 6
Ordinary high water	The limit of U.S. Army Corps of Engineers jurisdiction in nontidal waters of the United States, in the absence of adjacent wetlands; defined as that line on the shore established by the fluctuations of water and indicated by physical characteristics.	Ch. 17
Outliers	Data points that depart significantly from the trend of the remaining data.	Ch. 5
Owner	The person responsible for contracting for construction. For NRCS Federal contracts, NRCS is considered the owner during construction.	Ch. 15
Partial duration gage analysis	The analysis of the recorded peak flow values above a preselected base value that have occurred for each year in the duration of interest; typically used for the estimate of flows with return intervals less than 2 years.	Ch. 5
Pattern	Plan view of a stream reach.	Chs. 3, 12
Pebble count	Technique used to sample the surface layer of sediments in gravel-bed streams.	TS 13A
Perennial stream	A stream that flows continuously. Streams flowing continuously throughout the year and are generally lower than the water table in the region adjoining the stream.	Ch. 7
Performance of work agreement	An agreement that requires that the value of work to be performed by the sponsoring local organization be determined by negotiation between the sponsoring local organization and NRCS and be included in the project agreement. NRCS must estimate the cost of the work to establish the maximum value of work before signing the agreement.	Ch. 15
Pile foundations	Used to transfer foundation forces through relatively weak soil to stronger strata to minimize settlement. The most likely applications for pile foundations in stream restoration and stabilization projects are as support for bank stabilization structures (retaining wall) and as anchors for large woody material.	TS 14F
Pin deflectors	Variations of the permeable jetty, generally used in streams where only a small reduction in velocity is needed. Generally wood pilings are used for their construction.	TS 14H
Piston aerial sampler	Device used to facilitate underwater aerial sediment sampling of fine material.	TS 13A
Plan	A sequence of logical steps followed to reach a goal or objective.	Ch. 2

Planform	Horizontal alignment of a channel; view is perpendicular to the Earth's surface.	Ch. 12
Point bar	A depositional area formed on the inside bank of a meander that sometimes remains bare of vegetation due to the frequent recurrence of the bankfull discharge.	Ch. 12
Pool	The area in a natural channel deeper and somewhat narrower than the average channel section.	Ch. 12
Practice standards	See NRCS Conservation Practice Standards.	
Pressure head	The potential energy of water, usually the result of its mass and the Earth's gravitational pull.	Ch. 6
Programmatic General Permit (PGP)	A type of general permit issued to avoid unnecessary duplication of regulatory control exercised by another Federal, state, or local agency.	Ch. 17
Project agreements	Any agreement(s) entered into by NRCS and sponsors, in which detailed working arrangements are established for the installation of cost-shared measures.	Ch. 15
Pump intake fish screens	See Fish screens.	
Quality assurance (QA)	Tasks or procedures undertaken to ensure that procedures are adhered to that will assure that the work will meet the minimum requirements. Quality assurance activities vary in accordance with the complexity and hazard class of the stream restoration project.	Ch. 15
Quality assurance plan (QAP)	Identifies the individuals with the expertise to perform various QA tasks, outline the frequency and timing of testing, estimate the contract completion date, and be co-approved by all responsible supervisors.	Ch. 15
Quality control (QC)	Tasks or procedures undertaken to ensure that the work installed meets the minimum requirements of the contract.	Ch. 15
R^2	The coefficient of determination. This commonly used measure of the goodness of fit is a dimensionless ratio of the explained variation in the dependent variable over the total variation of the independent variable.	Chs. 5, 9
Reach	A length of stream or river having some defined uniform characteristics.	Ch. 1
Reclamation	A series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery. The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose, such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses.	Ch. 1

Reconnaissance	A preliminary investigation not involving detailed investigation and relying heavily on existing data and observations.	Ch. 3
Redirective structure	A flow-changing bank stabilization technique. Designed to be placed in the stream, minimize direct impact, and rely more on the characteristics of fluid mechanics to modify the streamflow direction.	TS 14H
Reference reach design method	An alluvial channel design approach whereby channel dimensions are selected from a similar stable channel.	Chs. 2, 9
Regime design method	An alluvial channel design approach whereby channel dimensions are selected with the aid of empirically derived equations.	Ch. 9
Regional curves	A tool frequently associated with the Rosgen geomorphic channel design approach, but also applicable to other design methods. It involves bankfull dimensions correlated to drainage area. See Hydraulic geometry design.	Ch. 11, TS 5
Regional general permits (RGPs)	A type of general permit issued regionally.	Ch. 17
Regression equations (gage analysis)	Used to transfer flood characteristics from gaged to ungaged sites through use of watershed and climatic characteristics as predictor variables.	Ch. 5
Regulated stream systems	Streams or rivers that are cleared of wood, dammed, channelized, leveed or constrained by other types of hard structures.	Ch. 1
Rehabilitation	Making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat.	Chs. 1, 2
Resource management systems (RMS)	Sets of approved conservation practices.	Chs. 2, 4
Restoration	The reestablishment of the structure and function of ecosystems. Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions.	Ch. 1
Retard	A flow-changing bank stabilization technique. A retard structure increases flow resistance by increasing drag, thereby slowing the velocity in the vicinity of the structure. These structures are more porous with a high percentage of open area.	TS 14H
Reynolds number	A dimensionless ratio, relating the effect of viscosity to inertia, used to determine (index) whether fluid flow is laminar or turbulent.	Ch. 6
Riffle	The area in a natural channel that is wider and shallower than the average channel section.	Ch. 12
Riffle pool spacing	The distance between the riffles and the pools in a channel.	Ch. 12

Rigid boundary stability	Attained when the interaction between flow and the material forming the channel boundary is such that the soil boundary effectively resists the erosive efforts of the flow.	Ch. 8
Rigid drop grade control structure	A complex type of grade control structure that is used for large drops. These structures are frequently constructed of concrete or a combination of sheet pile and concrete.	TS 14G
Riparian zones	The areas between aquatic and upland habitats.	Ch. 1
Riprap	Large stone used to provide immediate and permanent stream and river bank protection.	TS 14K
Riprap sizing	See Stone sizing.	
Risk	The exposure of life, property, and/or the environment to loss or harm.	Chs. 2, 5
Risk analysis	The assessment of the consequences of specific action or inaction to life, property, and/or the environment.	Ch. 2
River	A large natural waterway confined within a bed and banks. In the context of this handbook, the term stream is often used interchangeably with river.	Ch. 1
River classification	See Classification.	Ch. 3
Rolled erosion control products	Consist of both erosion control blankets used for temporary erosion protection and turf reinforcement mats for more permanent erosion protection.	TS 14D
Rootwad revetments	Use of locally available logs and root fans to add physical habitat to streams in the form of coarse woody debris and deep scour pockets.	TS 14I
Rosgen classification	A stream classification system based on measurements of existing morphology.	Ch. 3
Rosgen geomorphic channel design method	A hybrid channel design approach that incorporates geomorphic measurements, hydraulic geometry and some analytical calculations.	Ch. 11
Rosgen stream type	See Rosgen classification.	
Rotary drum fish screens	See Fish screens.	
Run	The steepest section and shortest longitudinally, starting at the downstream end of a riffle as the channel enters the next pool.	Ch. 11
Salmonid	Family of fish which includes the salmons, trouts and chars. All of the species breed in freshwater, are migratory, and spend part of their life cycle in the ocean.	TS 14N
Scour	Downward vertical erosion in a channel bed.	TS 14B

Seasonal stream	An intermittent stream that flows only during a certain climatic season, such as a winterbourne. A stream or segments of a stream that normally goes dry during a year of normal rainfall. Seasonal streams often receive water from springs and/or long-continued water supply from melting snow or other sources.	Ch. 7
Sediment budget analysis	A quantitative sediment impact assessment of channel stability using the magnitude and frequency of all sediment-transporting flows done by comparing the mean annual sediment load for the project channel with that of the supply reach.	Ch. 13, TS 13B
Sediment competence	The ability to move the largest particle made available to the channel.	Ch. 11
Sediment continuity analysis	The volume of sediment deposited in or eroded from a reach during a given period of time is computed as the difference between the volumes of sediment entering and leaving the reach.	Ch. 13
Sediment impact assessment	An evaluation of a designed channel's ability to transport the inflowing water and sediment load, without excessive sediment deposition or scouring on the channel bed.	Ch. 13
Sediment rating curve	Correlates sediment flow to discharge for a stream reach or section.	Ch. 13
Sediment rating curve analysis	Sediment impact assessment technique used to assess the sediment transport characteristics of an existing or proposed stream project. This approach uses sediment rating curves to compare the sediment transport capacity of the supply reach to the existing and proposed project reach conditions.	Ch. 13
Sediment sampling	Technique used to quantify sediment in streams and rivers.	TS 13A
Shear	The pull of water on the wetted area in the direction of flow, and measured in units of force/area.	Ch. 9
Shear stress (average)	The product of the energy slope, hydraulic radius, and unit weight of water. Spatial and temporal variation may result in a higher or lower point value for shear stress.	Ch. 8
Sheet pile	Flat panels of steel, concrete, vinyl, synthetic fiber, reinforced polymer, or wood. Typical applications include toe walls, flanking and undermining protection, grade stabilization structures, slope stabilization, and earth retaining walls.	TS 14R
Shields diagram	Classic method for determining critical shear stress.	Ch. 8
Shields parameter	See Dimensionless shear stress.	
Sinuosity	The channel centerline length divided by the length of the valley centerline.	Chs. 3, 12
Slope stability	See Geotechnical analysis.	

Soil anchor	Technique used to anchor woody material to the streambed or bank to resist fluvial forces.	TS 14E
Soil bioengineering	The use of live and dead plant materials in combination with natural and synthetic support materials for slope stabilization, erosion reduction, and vegetative establishment.	TS 14I
Soil cement grade control	Structures constructed with a mix of Portland Cement and onsite soils.	TS 14G
Specific energy	The energy per unit weight of water at a given cross section with respect to the channel bottom.	Ch. 6
Specific force	The horizontal force of flowing water per unit weight of water.	Ch. 6
Spur dikes	Short dikes that extend out perpendicular from the bank into the channel along a reach of eroded bank.	TS 14H
Stability	A channel is considered stable (or in dynamic equilibrium) when the prevailing flow and sediment regimes do not lead to long-term aggradation or degradation.	Ch. 13
Stakeholders	Individuals or groups who fund a project or are affected by the project.	Ch. 2
Standard individual permit (SP)	A type of permit issued for activities that have more than minimal adverse impacts to waters of the United States. The evaluation of each permit application involves more thorough review of the potential effects of the proposed activity.	Ch. 17
State administrative officer (SAO)	The person responsible for all administrative matters for contracts and most agreements.	Ch. 15
State conservation engineer (SCE)	The person responsible for the design and ultimately responsible for ensuring proper construction of projects in a given state.	Ch. 15
Steady state models	Predict conditions that occur for a given set of boundary conditions.	Ch. 1
Stinger	Metal rod used to facilitate planting live cuttings into rock riprap.	TS 14I
Stone sizing	Technique used to determine the minimum size stone to resist stream velocity.	TS 14
Stream	A small natural waterway with a detectable current. Defined within a bed or banks. In the context of this handbook, the term stream is often used interchangeably with river.	Ch. 1
Streambank	The sides of a stream or river.	Ch. 2
Stream barbs	A flow-changing bank stabilization technique that are low dikes or sill-like structures that extend from the bank towards the stream in an upstream direction. As flow passes over the sill of the stream barb, it discharges normal to the face of the weir.	TS 14H

Streambed	The bottom of a stream or river.	Ch. 1
Stream classification	See Classification.	
Stream corridor	Includes the stream and extends in cross section from the channel's bankfull level towards the upland (perpendicular to the direction of streamflow) to a point on the landscape where channel-related surface and/or soil moisture no longer influence the plant community.	Ch. 1
Stream corridor restoration	One or more conservation practices used to overcome resource impairments and reach identified purposes.	Ch. 1
Stream order classification	A stream classification system based upon the degree of channel branching. An nth order stream is formed by the intersection of two or more (n-1) order streams.	Ch. 3
Stream power	The product of shear stress and mean velocity. A measure of the available energy a stream has for moving sediment, rock, woody, or other debris.	Chs. 6, 11
Stream setbacks	A width required to allow a stream to self-adjust its meander pattern.	TS 14S
Surface sediment sampling	Techniques used to characterize the surface of a gravel bed.	TS 13A
Sustained swimming speed	Refers to the low swimming speeds of a fish species. In general, it can be maintained for extended time periods with little to no fatigue.	TS 14N
S_e or $S_{Y,X}$	The standard error of estimate, typically expressed as S_e or $S_{Y,X}$. This is a measure of the quality of a regression equation and is the root mean square of the estimates. It is a measure of the scatter about the regression line of the independent variable.	Ch. 5
Thalweg	The deepest portion of the channel, sometimes referred to as the low-flow channel.	Ch. 1
Threshold channel	A channel in which channel boundary material has no significant movement during the design flow. The term threshold is used because the channel geometry is designed so that applied forces from the flow are below the threshold for movement of the boundary material.	Ch. 7
Threshold channel design	A design approach whereby a channel configuration is selected so that the stress applied during design conditions is below the allowable stress for the channel boundary.	Ch. 8
Timber crib	See Crib wall.	
Time-and-materials contract	Contract used to procure supplies or services on the basis of direct labor and materials costs. See Contract types.	Ch. 15
Toe zone	The portion of the bank between the average water level and the upper edge of the bottom of the channel.	Ch. 4, TS 14I

Top width	The width of a channel cross section at the water surface.	Ch. 6
Tractive power design method	A threshold channel design technique used in the assessment of channels in cemented and partially lithified (hardened) soils.	Ch. 8
Transfer methods (gage analysis)	Technique used to extrapolate peak discharges upstream or downstream from a stream gage or from gage data from a nearby stream with similar basin characteristics.	Ch. 5
Transition channel	A stream or river which may behave as an alluvial channel in one flow condition and as a threshold channel in another flow condition.	Ch. 7
Tree revetment	See Brush revetments.	
Tributary	A continuous perennial stream.	Ch. 1
Turf reinforcement mats (TRM)	Used to provide permanent erosion protection.	TS 14D
Two-stage channel design method	A hybrid channel design approach that incorporates a natural alluvial channel nested with a constructed flood plain bench.	Ch. 10
U.S. Army Corps of Engineers Regulatory Program	Program that evaluates permit applications for most construction activities that occur in the Nation's waters, including wetlands.	Ch. 17
U.S. Forest Service: Framework of Aquatic Ecological Units	An aquatic framework containing standard terms and classification criteria for aquatic systems and their linkages to terrestrial systems at all spatial scales.	Ch. 3
Uncertainty	The likelihood of a consequence occurring.	Ch. 2
Undrained soil conditions	This is not a description of the water level in the soils, but rather a description of the pore pressure condition in the soil when loaded. An undrained condition assumes pore pressures will develop due to a change in load. The assumption is that the pore pressures that develop are not known and thus must be implicitly considered in the methods used to test samples for this condition. See Drained soil conditions.	TS 14A
Uniform flow	Occurs when the gravitational forces that are pushing the flow along the channel are in balance with the frictional forces exerted by the wetted perimeter that are retarding the flow.	Ch. 6
Unsteady models	Predict variations that occur with time, such as during the passage of a storm hydrograph, by dividing such an event into a series of steady-state time steps.	Ch. 1
Valley slope	The maximum possible slope for the channel invert and is determined by the local topography, and a channel with a slope equal to the valley slope would be straight.	Ch. 9

Vanes	Flow-changing structures constructed in the stream designed to redirect flow by changing the rotational eddies normally associated with streamflow. They are used extensively as part of natural stream restoration efforts to improve instream habitat.	TS 14H
Vegetated gabion	A vegetated gabion incorporates topsoil into the void spaces of the gabion. Woody plantings and/or grass are planted into or through the structure.	TS 14K
Vegetated geogrid	See Vegetated reinforced soil slope.	
Vegetated reinforced soil slope (VRSS)	A soil bioengineering technique that is made up of layers of soil wrapped in synthetic geogrid or geotextile, with live cuttings or rooted plants installed between the wrapped soil layers.	TS 14I
Vegetated riprap	See Joint planting.	
Vegetated rock wall	A mixed-construction soil bioengineering streambank stabilization technique. The structural-mechanical and the vegetative elements work together to prevent surface erosion and shallow mass movement by stabilizing and protecting the toe of steep slopes.	TS 14M
Vegetated soil lifts	See Vegetated reinforced soil slope.	
Vegetated stone	Combining rock with soil bioengineering treatments can achieve benefits from both techniques.	TSs 14I, 14K
Velocity head	The kinetic energy of water.	Ch. 6
Vertical fixed plate fish screen	See Fish screens.	
Vertical traveling fish screen	See Fish screens.	
Visual geomorphic assessment	A qualitative assessment that includes judgment of current conditions, expected future conditions, and the river's anticipated response to the designed project.	Ch. 13
Volumetric sediment sampling	The techniques generally considered to be the standard sediment sampling procedure. It involves the removal of a predetermined volume of material that is large enough to be independent of the maximum particle size.	TS 13A
W-weir	Technique used to provide grade control on large rivers.	Ch. 11
Waterjet	See Waterjet stinger.	
Waterjet stinger	A device that uses high-pressure water to hydrodrill a hole in the ground to plant unrooted cuttings.	TS 14I
Watershed	A topographically bounded area of land that captures precipitation, filters and stores water, and regulates its release through a channel network into a lake, another watershed, or an estuary and the ocean.	Ch. 1

Wattle	A soil bioengineering technique made up of rows of live stakes or poles with live plant materials woven in a basket-like fashion. A wattle fence can be used to deter erosion in ditches or in small dry channel beds to resist the formation of rills and gullies.	TS 14I
Wetlands	Defined for U.S. Army Corps of Engineers regulatory purposes as those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions.	Ch. 17
Wetted perimeter	The length of cross-section boundary between water and ground.	Ch. 6
Width-to-depth ratio	The bankfull width divided by the mean bankfull depth (dimensionless.	Ch. 3
Wolman pebble count	See Pebble count.	
Wolman walk	See Pebble count.	
Woody debris	See Large woody materials.	
Work	Force applied over a distance.	Ch. 6

Chapter Summaries

The NRCS Stream Restoration Design Handbook (NEH654) presents a variety of engineering and ecological assessment and design tools. This handbook is not meant to be read linearly as a book; it is a set of tools and approaches that can be applied to stream restoration designs. The terms river or stream may be used in this handbook, but the terms do not denote a statutory size or watershed drainage area limitation or requirement. Any work performed on rivers and streams is under the purview of all applicable Federal, state, tribal, and local guidelines.

Chapter 1 Introduction: Ecological and Physical Considerations for Stream Projects

The NRCS Stream Restoration Design Handbook provides guidance for teams of engineers, biologists, geomorphologists, hydrologists, landowners, and resource managers who are planning and designing stream restorations. Goals may include controlling floods or sediment sources, improving stormwater drainage, stabilizing banks, improving fish habitat, or restoring the ecological functions and processes of a stream and its flood plain. Many approaches and techniques can be used to reach these goals, but a good understanding of the living and nonliving components of the stream ecosystem, its watershed, how they interact and affect each other, and the timeframes over which stream processes occur will improve the probability of desirable outcomes. Chapter 1 presents a brief overview of current knowledge regarding stream ecosystem processes and functions important to consider when designing stream improvements. For a more comprehensive treatment of these processes, readers may wish to review one of several excellent references, including Stream Corridor Restoration: Principles, Processes, and Practices, developed by the Federal Interagency Stream Restoration Working Group.

Chapter 2 Goals, Objectives, and Risk

Chapter 2 addresses the development of goals and objectives and the assessment of risk from an ecological, as well as a life and property perspective. Identification of stream problems and their causes is a critical step in the overall planning process. Understanding the true nature of stream problems is challenging because of the dynamic nature of streams, their seasonal changes, responses to disturbances, and their ability to recover. Recognizing the current condition of a stream, comparing it to historical conditions, and projecting its future conditions are challenging; nonetheless, the conditions to be documented determine goals and objectives met through the outcomes of the plan. Risk and risk assessment is introduced in this chapter and also described throughout this handbook.

Chapter 3 Site Assessment and Investigation

Chapter 3 describes procedures for assessing watershed and site conditions. Stream corridor inventory and assessment techniques are identified and compared. Information is provided on stream stability, as well as geological and biological assessments. A description of the uses, advantages, and disadvantages of various geomorphic stream classification systems is also provided. This chapter addresses fluvial processes and broader geologic issues related to ecological function, as well as stream design and behavior.

Chapter 4 Stream Restoration Design Process

Conservationists are frequently faced with conditions along and in streams that are characterized as problems because certain functions are not being provided or simply that the overall character of the stream system has changed. It may be that the system is damaged and needs to be repaired or that a shift in perception of stream functions and values has occurred, spurring some sort of action to be taken.

Often, solutions to identified stream problems are suggested at the time that they are identified, such as: “The streambank is sloughing in. We need to put rock riprap on it.” It could be that the problem merits that response. It could also be that the nature of the bank erosion problem is more complex and may be related to a general instability of the stream system. This chapter describes design approach that is applicable to the variety of potential treatment alternatives that are employed.

Chapter 5 Stream Hydrology

Stream restoration designs should consider a variety of flow conditions from both an ecological, as well as a physical perspective. A wide variety of sources and techniques for obtaining hydrologic data are available to the designer. Chapter 5 provides a description of the flows and their analysis that should be considered for assessment and design. The computation of frequency distributions is presented. Transfer equations, risk, and low flow methods are also addressed. This chapter also describes advantages and limitations of four general approaches for estimating channel-forming discharge or dominant discharge for stable channel design.

Chapter 6 Stream Hydraulics

Human intervention in the river environment, especially with projects intended to restore a riverine ecosystem to some healthier state, must take full consideration of streamflow, or stream hydraulics. Chapter 6 provides working professionals, both engineers and non-engineers, with practical information about hydraulic parameters and associated computations. It provides example calculations, as well as information about the role of hydraulic engineers in the project design process.

Chapter 7 Basic Principles of Channel Design

Channel design may involve the stabilization or realignment of an existing stream, or it may involve the creation of an entirely new channel. A wide variety of sources and techniques for designing stable channels are available to the designer. These techniques may focus on open channel design work ranging from natural stream restoration to primarily structural rehabilitations. The purpose of chapter 7 is to provide a framework to the designer to assess the use and application of several analysis and design techniques, which are presented in greater detail in subsequent chapters. Chapter 7 provides background that should be useful in the evaluation of the appropriateness of these techniques to address specific goals, constraints, and conditions. To provide a context for the different design techniques, a clear description of threshold and alluvial channels is presented. In addition, a general description of channel design variables and approaches is presented. These broad and occasionally overlapping categories of stream types and design approaches can be used to evaluate the appropriateness of the design techniques for a specific objective and site.

Chapter 8 Threshold Channel Design

Threshold channel design techniques are used for rigid boundary systems. In a threshold channel, movement of the channel boundary is minimal or nonexistent for stresses at or below the design condition. Therefore, the design approach for a threshold channel is to select a channel where the stress applied during design conditions is below the allowable stress of the channel boundary. There are a wide variety of sources and techniques for designing stable threshold channels that are available to the designer. Chapter 8 provides an overview and description of some of the most common threshold channel design techniques. Examples are provided to illustrate the methods.

Chapter 9 Alluvial Channel Design

Alluvial channel design techniques are generally used for movable boundary systems. In an alluvial channel, there is a continual exchange of channel boundary material with the flow. Therefore, the design of an alluvial channel requires an assessment of sediment continuity and channel performance for a range of flows. Many sources and techniques for designing stable alluvial channels are available to the designer. Chapter 9 provides an overview and description of some of the most common alluvial channel design techniques. The use and application of regime, analogy, hydraulic geometry, and analytical methods are presented and described. Examples are provided to illustrate the methods.

Chapter 10 Two-Stage Channel Design

Constructed channels are part of extensive portions of productive agricultural land in the United States. These channels provide important drainage and flood control functions. However, these agricultural channels are often constructed as traditional trapezoidal ditches using threshold design techniques. While this approach is suitable in some areas, channels of this design can require frequent and expensive maintenance in other parts of the country. This maintenance is often in the form of dredging and cleanout of deposited sediment. In addition, natural ecological functions can be lost. This chapter presents an alternative design to the conventional drainage channel, which seeks to mimic natural alluvial channel processes through the use of a two-stage channel design. This two-stage channel system incorporates benches that function as flood plains. However, these two-stage channels are not an exact copy of natural streams, as the width of the benches is often small due to the confining geometry of the constructed channel. This chapter outlines measurement and analysis procedures that can used to design two-stage channel systems that are more self-sustaining than conventional one-stage constructed channels.

Chapter 11 Rosgen Geomorphic Channel Design

Chapter 11 outlines a channel design technique based on the morphological and morphometric qualities of the Rosgen classification system. This approach has been implemented throughout numerous locations in the United States and is often referred to as the Rosgen design approach. The essence for this design approach is based on measured morphological relations associated with bankfull flow, geomorphic valley type, and geomorphic stream type. This channel design technique involves a combination of hydraulic geometry, analytical calculation, regionalized relationships, and analogy in a precise series of steps. While this technique may appear to be straightforward in its application, it actually requires a series of precise measurements and assessments.

Chapter 12 Channel Alignment and Variability Design

Natural channel design includes establishment of a stable planform and often the incorporation of variability within the channel. The designer of a channel is also often asked to provide an assessment of natural bankline migration, as well. The purpose of chapter 12 is to provide systematic hydraulic design methodologies that can be used in the performance of these tasks. A wide variety of sources and techniques for these assessments are available to the designer. An overview and description of some of the most common design techniques are described. Examples are provided to illustrate the methods.

Chapter 13 Sediment Impact Assessments

Sedimentation analysis is a key aspect of design since many projects fail due to excessive erosion or deposition. A sediment impact assessment is conducted to assess the effect that a full range of natural flows will have on possible significant aggradation or degradation within a project area. Chapter 13 provides a brief overview of several types of sediment impact assessments along with their rigor and level of uncertainty. The focus of this chapter is primarily on techniques that are appropriate for the analysis of alluvial channel, but threshold channels are also described. While there are variants in each of the presented techniques, and more information may be required to perform the assessments described, it is the intent of this chapter to provide the reader with an introduction to sediment impact assessments sufficient to select the appropriate approach for many circumstances. References are provided that outline specifics regarding the mentioned techniques.

It should also be supplemented that while this analysis of the sediment impact assessment is presented in the context of following the channel design, much of this analysis should also be done in the sediment assessment phase of the design process that precedes channel design. However, it is supplemented here as an important closure loop on any proposed design.

Chapter 14 Treatment Technique Design

Stream design and restoration often includes specific treatments on the riparian area, on the bank, or in the bed of a stream. Treatments can include techniques that provide ecological enhancement, as well as protection of these areas. This chapter provides an overview of some of the frequently used treatment techniques for bank protection, grade protection, and habitat enhancement, using a wide range of plant materials, rock, and other inert materials. In addition, analysis techniques that are needed for the successful design of these and other techniques are provided. Where information is available, the benefits, flexibility, risks, and costs of each technique are described from a physical, as well as an ecological perspective.

The list of techniques in this chapter should not be interpreted as an endorsement of any product that is mentioned, nor should it be inferred that one treatment or approach is superior to another. The approaches listed are not exhaustive. Other techniques, as well as variations of each of the ones described, exist and may be appropriate and applicable for use in restoration designs. This chapter provides techniques which often focus on the treatment of local problems, but these techniques and other design elements are often used to provide a holistic approach in larger or more complex restoration projects.

Chapter 15 Project Implementation

Chapter 15 addresses general project implementation issues with an emphasis on NRCS programs, requirements, and guidance. The four phases involved in project implementation are planning, design, contracts and agreements, and installation. This chapter describes how each phase is interrelated, how each phase requires knowledge of the limitations or restrictions of the other phases, and provides a general overview of project implementation.

Chapter 16 Maintenance and Monitoring

Maintenance and monitoring are actions intended to ensure the objectives of the stream restoration project are met over time. Continued performance of the project features and stream system health are dependent on appropriate maintenance and monitoring of the system. Chapter 16 provides an overview of key issues in the development of monitoring and maintenance plans. Incorporation of adaptive management as a component of operations is included as a possible approach to maintenance and operation of the project.

Chapter 17 Permitting Overview

Stream design and restoration design activities are subject to various local, state, and Federal regulatory programs. Most of these regulations are aimed at protecting natural resources and the integrity of the Nation's water resources. Chapter 17 provides a brief overview of the regulatory authorities and programs that may be applicable to stream design work. The focus is providing an awareness-level understanding of this important issue and sources to obtain more and current information. The reader should not interpret the description provided in this chapter as the only source of regulatory requirements. Local, state, and Federal regulatory authorities should be consulted as part of the planning and design efforts.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 1

Introduction: Ecological and Physical Considerations for Stream Projects

Issued August 2007

Cover photos: *Top*—Restoring stream habitat is a balance between water, earth materials, plants and animals, and the goals and objectives of the restoration.

Bottom—The ecology of the stream must be characterized for the current and future conditions, with remedial measures in place.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 1 Introduction: Ecological and Physical Considerations for Stream Projects

Contents

Tables

Figures

Chapter 1

Introduction: Ecological and Physical Considerations for Stream Projects

654.0100 Purpose

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) National Engineering Handbook (NEH), Part 654, Stream Restoration Design provides guidance for multidisciplinary teams who are planning and designing projects to improve streams and their functions. Specific project goals may include flood control, sediment control, improving drainage, stabilizing banks, improving fish habitat, and restoring the ecological functions and processes of a stream and its flood plain.

Many approaches and techniques can be used to reach these goals, but a good understanding of the living and nonliving components of the stream ecosystem, its watershed, how they interact and affect each other, and the timeframes over which stream processes occur will improve the chances of success.

This chapter provides an overview of processes important to stream corridors and their ecosystems. Stream corridors include the stream channel, riparian zone, and flood plains (level areas near the channel, formed by the stream and flooded during moderate-to-high flow events). Stream corridor features are shaped by the forces of flowing water, which depend on local topography and geological characteristics. Stream corridors are also influenced by the cumulative effects of upland and upstream activities and practices, including agricultural production, forestry, recreation, other land uses, or urban development.

The chemical and biological processes that occur within stream systems are intricate and involve numerous interactions, linkages, and feedback loops. Accordingly, this chapter presents a brief overview of current knowledge regarding stream ecosystem processes and functions important to consider when designing stream improvements. For a more comprehensive treatment of these processes, readers may wish to review one of several references, including Stream Corridor Restoration: Principles, Processes, and Practices, developed by the Federal Interagency Stream Restoration Working Group (FISRWG) (1998).

654.0101 Introduction

In 1998, water quality in at least 40 percent (by length) of assessed streams in the United States was listed as impaired by the U.S. Environmental Protection Agency (EPA) (EPA 2000). Reports of the status of freshwater species are also dismal: about a fourth of native freshwater fish species (Williams et al. 1989; Stein and Flack 1997), a half of native freshwater mussel species (Williams et al. 1993), a fourth of native amphibians (Stein and Flack 1997), and a third of native crayfish species (Taylor et al. 1996) are imperiled or extinct. Aquatic species are not only valued natural resources—they are indicators of water quality. The continued rapid decline in aquatic biodiversity (Ricciardi and Rasmussen 1999) places great responsibility on those who work in streams.

654.0102 Restoration, rehabilitation, and reclamation

Some methods of determining objectives have pitfalls. It is probably not possible to fully restore all the functions and values of a stream to a specified original condition, or, more accurately, a condition at a particular point in time. This ignores how streams form and how they maintain themselves. Taking a stream backwards is contradictory to what is known about modern ecology because it implies some static climax state that a natural system tends towards, both elastically and linearly.

Some stream work is clearly repaired in nature, which may be to fix simple erosion problems. Even simple erosion control projects on streams should be designed to maintain or improve ecological functions and values. Repairs can become little more than temporary bandages to treat what is actually a larger problem. This may result in wasted time and resources, if the problems are systemic in nature and reflect more serious imbalances between the stream, its riparian area and corridor, and its watershed.

The following terms are sometimes used interchangeably with regard to working on streams to restore specific functions and values (FISRWG 1998):

- **Restoration** is the reestablishment of the structure and function of ecosystems (National Research Council 1992). Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. Implicit in this definition is that ecosystems are naturally dynamic. It is, therefore, not possible to re-create a system exactly. The restoration process reestablishes the general structure; function; and dynamic, but self-sustaining, behavior of the ecosystem.
- **Rehabilitation** is making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat (Dunster and Dunster 1996). Rehabilitation does not necessarily reestablish the predisturbance condition, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic. Most of the stream projects that NRCS has been involved with are rehabilitations.
- **Reclamation** is a series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery (Dunster and Dunster 1996). The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose, such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses. Restoration differs from rehabilitation and reclamation in that restoration is a holistic process not achieved through the isolated manipulation of individual elements. While restoration aims to return an ecosystem to a former natural condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose (National Research Council 1992).

It may be difficult or impossible to restore a stream to a particular historical condition due to changes in watershed land use and human population, as well as slight to major climatic changes. It may also be difficult or impossible to adequately describe the desired historical condition, both in terms of the stream's pattern and physical characteristics, as well as its physical, biological, and chemical attributes—its ecology. For the purposes of this document, the planned stream actions, for which designs are needed, may be termed restoration, rehabilitation, or reclamation, in the context of the plan's objectives and goals. It is also possible that the plan may create or re-create some functions and values that are new to the stream, or are logical, given historical watershed changes. Most stream work done by the NRCS may be best termed rehabilitation, except where efforts are clearly focused on restoring a range of ecological functions and values to a defined historical condition.

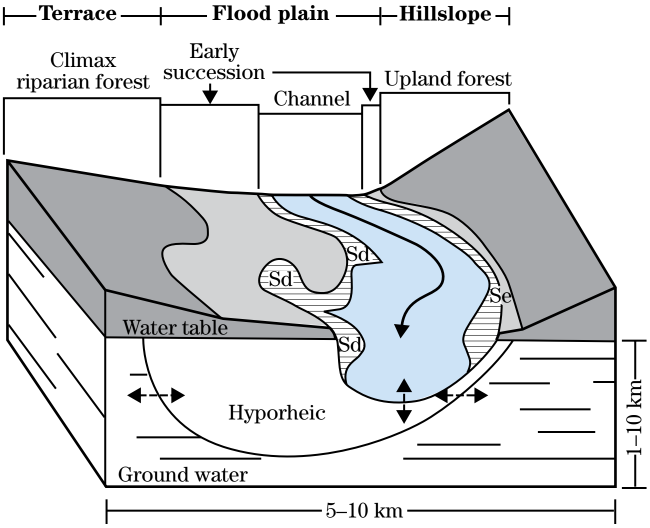
Restoration actions may be passive, simply to remove or attenuate chronic disturbances. Restoration may also be active, to intervene and install measures that are specifically designed to repair damages to the ecological structure and functions of stream corridors.

654.0103 Understanding stream corridor dynamics

Stream corridors are complex and dynamic. Natural or minimally altered stream corridors tend to be physically heterogeneous regardless of their size, with diverse patterns and types of habitats. Larger river corridors show more variation and complexity lateral to the channel, while smaller stream corridors tend to vary more longitudinally. Fluxes of energy, water, and materials throughout the stream corridor system create a dynamic three-dimensional (length, width, depth) mosaic of habitats and physical features (fig. 1–1 (modified from Stanford and Ward 1992)).

Length, width, and depth may also be identified as longitudinal, lateral, and vertical dimensions. These physical features change with time and contribute to the high level of biological diversity typical of stream corridors. The interactions occurring among the different elements of stream corridors are extensive for many of the plant and animal species that inhabit or use them. For example, bats living in the riparian zone eat aquatic insects living in the stream, while stream fishes eat both aquatic and terrestrial insects that thrive in riparian vegetation.

Figure 1–1 Cross-sectional view of generalized stream corridor showing three spatial dimensions in which stream corridor habitats are formed through time



Biota (the flora and fauna of a region) may reside in all habitats (riparian, inchannel, hyporheic, and/or ground water zone). The hyporheic zone is the saturated interstitial area beneath the streambed and in the streambanks, where surface and subsurface waters mix (fig. 1–1). Sd designates sediment deposition sites and Se is a site of bank erosion.

Human activities in stream corridors often simplify physical structure (by removing riparian vegetation). Human activities also may fragment connections, such as between the stream and its flood plain, preventing or diminishing natural processes important to many species. Projects designed to restore or maintain the inherent complexities of stream corridors, ecological linkages, and their physical connections are one solution to arrest the decline of aquatic and riparian species and to improve the Nation's water quality. Of course, projects can also address degraded/altered water quality, flow alteration, habitat enhancement, and other problems confronting stream ecosystems.

(a) Science and stream project design

The complex physical, biological, and social nature of stream corridors creates a challenge to professionals responsible for improving stream functions and conditions. Ward et al. (2001) suggested that scientists often misinterpret stream corridor processes because they usually study regulated systems—those already cleared of wood, dammed, channelized, revetmented, leveed or constrained by other types of hard structures. Systems with more intact natural flow regimes are characterized by high levels of heterogeneity, both in space and in time. From a human perspective, they are also less well behaved, less predictable, and increasingly rare in today's landscapes.

Much additional work is needed to understand the physical and biological processes typical of natural fluvial systems, or even partially altered systems, especially those with braided river channels. Scientifically validated models that help predict the physical behavior of stream systems are based mostly on single-thread meandering channels (Shields, Copeland, et al.

2003). Recent studies in stream ecology emphasize the importance of links between stream channels, riparian areas, flood plains, and hyporheic zones (Gregory et al. 1991; Naiman et al. 1992; National Research Council 1992; White 1993; Brookes, Knight, and Shields 1996; Huggenberger et al. 1998; Molles et al. 1998; National Research Council 2002).

Stream project designers rely on science and professional judgment as they develop stream improvement plans. Because professional judgment is often subjective, and applied experience may be limited, stream improvement project designs may become controversial when different disciplines are involved. Stream corridor projects that integrate the disciplines of fluvial geomorphology, hydrology, aquatic and riparian ecology, and hydraulic and geotechnical engineering are more effective at meeting multiple objectives that accommodate both economic and ecological considerations.

(b) Channel form and fluvial processes: Understanding stream corridor dynamics

Older science regarding physical aspects of streams contains many interesting observations about stream form. Earlier workers argued that form variables like the bed slope, channel width-to-depth ratio, meander wavelength, and bed-material size were related by functional relationships. Furthermore, they argued that disturbed channels (channelized streams) would not conform to these relationships, but would experience adjustment through erosion and deposition that eventually would return them to the appropriate (stable) form. Form studies naturally led to an effort to classify stream reaches based on form variables, and stream classification systems have been developed, ranging from very simple schemes with three or four categories (Shields and Milhous 1992) to those with several dozen categories (Rosgen 1996). More recent science has focused on physical, chemical, and biological processes that produce stream forms.

Since processes are driven by the dynamic variables of climate, tectonics, biological processes (plant succession, die-off, human population growth), the focus on processes has prompted reconsideration of the idea that without human intervention, fluvial systems will tend to approach an equilibrium or stable form. Although earlier workers knew the importance of processes in controlling forms and correctly identified most of the key processes (Leopold, Wolman, and Miller 1964), they often lacked the technology to monitor processes and develop mathematical descriptions. Recent advances allow scientists to collect large quantities of directly measured or remotely sensed data and use the data to build and revise their computational models. Much work remains to be done in understanding and predicting the behavior of stream ecosystems, but recent advances indicate that the best design work is usually based on general, analytical process-based approaches, rather than more subjective or site-specific empiricism.

(c) Using models to understand and manage complex systems

Models are descriptions of systems, which are collections of interrelated objects. An object is some elemental unit on which observations can be made, but whose internal structure either does not exist or is ignored (Haefner 1996). There are many types of models. Conceptual models describe the objects and relationships either with words or diagrams. Physical models, like plaster models of a watershed, are three-dimensional representations, usually at some relevant scale. Formal mathematical models represent objects and interactions quantitatively with equations and are typically implemented on computers.

Conceptual models are valuable frameworks for designing stream projects because they identify important components of the ecosystem and the processes that maintain it (Vannote et al. 1980; Schlosser 1987; Simon 1989). Project design teams can use these models to develop a common understanding of the system and to determine actions that are more likely to result in desired outcomes.

Applications of models

Model realism, precision, and generality should be considered when selecting a model (Levins 1966). Model realism and generality are important when using models as frameworks for understanding the stream (Haefner 1996). Models selected for predicting the outcome of a project (change in channel dimensions, change in fish abundance or community structure) must be precise and realistic, but they do not need to generally apply to all systems. Defense of a model should include explanation of basic algorithms and calibration, as well as an independent validation. Models may not perform well in design of restoration or management actions at a site if they:

- fail to consider important components or processes within the system
- represent critical relationships too simplistically
- substitute professional judgment because data from the system of interest are not available
- use data from recent observations to project responses over decades to centuries
- address only part of the system or part of the life histories of the aquatic and riparian organisms
- do not account for disturbances and unpredictable processes that are important in the system
- do not account for site-specific geological conditions, or assume that they are constant in different watersheds

A good model produces results for existing data or observable conditions. Such a model may provide an expected result for a restored or altered condition, subject to model and data limitations. Remember that no perfect model exists, but models may show the relative differences or directions of changes in a stream ecosystem when alternative treatments or systems are considered.

654.0104 Fluvial systems

(a) Watersheds

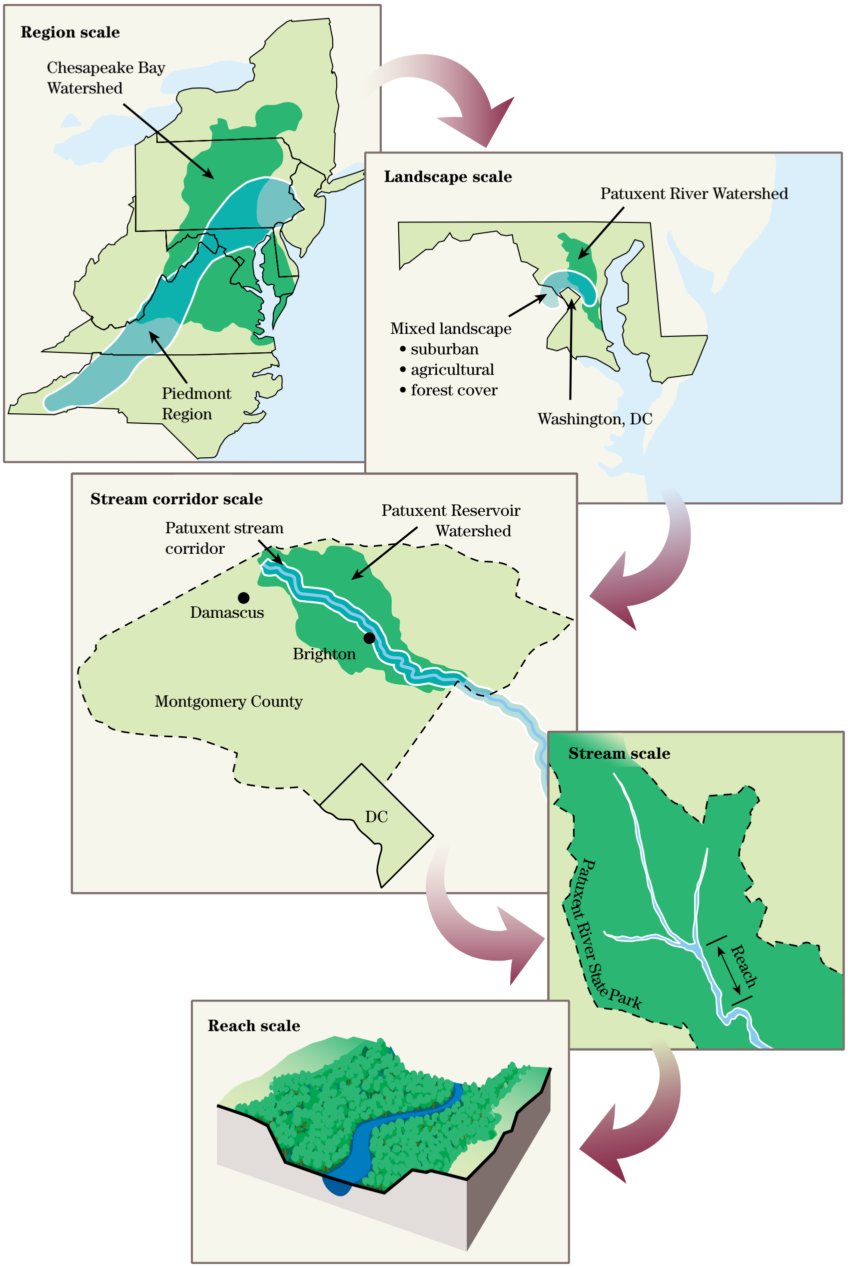
A watershed is a topographically bounded area of land that captures precipitation, filters and stores water, and regulates its release through a channel network into a lake, another watershed, or an estuary and the ocean. Watersheds are nested within one another, with larger watersheds composed of many smaller tributary watersheds, and these smaller tributaries drained by even smaller intermittent channels, ephemeral channels and rills. Watersheds are comprised of a mosaic of soil types, geomorphic features, vegetation, and land uses. If a watershed is divided into uplands and stream corridors, the uplands comprise most of its area (in most basins). Upland features control the quantity and timing of water and materials that make their way to the stream corridor. The environmental conditions of the stream corridor (such as water quantity and quality, riparian function, and fish habitat) are, therefore, linked to the entire watershed, and these linkages go both ways. For example, animals living primarily in upland habitat frequently rely on stream corridors for movement, food, cover, and water. Recent studies have also shown that marine derived nutrients carried up stream corridors in the tissues of salmon enhance the growth and survival of adjacent forest stands from which large wood in those rivers and streams originates (Helfield and Naiman 2003). Although stream project designers may have little or no control over how a watershed is managed, their plans and designs still should consider the past, present, and future status of watershed land use and historical watershed conditions.

Landscape consideration of watersheds: spatial scales

A landscape perspective is important when managing natural resources. The spatial structure of landscapes influences ecological and physical processes such as energy flow, material transport, and species dispersal within a landscape. These processes occur in all three spatial dimensions and over time within a watershed or river basin (Stanford and Ward 1992; Beechie and Bolton 1999).

Resource managers consider spatial structure of landscapes at very large scales (to analyze satellite imagery of large sectors of the Earth's surface) and at much smaller scales (to manage habitat in a stream reach), depending on the issue at hand (fig. 1–2 (FISRWG 1998)). Regardless of project scope, some consideration should be given to all scales. For instance, focusing only on the reach scale may overlook important issues that will dramatically impact the project. While many NRCS projects are applied on relatively short reaches, the stream's watershed should always be considered.

Figure 1–2 Spatial scales surrounding stream corridor ecosystems

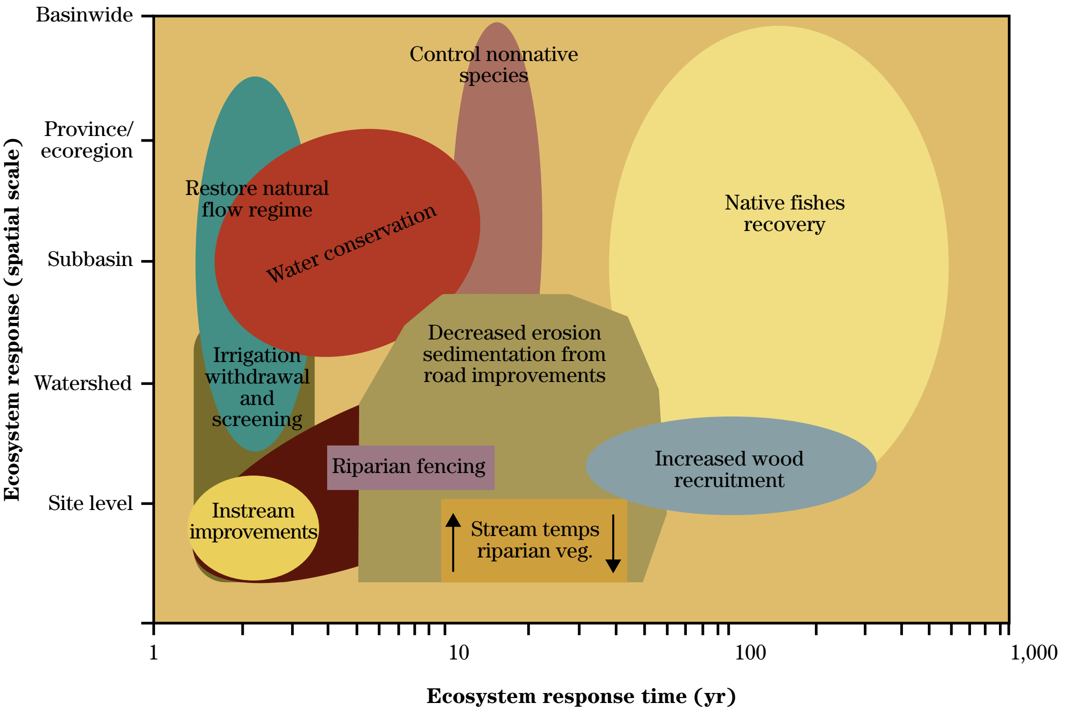


Rivers and streams, and the corridors through which they flow, may be considered long ribbons of aquatic habitat or riverscapes (Fausch et al. 2002). Riverscapes are also important to terrestrial plants and animals because stream corridors provide a transition between wet and dry habitats. Habitat is the place where an organism lives, and includes the range of environmental conditions (physical, chemical, and biological) it needs to grow and reproduce (Odum 1971). The spatial and temporal scales of a habitat are not fixed, but rather determined by the physical and biological processes that create it, the range of activities (home range) of the organism, its interactions with the biotic community, and the population dynamics of the species.

The habitat of a large or relatively mobile organism (Pacific salmon) contains the smaller scale habitats of smaller, or less mobile, organisms (aquatic insects and crayfish). This kind of organization implies a hierarchy of habitats and interactions that are formed by processes and nested in space. How long it takes for these multiple habitats to respond to stream restoration depends on the project's nature and scope and the dynamics of its landscape (fig. 1–3). Species responses to habitat modifications depend not only on the actual site work but also on the ecology of the surrounding watershed.

A hierarchical approach to stream design identifies the main spatial scale at which each ecosystem component influences the characteristics of the stream, but it does not imply that components at lower hierarchical levels are less important than those at higher levels. In fact, the connectivity of the stream environment involves feedback mechanisms by which smaller scale components may influence larger scale patterns and processes (DeAngelis, Post, and Travis 1986; Naiman 1988). Therefore, an effective stream restoration plan should consider factors affecting stream corridor processes at different spatial scales, from landscape to watershed to microhabitat. The plan should also consider factors that influence long-term population status and dynamics of aquatic species and the community of species with which they interact. This type of biological information is often available from researchers at

Figure 1–3 Spatial and temporal responses of ecosystem conditions to stream and watershed restoration actions



local universities or biologists of local fish and wildlife agencies. Focusing exclusively on maintaining local fish habitat by protecting or enhancing selected stream reaches may be ineffective in the long term because effects may be negated by changes in the stream system that occur at larger scales (Frissell and Nawa 1992).

Watersheds, stream corridors, and the dimension of time

Configurations of stream corridors change over time, as does the capacity of a channel to convey and retain water. Over geologic time all streams and their flood plains are active, often reworking entire valley floors by eroding and depositing sediments within their channels and the adjacent flood-prone areas. During smaller timeframes, pools within stream reaches are formed and maintained by erosion, and organic deposits and riffles are formed by deposition of sediments. Long-term trends in fluvial variables can be obscured by fluctuations over shorter timeframes. Stream projects are typically designed based on conditions that prevail over many decades, and they usually have projected lifetimes that do not exceed 50 to 100 years. Some geomorphologists have suggested that fluvial systems tend to reach a physical equilibrium or stability over periods that range from decades to centuries, and have termed this state "dynamic metastable equilibrium" (Schumm 1977).

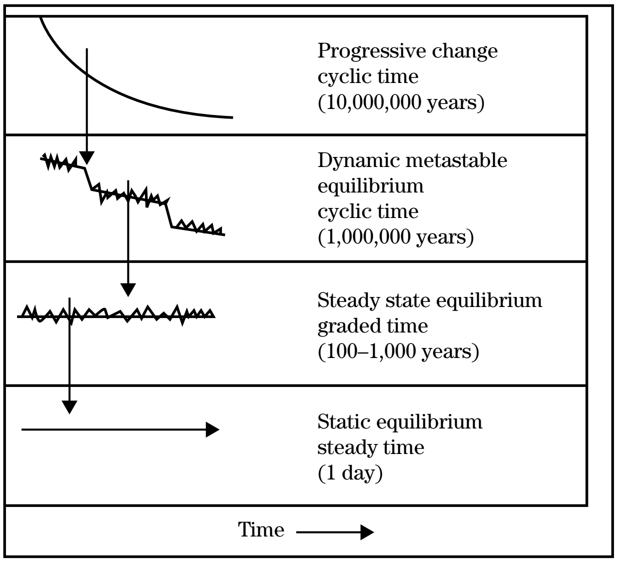
According to this theory, the physical characteristics of channels remain relatively constant during the equilibrium periods, and undergo rapid changes during short episodes that occur when the system exceeds some internal threshold (fig. 1–4). During periods of equilibrium, the channel is adjusted to inputs of water and sediment so that average channel width, depth, slope, and sediment grain size change little for any given reach. The channel transports the same amount of sediment that it receives and experiences no net erosion or deposition, although erosion or deposition may occur at smaller spatial scales, such as pool and riffle habitats. This concept of a dynamic metastable equilibrium has been useful in analyzing the response of stream channels to changes in the watershed, but it may not be valid for all streams. Nevertheless, designers attempt to select channel geometries (width, depth, slope, meander wavelength, bed and bank roughness, bed sediment size) that correspond to a stable condition defined by empirical or theoretical equations. At best, these constructed geometries will be appropriate during the periods of equilibrium. Harder, structural measures may be necessary to prevent changes across a threshold. Less intervention may be required if the stream is allowed to move in its flood plain, or if sediment production from the watershed can be managed.

Movement of water

Water that enters the watershed in the form of precipitation moves from the land into the stream channel as surface runoff or, if it infiltrates, enters as subsurface and ground water flow. Based on its pathways to the channel, streamflow is classified as stormflow or baseflow. Stormflow is the water from precipitation that reaches the channel over a short period of time (during and immediately after a storm event) through surface or subsurface routes. Baseflow is the water that percolates slowly through the ground before reaching the channel, where it maintains flow during periods of little or no precipitation.

Variability of flow is a key factor influencing the biotic and abiotic processes that determine the structure and dynamics of stream ecosystems (Poff and Ward 1990; Covich 1993). The path that water takes through a watershed determines the quantity of sediment and dissolved matter that reaches the stream. In general, the

Figure 1–4 Concepts of geomorphic equilibrium in stream corridor systems



amount of sediment suspended in the water column is greatest in small channels, gullies, and rills, intermediate in sheet flow, and lowest in ground water. Nutrient levels in water are often reduced as subsurface runoff percolates through riparian root zones. Once in the stream, nutrient concentrations are influenced by structures and processes that retard flow or promote retention, including vegetation and large wood within the channel, exchange with the hyporheic zone, or slowing of streamflow in meanders, sloughs, and flood plain depressions. In general, deposition and processing of nutrients are increased by longer flow retention time. Flood control systems designed to increase flow velocities and reduce net retention time of flood waters can greatly alter nutrient dynamics in stream corridor ecosystems.

Movement of inorganic sediments

Watersheds transport sediment, as well as water, but sediment transport usually varies as a function of discharge. As a result, changes in discharge magnitude and duration (downstream of a flood control dam) throughout the watershed magnify changes in sediment discharge. Alluvial channels (those with beds and banks made of materials readily transported by the stream, in contrast to threshold channels that are controlled by bedrock outcrops or materials too large for the stream to frequently transport) constantly adjust their geometry in response to the sediment load they receive.

Sediments range in size from clay particles, only a few microns in diameter, to large boulders, but a given stream is typically dominated by a smaller range of sediment sizes (sand to gravel or just fine sand). The types of stream organisms reflect the quantity and size distribution of sediments that move along or lie on the bed of the stream corridor. Aquatic organisms are quite sensitive to the size distribution of sediments (Shields and Milhous 1992). The frequency of bed-material movement and sediment-size distribution controls the size of microhabitats provided by interstitial spaces of bed substrates. Those streambeds dominated by uniform and small size particles (fine sediments) naturally sustain fewer species of aquatic insects (Benke et al. 1984).

Typically, species-rich stream substrates have particles of a wide range of sizes coarser than sand. The resulting high porosity of the streambed allows exchange of well-oxygenated water in the channel and within the hyporheic zone. This component of stream corridors is yet another zone of complex gradients and transitory boundaries over space and time.

Movement of organic material

Movement of organic material within a stream corridor system also occurs in four dimensions. The timing, quality, and quantity of organic matter transport through a stream system are related to streamside vegetation, channel complexity, aquatic food web dynamics, light intensity (from the sun), seasonal fluctuations in flow, and all of the aforementioned physical processes that influence the movement of water and sediments. Organic material includes parts of trees and shrubs, insects, nutrients in surface runoff, and aquatic organisms.

In forested landscapes, trees in upland areas become structural elements of stream corridors when carried to channels by landslides. In most landscapes, trees and/or shrubs border stream channels, even if the rest of the watershed is too arid or too developed to support woody species. Riparian trees fall into streams and flood plains during windstorms, floods, or bank sloughing and mass failures. Trees and other woody material are critical elements of aquatic ecosystems, affecting both the physical and ecological structure and function of stream corridors (Gregory, Boyer, and Gurnell 2003). The mobility of wood in streams and rivers is highly variable from site to site, depending on the size, slope, and configuration of the channel, as well as the characters of the wood (especially its size, morphology, density, decay rate, and extent to which it is lodged in the channel). Wood accumulations or single logs in unaltered, low-order streams may stay in place for decades or centuries, creating stable step-pool habitats.

Wood in large river channels often shifts with seasonal flows. This can cause considerable concern for river managers who are responsible for ensuring the safety of recreational users or for minimizing risks to infrastructure such as bridges. Still, the growing recognition that large wood is an important component in stream systems has led researchers and managers worldwide to develop innovative techniques for adding large wood to streams and rivers (NEH654 TS14J; Reich, Kershner, and Wildman 2003). Because woody debris can alter the flow path and shape of stream systems, programs exist to both remove and to retain wood in the stream.

654.0105 Channels

(a) Describing channels

The cross section of an average stream channel can vary greatly depending on water flow, amount of sediment carried by the water, and the geology of the terrain. The dimensions of a channel cross section between the sloped banks define the active channel and determine the amount of water that can pass through without spilling over the banks (fig. 1–5). The deepest part of the channel is referred to as the thalweg.

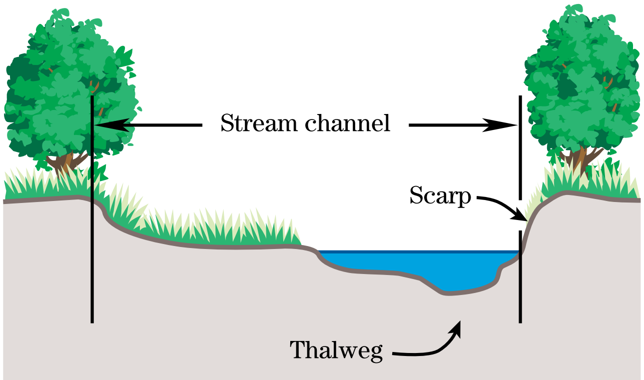
Channel slope is the average slope of the longitudinal thalweg profile. Flow velocity and stream power are proportional to the slope. Because these variables determine the rates of erosion, sediment transport and deposition, channel slope is an important controlling factor in channel form and pattern.

The form of a channel changes from its headwaters to lower elevations. In the steeper terrain of the headwaters, stream channels tend to be single and relatively straight. Channels of intermediate slope tend to maintain a single channel, but with increased sinuosity (curvature). Once in the depositional, flat slope of a watershed's lowlands, channels tend to develop multiple threads (or channels) and very high sinuosity. Multiple thread streams are further divided into braided and anastomosed streams. While static, braided streams are not often observed, they usually are formed in response to erodible banks, high bed-material sediment load, and rapid and frequent variations in stream discharge. The multiple channels of braided streams tend to be shallow and wide. In contrast, the multiple channels of anastomosed streams tend to be narrow and deep, because their banks are typically cohesive sediments. Anastomosed channels are often found on alluvial fans. While the description is a generalization, it should be noted that large parts of the country such as the Midwest have very flat channels, and these channels may either steepen or remain flat with distance downstream.

Natural stream channels are typically never totally straight and display different amounts of curvature or sinuosity. The sinuosity of a stream reach is calculated by dividing channel length by valley length. Sinuosity can also be calculated by dividing valley slope by stream slope. The degree of meandering is low if the sinuosity is less than 1.2, appreciable for sinuosities of 1.2 to 1.5, and high for sinuosities above 1.5. Sinuosity is related to both streamflow and gradient. In general, low to moderate levels of sinuosity are found in the headwaters, and these levels increase as the stream enters the flat and broad valleys downstream.

Independent of their form, stream channels are rarely uniform in depth and tend to have alternating, regularly spaced, deep (pool) and shallow (riffle) areas. Pools typically form where the thalweg approaches the outside bank of the channel at bends, whereas, riffles usually form between channel bends in the zone where the thalweg migrates from one side of the channel to the other. Streambed composition affects the pool and riffle characteristics, as well. Streams with coarse substrates, gravel to cobble-size particles, tend to have evenly spaced pools and riffles, to the extent that pool-to-pool distance is approximately five to seven times the width of the channel at bankfull discharge (the discharge that fills a stable alluvial channel up to the elevation of the active flood plain). In such systems, cobbles and large gravels accumulate in the riffle areas, while smaller particles tend to deposit in the pools. On the other end of the spectrum, streams with sand and silt-dominated substrates do not form true riffles due to the absence of coarse grain sizes. However, they still have evenly spaced pools connected by shallower runs or glides.

Figure 1–5 Cross section of stream channel



For assessment and design, it is useful to categorize stream channels as threshold channels or alluvial channels. Threshold channels have beds and banks that are not easily mobilized by the stream or river flow, while alluvial channels are continuously or frequently reshaped by erosion and deposition. Alluvial channels are shaped constantly by their streamflow. Differentiating between these two types of channels is subjective, since almost all channels have mobile boundaries under extremely high flows. Alluvial channels may be preliminarily assessed with one dominant discharge, but are assessed under a range of expected flow conditions. Threshold channels are so called because the flow forces during a given discharge are at or below the level (threshold) needed to move particles on the channel bed or banks. Typically, threshold channel boundaries are assessed for mobility under design flow conditions. Threshold channels occur when there are bedrock outcrops, or when coarse boundary materials are remnants of earlier fluvial processes, such as glacial outwash. Threshold channels have beds and banks that are mobilized slowly by the streamflow or riverflow, provided there are no human-induced changes in the watershed and stream system. In alluvial channels, there is a frequent exchange of channel boundary material with the flow. Meander migration in stable threshold channels might be a few feet or less annually, while in alluvial channels it could be many feet of movement in response to a single stormflow. The distinction between alluvial and threshold streams is addressed in more detail in NEH654.07.

(b) Key physical variables

Stream channels require up to 13 variables for a complete physical description, but only three governing equations are known, and only about six of the variables are fixed by site conditions (table 1–1 (Hey 1982, 1988)). See FISRWG 1998 for a fuller description of the meaning of each of the variables. Since there are more unknowns than equations, channels are indeterminate systems. For threshold channels, most variables are fixed by site conditions or by the choice of the designer, but alluvial channels can adjust their geometry in several dimensions. Existing models are not capable of accurately predicting long-term behavior of channels even when water and sediment in flows are specified.

Table 1–1 Degrees of freedom and governing equations

Type of channel	Governing equations	Fixed variables	Independent variables	Degrees of freedom	Dependent variables
Threshold, fixed bed, no sediment transport	Continuity, flow resistance	S, W, d_m, λ, Δ, p, z	Q, D, D_r, D_l	2	V, d
Planform and width are fixed, bed is mobile	Above, plus sediment transport	W, d_m, λ, Δ, p, z	Q, Q_s, D, D_r, D_l	3	V, d, S
Fully alluvial	Above equations, plus six additional process equations needed to render the system determinate, but these are generally not available		Q, Q_s, D, D_r, D_l, S_v	>3	All but independent variables

V = mean flow velocity; d = mean depth; S = bed slope; W = width; d_m = maximum flow depth; λ = bedform wavelength; Δ = bedform amplitude; p = sinuosity; z = meander arc length; Q = water discharge; Q_s = sediment discharge; D, D_r, D_l = characteristic sizes of bed, right and left bank sediments, respectively; S_v = valley slope.

Predicting the type of planform a channel will develop (straight, braided, or meandering) or the rate of lateral erosion of streambanks (meander migration) is difficult at best.

(c) Using conceptual models to understand stream channel dynamics

Conceptual models often link structural properties of stream channels with critical processes that operate within them in a qualitative fashion. An example of a process based conceptual model is the incised channel evolution model (CEM) (Schumm, Harvey, and Watson 1984; Simon 1989), which describes changes in straightened channels that are undergoing headward incision. Presented in greater detail in NEH654.03, this conceptual model is based on observations of channels in watersheds undergoing systemwide disturbance.

Although the model does not allow prediction of the magnitude or rate of channel changes, it does link processes and allow qualitative prediction of outcomes (channel widening, progression of incision, and incision control options). The CEM is idealized, and any processes or conditions that are different than the fundamental conditions assumed in the model may alter the outcomes. For example, channels may change the trajectory or location of incision if boundary conditions are changed or pulses of sediment are supplied by incising tributaries. Another important feature of the CEM is that it allows resource managers to differentiate between local instabilities (erosion of the outside of a particular bend due to impinging flow) and systemwide instabilities (increased peak flows related to increases in impervious surfaces), which are much more complicated to control.

Conceptual models are widely used by stream ecologists, as well. Major conceptual models in stream ecology include the river continuum concept (Vannote et al. 1980), flood pulse concept (Junk, Bayley, and Sparks 1989), nutrient spiraling concept (Newbold et al. 1981), natural flow regime (Poff et al. 1997), patch dynamics concept (Townsend 1989), serial discontinuity concept (Ward and Stanford 1995b), and ecosystem perspectives of riparian zones (Gregory et al. 1991). Such models help organize ecological thinking about streams and rivers, much the same as the CEM helps hydrologists and geomorphologists understand the process of incision in stream channels.

As an example, the river continuum concept (RCC) suggests that the physical form of streams and rivers is generally predictable from headwaters to large flood plain rivers. In all these cases, the RCC provides a conceptual model that helps people think about how they expect the stream ecosystem to be structured and what processes are most likely to occur along the network from headwater streams to large rivers. Such conceptual models are useful in assessing stream degradation and setting restoration goals because they describe how physical habitats are related to aquatic community structure and the ecological processes that are important to them.

(d) Using classification systems to describe channels

Although every stream is a unique combination of watershed characteristics, channel boundary conditions, and hydrologic and climatic regimes, people have long attempted to generalize their knowledge about streams by developing classification systems (Hawkes 1975; Bryce and Clarke 1996; Rosgen 1994; Frissell et al. 1986; Montgomery and Buffington 1993a, 1993b; Thorne 1997). Environmental classification systems are thoroughly reviewed by Zonneveld (1994) and stream classification systems by Kondolf (1995), Kondolf and Downs (1996), and USDA NRCS (2001c). Classification systems generalize field observations, facilitate communication, and identify dominant groups of processes. Classification systems are useful tools for communicating descriptive information since it saves time to simply state that a stream is type X, rather than specifying values for all of its component variables.

Overly simplistic use of categories can lead to misunderstandings and cookbook approaches, rather than an understanding of how a stream reach is functioning. Some workers have suggested that stream classification may be used to develop restoration prescriptions or to predict changes in morphology or ecology. Extremely simple classification systems include those based on flow habit (ephemeral, intermittent, perennial), planform (straight, braided, or meandering), or boundary mobility (threshold or alluvial). Others include physical variables (bed-material size, slope, sinuosity, channel width, valley shape) or biological characteristics (riparian vegetation, insect communities, or fish communities). Most stream classification systems are based on morphological or form variables (how streams look), rather than process variables (how streams behave, for example, widening or degrading). It is always easier to determine form, rather than process because processes act over time. Therefore, process determinations require sequential observations, historical data, or some surrogate, such as a space-for-time substitution. Unfortunately, fluvial systems are complex (threshold responses, variable responses, biological adaptation) and frequently changing (climate, streamflow, tectonic events, land use changes). It is difficult to accurately predict future stream behavior from current morphology.

Accordingly, a classification system alone should not be used for determining the type, location, and purpose of restoration activities (FISRWG 1998). Some have proposed the idea of a diagnostic or weight of evidence approach as an alternative to process models, evolution or conceptual models and classification systems (Ward and Trimble 2004).

(e) Using mathematical models to predict channel responses

Quantitative predictions usually require a series of numerical calculations. Like most environmental systems, stream and watershed systems are complex, so the series of numerical calculations needed to make a prediction have been incorporated into a wide range of different models. The components of mathematical models are described in measurable units, and the relationships and processes within the models are represented by explicit mathematical formulas. Most complex mathematical models require specialized training in the scientific discipline that is being modeled (phytoplankton or sediment transport). Some complex mathematical models include user interfaces that ask specific questions and make it possible for an informed resource specialist to apply the model. Even in such cases, users of complex mathematical models should be aware of the context for which the model was developed, assumptions within the model, and data required to run the model. As a result, mathematical models are less popular for general application in stream project designs than broader conceptual models. However, the quantitative projections and predictions of mathematical models can greatly enhance the design of a project if the appropriate expertise is available to the design team.

Quantitative models of streams have become quite complex, and normally require specialized academic training for successful application. Models may be classified based on the characteristics they simulate and the way they handle temporal and spatial variations. Models of streamflow that predict the depth and velocity in a stream channel for a given geometry and discharge are most common, but models that include sediment movement, water quality, and some index of physical habitat quality are also widely used.

Stream ecosystem models simulate changes in habitat, biological populations, community structure, and ecological processes for stream ecosystems. Water quality (dissolved oxygen, temperature, suspended sediment, nitrogen and phosphorus) for streams and rivers are widely modeled for different regions and land use practices (Brown and Barnwell 1987; Lisle and Lewis 1992). Phytoplankton and benthic algae abundance along streams have been modeled for both streams and rivers (Brown and Barnwell 1987; McIntire 1973; McIntire et al. 1996; Stevenson and Smol 2002). Macroinvertebrate community structure and relationships to water quality and habitat have been modeled (Reynoldson et al. 1997; Karr et al. 1986; Hawkins et al. 2000). Hundreds of models are used around the world to relate the abundance of fish populations to physical habitat availability (Armour, Fisher, and Terrell 1984; Fausch, Hawkes, and Parsons 1988; Lee 1991). A recent review of models of large wood in streams identified 14 simulation models developed for streams and rivers (Gregory, Meleason, and Sobota 2003). In addition, several models simulate entire stream ecosystems (McIntire and Colby 1978; Newbold et al. 1983). Regional resource agencies often provide expertise to cooperating agencies and public groups to allow the application of more complex models in stream project design. A major limitation, particularly in models, is the poor linkage between ecology, water quality, and geomorphology. Multiple stressors are at work impairing health of many stream ecosystems, and it is often difficult to establish which are the most important.

A parametric model has parameters that must be estimated in some fashion. An empirical model contains any empirical relationship, one that is based on data. An empirical model is based, at least in part, on observed data, rather than a thorough understanding of the underlying physical principles. A lumped model describes processes on a scale larger than a point, while a distributed model describes all processes at a point then integrates processes over space and time to produce a total system response (Haan, Barfield, and Hayes 1994). A stochastic model is one whose outputs are predictable only in a statistical sense. Repeated use of a given set of model inputs produces outputs that are not the same, but follow certain statistical patterns (Haan 1986).

Model quality and capability vary widely. Several fundamental types of mathematical models are:

- Steady-state models predict conditions that occur for a given set of boundary conditions. For example, a flow model might predict the water surface elevation, given a fixed channel geometry and a constant flow.
- Unsteady models predict variations that occur with time such as during the passage of a storm hydrograph by dividing such an event into a series of steady-state time steps. Complex unsteady models have feedback loops that allow channel boundaries or other key variables to respond to inputs and change between time steps.

From a spatial perspective, models may be one-, two-, or three-dimensional:

- One-dimensional models only consider forces that occur in one (usually the streamwise) direction. Velocity and other stream properties may vary upstream and downstream, but not from bank to bank and not from the bed to the water surface. A common example is HEC–RAS.
- Two-dimensional models are usually depth averaged. They simulate variation in the horizontal plane, but assume no variation in the vertical.
- Three-dimensional models simulate variation in all three directions. Model cost, size, and complexity increase by roughly an order of magnitude with each added dimension.

654.0106 Key processes affecting stream corridor ecosystems

Stream channels are dynamic. Therefore, stream project planners and designers must be able to identify and understand key processes. Physical processes include hydrologic and geomorphic processes. Both biological and physical processes occur longitudinally, laterally (across the corridor), and vertically (above and underneath the corridor) over time. Abrupt changes in stream channels and their riparian areas by natural features (geologic differences along the river, vegetative changes related to geology, soils, or regional climate) and human activity (land conversion, urbanization, agriculture, forestry) often disrupt ecological processes.

(a) Physical processes

Longitudinal adjustment

The longitudinal profile of a stream typically displays the effect of headwater erosion and downstream deposition over long periods of time. In the shorter timeframe, bed profiles may become locally steeper or more gradual, or they may exhibit aggradation (deposition of sediments) or degradation (channel deepening), as supplies of sediment and stream power fluctuate in response to changes in discharge. Since the energy gradient that drives the fluvial system is normally equal to the bed slope, other channel variables are quite sensitive to slope changes. Ecological impacts of slope change are generally related to changes in water velocity or sediment transport. For example, degradation of stream channels can lead to a lowering of the water table and consequent dessication and loss of riparian vegetation. Severe aggradation of stream channels decreases water depth and flow and can result in excessive temperatures or decreased dissolved oxygen during summer. Aggradation can also cause a lack of cover and smothering of coarse-grained substrates. During periods of low flow, aggraded stream channels may be too shallow to allow movement of fish. Excess sediment is most damaging where aquatic life is not adapted to these conditions.

Lateral adjustment and bank erosion

Mean bank erosion rates vary from a few millimeters per year to 800 meters per year (Lawler 1993). Bank erosion is the result of about 10 processes, several of which are usually operating on a given site. Processes may be loosely grouped into hydraulic processes (removal of sediment by flowing water) or geotechnical processes (collapse, slumping, or sliding of sections of bank due to gravitational forces exceeding resisting forces). Hydraulic processes include scour of particles or aggregates of bank material. Fluid shear forces tend to be greatest for the bank toe, but erosion can occur anywhere on the bank, especially if not well vegetated. When the bank toe is eroded, often the upper bank is undermined, cantilever-type geometries result, and banks ultimately fall into the channel. Hydraulic processes also include erosion of the bank face by overbank flows that concentrate into rills and gullies, sometimes called valley trenches.

Geotechnical failures usually occur when large blocks of bank material fall into the channel from high, steep banks. These failures are often observed when erosion has lowered the channel bed, increasing bank height and angle. Shallow ground water flow toward the channel often facilitates failure by increasing soil weight, decreasing soil strength, creating voids by piping erosion, and lubricating planes of weakness. Geotechnical failure requires that banks be high and steep enough to create gravitational forces that exceed soil strength, which varies with soil type, soil moisture, vegetation, and other site-specific factors. A high bank may be only a few feet for noncohesive soils and more than 20 feet for cohesive soils.

Ideally, threshold channels (those for which hydraulic forces are at or below the threshold needed to initiate motion of boundary sediments) resist hydraulic erosion processes. Since alluvial channels are constantly shaped by streamflow, their banks are more mobile than threshold channel banks. However, rates of bank retreat vary widely from point to point along the bank and through time. For example, as an alluvial channel meanders freely across the flood plain, the current direction may shift, forcing the flow onto a section of bank that has been stable for years. A period of rapid bank erosion ensues. All channels experience some degree of bank erosion. Most sediment inputs are relatively small and are incorporated into stream corridor processes, such as flood plain development. Human activities can accelerate or decelerate bank erosion rates by orders of magnitude. In both cases, ecological impacts may be significant. Increased bank erosion can lead to deposition of clay and silts that is especially damaging to fish spawning habitats and habitats of benthic macroinvertebrates that live in the interstitial spaces of cobble and gravel substrates.

Channel avulsion and flood plain construction

When bank erosion and longitudinal adjustment occur at a large scale, rapid changes in channel planform (avulsions or cutoffs) occur. These events typically occur during floods or high flows and trigger an episode of rapid local change in the region surrounding the avulsion. Typically, such events produce shorter, steeper channels in the short term, with erosion of upstream reaches and deposition in former channels and downstream. Channelization of streams often proceeds by construction of a series of artificial cutoffs to straighten the channel, with extreme impacts on channel stability if control structures or erosion resistant lining are not provided.

The impact of natural cutoffs is less than that of channelization because natural cutoffs normally occur one at a time, so that the overall length (and average bed slope) of a long reach does not change much. Since avulsions often trigger periods of large-scale, unpredictable instability, erosion control structures are often designed and placed to prevent them. However, in unmanaged stream corridors, major avulsions provide habitat complexity and diversity for aquatic species. Sloughs and oxbows that are abandoned channels provide low-energy habitats and refugia from the sporadic or seasonal fast water in the main channels. Newly deposited sediments in these areas and on the outside of meander bends provide substrate for pioneering plant species, while erosion topples older riparian forest communities and induces recruitment of wood to the stream. Flood plains that are periodically reworked by avulsions tend to be rich mosaics of plant communities of several successional stages. Over long periods of time, an unmanaged stream corridor will migrate back and forth across the entire valley, generally increasing the elevation of the flood plain through depositional processes. This generalization has exceptions such as deeply incised headwater streams or streams experiencing a drop in base level.

Sediment transport

Sediments are transported and sorted during high flows, so flow regimes are critically important to aquatic species. Unaltered streams receive sediments from their watersheds, beds, and banks and subsequently sort these sediments by size into well-defined spatial patterns. Coarse sediments (larger gravel and cobble) occur along the axis of highest velocity and greatest depth, and finer sediments are deposited along the margins of stream channels or in the velocity shadow of larger inchannel obstructions (logjams, large boulders). Channel beds often feature a surface layer of coarse particles (armor) that is only one- or two-grain diameters thick, with a more heterogeneous mixture of sediment sizes underneath. Bed sediment size distribution or sediment texture is one of the most dynamic aspects of a fluvial system, changing rapidly in response to changes in other variables (channel bed slope, discharge, or amount of large wood). In turn, sediment transport is very sensitive to bed sediment size. Benthic organisms such as insects and small plants (periphyton) that live on the surface of coarse sediments are sensitive to changes in sediment size, sediment porosity, and the frequency of bed sediment movement. Biota from regions with naturally occurring fine-grained substrates are less sensitive to sediment than biota from regions with coarser-grained substrates. Fish that reproduce by laying eggs in gravel are particularly sensitive to changes in particle size, as they must rearrange stones to create redds. Also, well-aerated, intragravel flow is important for egg survival and larval growth.

Sediment sorting processes are less evident in fine sediment, where deposited in flood plain depressions, sloughs, and oxbows and within eddies along channel margins. These silty and clayey deposits provide media for colonization by terrestrial macrophytes when they are exposed by falling stages, or if they are low enough to remain under water, provide substrate for burrowing types of macroinvertebrates not found in the sandy main channel bed.

(b) Ecological processes

Energy flow and nutrient cycling

The flow of energy and nutrient dynamics in aquatic ecosystems occur in all dimensions and is influenced greatly by the physical dimensions of the stream channel. In turn, these processes strongly influence the community structure of stream ecosystems and the ecological processes along their longitudinal network. In small headwater streams, channels are narrow and shallow. In forested landscapes, inputs of solar radiation to the channel are, therefore, generally very small, and inputs of organic matter from the terrestrial ecosystem are relatively large.

Aquatic invertebrate communities are dominated by organisms that shred the larger terrestrial inputs (leaves, twigs) or by collectors that feed on the fine particles transported in from the terrestrial ecosystem or created by the shredding of large particles into smaller particles in the stream ecosystem. Since streams get larger as they flow downstream, channels generally become wider and deeper. Openings in the riparian canopy over the stream increase the inputs of solar radiation, causing increased production of algae and vascular aquatic plants, reducing the relative inputs of terrestrially derived organic matter. As a result, aquatic invertebrates are dominated by organisms that scrape algae off the streambed and collectors that feed on small particles of organic matter. The change in the longitudinal gradient of streams is also the primary factor driving hyporheic exchange flows (Harvey and Bencala 1993). This change creates unique physical, chemical, and hydrologic environments in streams and riparian zones, providing a diversity of habitats for many specially adapted macroinvertebrates (Stanford and Ward 2001).

The lateral exchange of water between a river and its flood plain is the driving force for nutrient cycling and the dynamics of the flood plain biotic community. Primary productivity of flood plain habitats is closely tied to hydroperiod, the periodic or regular occurrence of flooding or saturated soil conditions (Marble 1992), or the ratio of flood duration divided by flood frequency over a given period of time (Mitsch and Gosselink 1986). Productivity is greatest in wetlands with pulsed flooding (periodic inundation and drying) and high nutrient input, and lower in drained or permanently flooded conditions and low-nutrient water. Riparian wetlands may also influence stream channel morphology and flows, buffering the stream channel against the physical effects of high flows by dissipating energy as waters spread out onto the flood plain. Alternately, as streamflows recede, riparian wetlands provide water storage, slowly releasing water back to the stream through subsurface transport, thereby influencing stream baseflows.

Recruitment of large wood

Wood is important from headwater streams to large rivers and estuaries (Maser and Sedell 1994). Wood

in the stream provides structure and organic matter that creates and enhances habitat diversity, and is a food source for many riparian and aquatic organisms (Boyer, Berg, and Gregory 2003).
Wood in streams also increases channel roughness and habitat complexity, triggers the formation of islands, and forms dams that trap leaves, twigs, and fine sediments. Fine particulate organic matter (particles smaller than 1 mm in diameter) retained by large wood pieces provides food for insects and other aquatic invertebrates.

Small, steep headwater streams with wood input often contain a series of step pools formed by fallen logs that cross the channel and trap smaller pieces of woody material and leaves. At the other end of the spectrum, some large rivers have been completely blocked by natural accumulations or rafts of large wood that dominate stream corridor processes (Triska 1984; Collins, Montgomery, and Sheikh 2002). Natural channel widening and bar formation associated with wood obstructions allow development of the short, braided reaches and secondary channels that are important spawning grounds for salmon and trout in the rivers of the Pacific Northwest. In the sand-bed coastal plain rivers of the southeastern United States, wood also provides important habitat for invertebrates and provides fish with a source of food (Wallace and Benke 1984). Therefore, in many streams and rivers throughout the world, fish abundance and diversity depend on accumulations of large wood.

Wood recruitment processes are complex since they involve site-specific variables (size, species, density, and condition of riparian trees, bank geometry, and erosion) and stochastic events (tree death, tree blowdown, high flows, bank failures). Continuously submerged wood resists decay for centuries, but wood subject to alternate wetting and drying may disintegrate and decay in less than a decade, with exact rates dependent on species and regional climatic factors (NEH654.14 and NEH654 TS14J). Transport of fallen wood is inversely related to the ratio of wood length to channel width; logs with lengths greater than channel width may lodge in place for a lengthy time period.

Removal of wood is perhaps the most widely practiced type of stream channel management, and the practice of removal (de-snagging or clearing and snagging) along with deforestation and removal of beaver have left many streams with only a trace of the large wood that existed previously. For a full description of the effects of wood in streams and rivers, see Gregory, Boyer, and Gurnell (2003).

654.0107 Stream corridor habitats

Stream channels are usually the focus of stream restorations, but how these channels are ecologically linked with other parts of the landscape, watershed, and corridor should be considered and addressed. The dynamic nature of streams and their response to floods and other disturbances create many diverse habitat types and conditions, both in the stream and along its corridor. These habitats and the processes that occur among them affect each other dramatically, adding to the habitat complexity and species interactions in the stream and riparian area. Stream corridors support a disproportionately rich biological community, relative to the rest of the landscape.

Confounding this ecologically valuable richness, however, are the challenges that river and stream processes such as flooding present to humans. Add to these the many human demands on streams as water supplies, and as agricultural, recreational, and urban development sites, and managers feel compelled to take actions that compromise the ability of watersheds to sustain important ecological functions of habitats. Stream corridors provide filtering, buffering, retention, and conduit functions for water, sediment, wood, chemical compounds, seeds, and habitat for aquatic and riparian organisms. Therefore, maintaining multidimensional connectivity along a stream corridor is important to maintaining the species and habitats within them.

(a) Stream channel habitats

Instream habitats are as diverse as the systems that form them. High quality stream habitats are a mosaic of great spatial diversity created by various combinations of water quality and quantity, water depth, velocity, large wood substrates, mineral substrates, riparian vegetation, and the organisms that inhabit stream corridors. For example, shallow, swift flow over coarse bed material occurs in riffles that are often found at the inflection points of meanders. These habitats are important for stream invertebrates and as spawning sites. Generally speaking, aquatic organisms need what most organisms need to survive: clean water, oxygen, a steady food source, a place to hide or find refuge, and a place to successfully reproduce and grow to adulthood. Some aquatic organisms such as microscopic zooplankton live almost entirely in the water column; others, such as fish, use the water column and bottom substrates. Still others rely on the interstitial spaces of hyporheic habitats in and below the streambed.

Considerable research over the last several decades has described the importance of hyporheic zones to many alluvial stream corridor systems. These functions include:

- regulation of stream temperature by ground water upwelling
- water retention and storage which can reduce peak flows during floods and sustain baseflows during dry periods
- habitat creation, especially for aquatic invertebrates such as crustaceans, and vertebrates such as larval fishes
- buffering and filtering nutrients from streamflows and ground water
- aquifer recharge
- nutrient enrichment

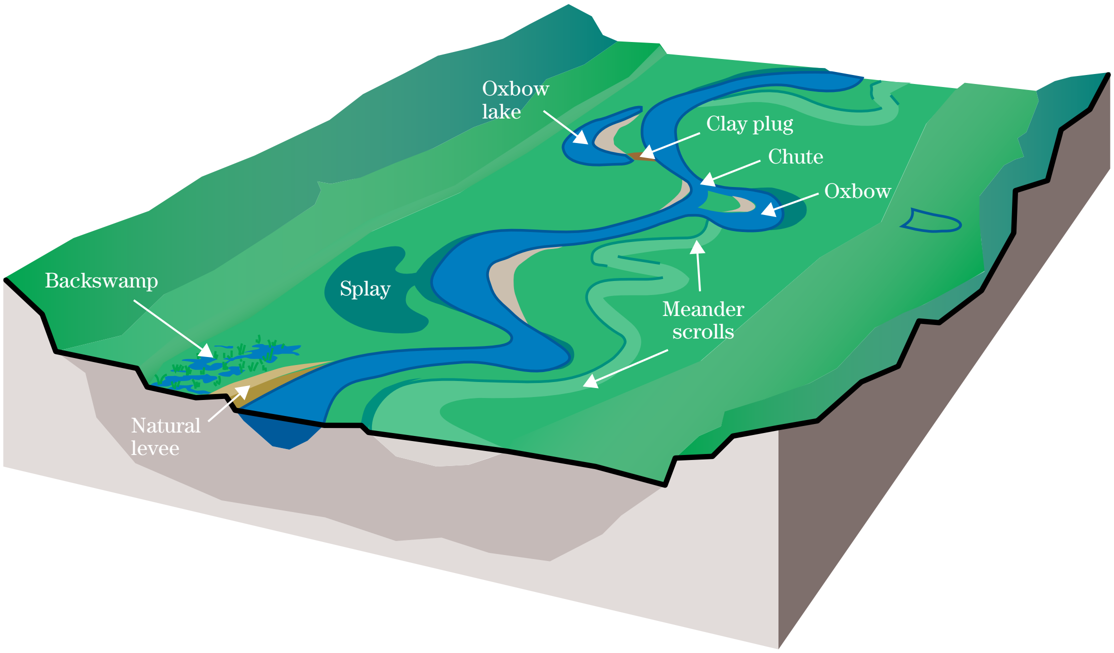
Most species use a variety of habitats during the course of their lives, some moving upstream or downstream, others into and out of the flood plain, a few into or out of the substrate, and still others to and from the ocean, all depending on the season, their age and physiology, and the conditions they face in their habitats. The complexity of their life cycles requires comparable complexity in their habitats and connections among them to allow movement at the appropriate time. To sustain aquatic communities, stream corridor project designers should consider the habitat needs of aquatic organisms throughout their life stages and the physical and ecological processes that provide them.

(b) Riparian and flood plain habitats

A stream corridor is comprised of the stream channel and its riparian zone. The riparian zone forms an ecotone or transitional zone between the stream and uplands and provides value, both in productivity and biotic diversity, far greater than its relatively small area would indicate. Riparian zones may or may not include flood plains, depending on the valley form of the stream corridor. In relatively wide stream corridors, flood plains are prominent components of the riparian zone. Whereas stream channels have often been the focus of stream restoration projects over the past few decades, project designers today recognize the links between the stream channel and its riparian areas and flood plain or riparian wetlands. Projects that consider these linkages are becoming more common (Middleton 2002). Flood plain/riparian wetlands, which include swamps, oxbows, sloughs, ponds, backwaters, abandoned channels, and flood plain lakes, usually are remnants of historic river channels or shallower depressions created by scouring and sediment delivery associated with flooding (fig. 1–6). Riparian wetlands receive water from the stream during overbank flow events; however, runoff from adjacent uplands, ground water seepage, and precipitation can be significant or dominant contributors to wetlands depending on regional climate, soils, and other variables. During overbank flows, these wetland habitats are connected to the river by surface water, but as a stream recedes, water is trapped in low lying areas forming seasonal, isolated wetlands varying in size, shape, permanence, and significance for aquatic species.

The occurrence and relative importance of riparian wetlands in a stream ecosystem changes with stream gradient. High gradient streams are steep with small riparian zones, and few developed riparian wetlands. In contrast, lower gradient streams have broader riparian zones and flood plains characterized by more predictable hydroperiods and more extensive riparian wetlands systems. In these systems, flood plain wetlands can contribute significantly to stream ecosystem productivity and function.

Figure 1–6 Flood plain features important for aquatic species



The hydrological characteristics of wetlands vary from permanently flooded backwaters to wetlands that have overland sheet flow during floods, to ephemeral, isolated pools. In lower gradient streams, plants, invertebrates, and vertebrates have evolved survival strategies that depend on occasional or seasonal flooding or ponding. Some macroinvertebrates complete their entire life cycle in these habitats, persisting in seasonal wetlands in a drought resistant form, such as an egg. Vertebrates (fish, amphibians, mammals, and birds) frequently make seasonal movements into flood plain wetlands (from the stream, wetlands outside the flood plain, or surrounding uplands) and time key periods of their life cycle (breeding, rearing young, or migration) to riparian zone ponding and flooding. Riparian wetlands are also important habitats in stream corridors as they provide low velocity refugia for organisms that benefit from stream processes, but cannot survive for long periods in moving water, such as frogs. Temporary and seasonal flood plain wetlands provide vernal pool habitat for amphibians and other organisms. Importantly, simply returning water to a stream's flood plain is not adequate for reestablishing function for all organisms, because each may be dependent on a specific timing, depth, duration, or frequency of flooding.

Just as riparian wetlands can influence stream function, anthropogenic changes in stream channel morphometry can influence the function of a flood plain wetland. Riparian wetlands are often filled or isolated from the stream by constructed levees, channel incision, or channel straightening projects. Physical isolation changes the hydroperiod and precludes access to the flood plain by many stream obligate organisms (fish). Channelization can result in streambed incision that changes the frequency of overbank flows, and therefore, the hydroperiod of flood plain wetlands. In urban areas, stream incision causes loss of riparian wetlands by lowering the flood plain water table. Similarly, channel stabilization usually precludes avulsive processes (a sudden change of course of a stream) that can form new flood plain wetlands and create complex mosaics of different successional stages. This latter point is critical to maintaining habitat diversity in the riparian zone. Therefore, stream restoration projects that produce normal overbank flooding regimes can be more successful at restoring stream ecosystem function and the species that depend on them.

654.0108 Disturbance and response in aquatic ecosystems

(a) Definitions of disturbance

Fluvial systems can experience abrupt changes in environmental conditions that are often considered to be disturbances. However, simple variation in physical (discharge, sediments) or environmental (temperature, dissolved oxygen) conditions are inherent in any system and should not be considered disturbances without the context of their effects on ecosystems. The most widely accepted definition of ecological disturbance is: "*… any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, and the physical environment*" (White and Pickett 1985). Fluvial ecosystems are inherently variable and can be naturally subject to wide ranges in flow conditions.

Stream ecologists have limited this general ecological definition of disturbance to include only those events characterized by frequency and intensity that are outside a predictable range (Resh et al. 1988). These definitions separate disturbances from inherent variation in terms of (1) the disruption of a biological system, (2) the change in resources or physical environment, and (3) rarity or unpredictability outside a range of commonly observed variation. It is important to recognize that disturbances are not just events that cause decreases in abundance of organisms. In these definitions, any event that disrupts—either increasing or decreasing—the structure of the ecosystem, community, or populations of species is considered a disturbance. For example, abrupt releases of fertilizers that cause an increase in algae would be considered a disturbance.

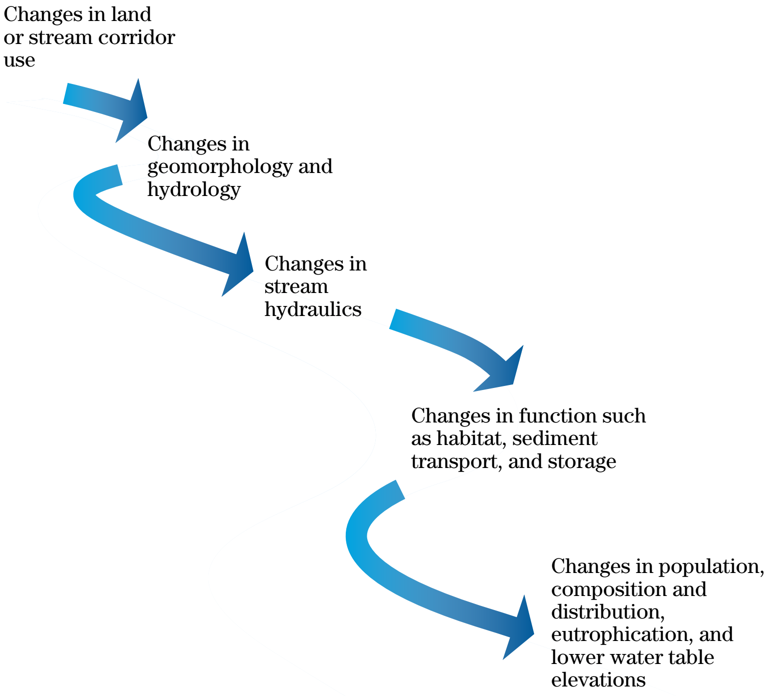
The biological communities and physical form of a stream, river, riparian corridor, or watershed exhibit the influences of small- and large-scale disturbances that have occurred (fig. 1–7 (FISRWG 1998)). Natural disturbances include floods, fire, drought, or storms. Disturbances induced by land management actions are more aptly called perturbations and include such activities as timber harvest, urban development, dam construction, and agricultural production. The intensity, magnitude, duration, recurrence intervals, and interactions of a disturbance or perturbation affect the manner in which fluvial systems respond to them.

(b) Physical responses to disturbances

The U.S. Army Corps of Engineers (USACE) (USACE 1994d; FISRWG 1998) describe disturbances in rivers and the physical responses of channel form and bed composition. Over some timeframe, stream systems tend to seek a condition of equilibrium. However, the behavior of fluvial systems is nonlinear due to time lags in response and the existence of thresholds (Schumm 1977). An illustration of a threshold in a fluvial system is the response of a hypothetical channel to urbanization. Initial deforestation and construction within the watershed produces little change in channel morphology, but when the impervious area of the watershed exceeds a threshold, for example 10 percent, rapid bed and bank erosion occur.

These types of nonlinear behavior often result in a complex response (Schumm 1977), defined as a response to disturbance that is *not* progressive and systematic. Another example of a complex response is provided by the changes in bed elevation that occur downstream from a hydraulic control structure such as a culvert, bridge crossing, weir, or dam. A dam placed on a hypothetical stream reduces sediment supply downstream, leading to bed scour and degradation. In addition, the lower flood stages affect base levels for tributaries, triggering incision and headward progressing bed erosion within the tributary watersheds, contributing sediments to the main channel below the dam. However, since flood flows are reduced by operation of the dam, the main channel is no longer capable of moving larger size particles, leading to long-term main channel bed aggradation. For many small watershed projects, changes in land cover and channelization have triggered instabilities that resulted in incision of upstream tributaries and aggradation along the main stem. The main stem aggradation reduces

Figure 1–7 Disturbance to a stream corridor system typically results in a causal chain of alterations to stream corridor structure and function.



channel capacity and increases the frequency of flooding. Small dams can stop the migration of headcuts and reduce flood peaks along the main stem.

Often macroscale stream corridor features are created or destroyed by the influence of large scale disturbances such as glaciation, earthquakes, tectonic movements, volcanic eruptions, large forest fires, and climate change. These processes and events affect watersheds on a regional or even continental scale. At a smaller scale, floods can alter a stream corridor. Disturbances can gradually or suddenly transform the bed type, planform, or cross section of a stream reach and its flood plain and riparian area. Stream project planners and designers usually have no way to influence natural disturbances or upstream human perturbations on the landscape, but they should be aware of their impact on the stream system of interest. Inadequate consideration of disturbances can rapidly diminish the sustainability and benefits of stream restoration and protection projects. The responses of aquatic species to disturbances depend on the scale of the disturbance, the population structure of the species, and the connectivity of the watershed both before and after the disturbance.

Streambeds within the active stream channel experience the greatest frequency of geomorphic disturbance that may be on the order of every year or two (sediment transporting events). Side channel and backwater areas are not as frequently disturbed, but are affected by higher flow events and channel avulsions (perhaps 5- to 10-year flows). Generally, flood plains have even less frequent disturbances than the main and side channel; it may require a 10-year or larger flood event before a flood plain can be significantly altered. Terraces and hill slopes typically have the lowest frequency disturbance regime when placed in context of stream processes (slope failures and mass movements). Common to all of these disturbances is the episode of disturbance followed by a period of recovery. If the disturbances become so frequent that the system cannot recover before the next disturbance event, then the stream is held in a constant state of disequilibrium or instability (National Oceanic and Atmospheric Association National Marine Fisheries Service (NOAA Fisheries Service) et al. 2006). In these situations, the concept of dominant discharge (channel-forming discharge) is not applicable.

Change in discharge

Long-term changes in discharge magnitude or duration have important implications for channel form and process. Urbanization, deforestation, and fires destroy vegetative cover, increase peak discharges, and lead to channel erosion, while flood control impoundments dampen peak discharges, and smaller, simpler channel forms develop downstream. Sharp increases in peak discharge and resulting decreases in baseflow are often observed in smaller watersheds undergoing development. Conversely, urban stormwater management activities may significantly increase the time that the flow is at bankfull stage, causing an increase in channel erosion. Changes in the discharge may also produce changes in water quality, sediment yield, bed sediment texture, pool habitat availability, and flood plain ecosystems that depend on lateral channel migration processes. Impacts for certain threshold-type channels may be particularly severe if flow forces required for bed movement occur much more frequently under the new discharge regime.

Changing sediment loads

Watershed developments and agricultural practices often generate higher sediment loads. Sediment can be a major concern for water supply reservoirs and navigation channels. Elevated sediment loads may cause real or perceived detrimental impacts on the stream and receiving water ecosystems. Impacts tend to be most severe in coarse-bed threshold systems with low turbidity and normally stable bed conditions. Elevated loads of sand and finer material may blanket gravel or cobble riffles, filling interstitial spaces that are key habitats for invertebrates and gravel-spawning fish. Elevated sediment loads in alluvial systems can result in filled or plugged channels that overflow many times a year and provide little deep water habitat. In other cases, elevated sediment loads have triggered accelerated channel widening or even a shift in channel form from single-thread to braided, with consequent changes in the riparian and aquatic community structure.

Changing water and sediment discharge

When both water and sediment discharge regimes change, fluvial response may be more complex. In the absence of complicating factors, a decrease in bed-material load and water discharge might produce a narrower or shallower channel. If bed-material and water discharge both increase, but water discharge increases more, the alluvial channel will become wider and deeper. For example, in long-term urbanization, the frequency and magnitude of discharges increase, triggering channel erosion. If sediment supply and water discharge both increase but sediment supply increases more, channels will become wider and shallower.

Changing bed sediment size
Any of the mentioned changes can cause shifts in bed sediment size. Bed sediment size and frequency of movement is a fundamental characteristic of stream habitats that is used to classify or organize stream habitats at the reach scale (Shields and Milhous 1992). However, bed sediment size can change rapidly in disturbed watersheds, in response to changing hydraulic conditions and changes in sediment supply (Doyle and Shields 2000). Formation and destruction of armor layers (layers of coarse sediments on the surface of more heterogeneous deposits) may control the frequency of bed movement and stability. Feedback loops occur in fluvial systems since bedforms, flow resistance, depth, and velocity are governed by bed sediment size.

Changing channel geometry
Erosion that produces channel widening or deepening over a long reach usually signals a change in inputs (increasing discharge) or boundary conditions (lowering a water table leading to death of riparian vegetation and accelerated bank erosion). Changes in channel geometry are also symptomatic of systemic erosion and deposition that accompany channel incision. The most direct result of changes in channel cross-sectional areas is shifts in water depth and velocity at flows that do not overflow the channel banks and the loss of flood plain wetlands and other habitats.

These changes have major implications for aquatic organisms. As larger channels convey higher flows without overflow, more of the erosional forces are focused on the channel bed and banks, rather than dissipated across the flood plain. This can result in loss of productive lands adjacent to the river, loss of riparian vegetation, and discontinuity of stream corridor processes.

(c) Responses of stream corridors to flooding

Physical responses
Unaltered streams usually overflow their banks regularly. Although current thinking among designers is that stream geometry (width, depth, slope) reflects a channel-forming discharge (Copeland et al. 2001), debate continues about the relative influence of rare, extremely large floods. Regional factors such as relief, geology, vegetation, and weather patterns govern the geomorphic significance of large floods relative to smaller ones (Werrity 1997). Clearly, major changes in channels and flood plains occur during high flows. Perhaps less obvious are important ecological functions that occur due to exchanges of water, sediment, nutrients, and organisms between the main channel and the flood plain during floods. The fact that flood plains along large rivers owe their fertility to seasonal floods that deposit thin layers of silt has been recognized for millennia, but the key role that low-velocity regions on flood plains play as refugia and nurseries for aquatic organisms has not. Flooding and associated erosion are often managed or eliminated by water resources projects due to their perceived and real deleterious effects on riparian land uses such as crop production and recreation.

Ecological effects of floods on stream ecosystems
Floods are the most common type of natural disturbance in streams (Resh et al. 1988; Fisher 1990). These high-flow events erode, transport and deposit sediments on flood plains, move large wood, add trees into the channel, flush fine sediments and silts out of streambeds, and transport nutrients and organic matter into streams from the surrounding terrestrial ecosystems (Junk, Bayley, and Sparks 1989; Gregory et al. 1991). The effects of disturbances on stream ecosystems have been reviewed extensively (Ward and Stanford 1983; Niemi et al. 1990; Steinman and McIntire 1990; Wallace 1990; Yount and Niemi 1990; Lake 2000). Aquatic organisms have evolved to not only withstand the potential impacts of floods, but actually benefit from these events (Kimmerer and Allen 1982; Meffe 1984; Matthews 1986; Remillard, Gruendling, and Bogucki 1987; Bayley 1991; Allan and Flecker 1993). For example, trout and salmon deposit their eggs in gravel nests or redds. Silt and fine sediments can smother the eggs and prevent emerging alevins from reaching the stream surface. Floods flush the fine sediments from gravel deposits in streams and create a variety of areas for spawning and clean gravel environments and habitats for rearing fry and juvenile trout and salmon. However, the ecology of trout and salmon is synchronized with these seasonal high flows or floods, so that sensitive life stages (eggs and alevin)

are usually absent or physiologically capable of surviving channel flushing events.

Aquatic organisms differ greatly in their life histories, their vulnerability, and their ability to recover from disturbances (Resh et al. 1988; Yount and Niemi 1990; Lake 2000). The recovery of stream and river ecosystems following disturbances was the focus of a special issue of Environmental Management in 1990. A review of field studies of responses to flooding reveal that, in general, algae and microbes recover in days to weeks, macroinvertebrates recover in less than a year, and fish recover in 1 to 2 years, with a few species requiring decades (Yount and Niemi 1990). The conditions of the ecosystem and riparian corridors are critical factors in determining resistance to the disturbance and the subsequent rate of recovery (Reeves et al. 1995). Refugia from disturbances are important factors in recovery and the design of stream restoration projects (Sedell et al. 1990). Flood plain rivers are larger and more complex than small streams, but the enormous power and frequency of flooding create natural processes for restoring large rivers and their flood plains (Bayley 1991; Sparks et al. 1990).

Disturbances as restoration processes
Disturbance processes, such as floods, fire, and droughts are natural processes of restoration (Gregory et al. 1991; Sedell et al. 1990; Sparks et al. 1990; Reeves et al. 1995). Design of restoration projects or changes in stream management should consider the frequency and location of disturbance events and make certain that their beneficial effects of floods and other disturbances are not negated by the rush to harden streambanks, prevent channel change, and remove habitat features that provide complexity and heterogeneity (large wood, gravel bars, islands, sloughs). In some areas, past projects that were originally designed to minimize the effects of disturbances (levees, riprap, tidal gates) are being removed to restore streams, rivers, and estuaries (CALFED 2003). Restoration projects also should consider natural processes of riparian regeneration (Boyer, Berg, and Gregory 2003). River channels may reoccupy old or abandoned side channels, if revetments and other barriers are removed. Careful design and analysis can achieve a balance between taking advantage of the restorative processes of natural disturbances and the need to protect property and communities from them.

654.0109 Human land uses and their effects on stream corridors

The ecological integrity of stream corridors is intrinsically related to the pattern of streamflow (Poff et al. 1997). The magnitude and timing of water and sediment inputs reflect watershed land use. Their effects on physical habitat and biological communities follow (Wang et al. 1997). Refer to table 1–2 for a list of physical responses of stream corridors to human activities (Gregory and Walling 1973).

(a) Agricultural land use

Typically, both water and sediment runoff increase, and infiltration decreases when forests or grasslands are cultivated or grazed. Irrigation return flows to streams can diminish water quality, but generally do not increase sedimentation and erosion to the extent cultivation and grazing do. Impacts of livestock grazing on stream corridors include destruction of riparian vegetation, soil compaction, bank erosion, water pollution, and degradation of fish habitat and riparian habitat quality. Destruction of vegetation by livestock or by farm equipment may be more damaging adjacent to channels with relatively erosion-resistant beds; if banks are more erodible than the bed, flow energy directed against the banks may produce channel widening and loss of productive land. However, the severity of impacts diminishes when grazing management practices are designed to accommodate seasonal conditions, watershed soils, slopes, climate, and other factors. Similarly, effects of cultivation on stream corridors can be mediated by using conservation practices such as conservation tillage, grassed waterways, and riparian buffers.

(b) Woodland and timber management

Forest management activities affect stream corridors. Regional changes in precipitation runoff relationships have been attributed to development (afforestation or reforestation) or clearing of woodlands. Clearing is usually associated with reduced infiltration and increased runoff and sediment loading. Forestry practices also affect large wood recruitment to streams. Although forests often regenerate rapidly following

Table 1–2 Types of human activities that produce physical changes in stream corridors

Change in stream corridors	**Human modifications**	**Form affected**		
Direct changes				
Drainage changes	Irrigation networks		N	
	Drainage schemes		N	
	Agricultural drains		N	
	Ditches		N	
	Road drains		N	
	Stormwater sewers		N	
Channel changes	River regulation	G	P	
	Bank stabilization	G	P	
Water and sediment balance	Abstraction of water	G		
	Return of water	G		
	Waste disposal	G		
Indirect changes				
Land use	Cropland	N	P	G
	Building construction		P	G
	Urbanization	N	P	G
	Afforestation	N	P	G
	Reservoir construction		P	G
Soil character	Drainage			
	Plowing	N		
	Fertilizers	N	P	

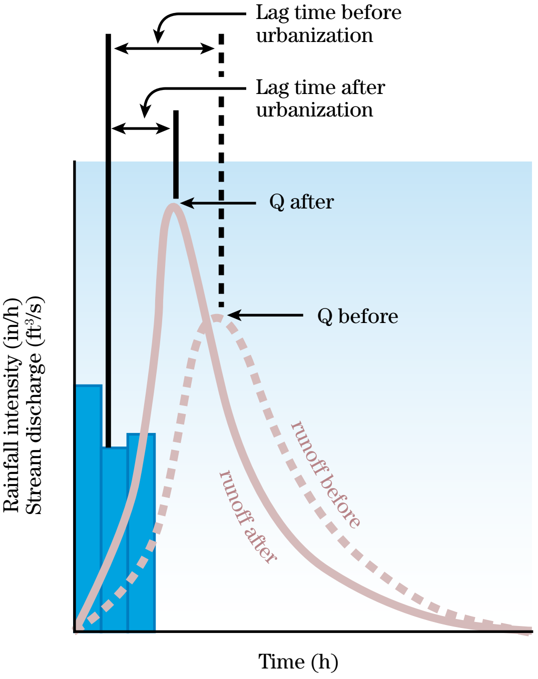
N=modifications of drainage network
G=channel geometry
P=channel planform

harvest (either due to natural succession or replanting), roads and stream crossings may have severe, long-term impacts on stream habitats if not properly designed and maintained. Best management practices such as riparian buffers of minimum widths mitigate the environmental effects of timber harvesting. There are local and regional variations in regulations, and therefore, variable success at protecting stream corridor resources.

(c) Urban development

The primary effects of urbanization are increased surface runoff and reduced baseflows (fig. 1–8). High-flow events of a given magnitude become more frequent (Moscrip and Montgomery 1997). During initial development, sediment yield may increase by an order of magnitude or more, but usually declines as construction projects are completed (Wolman and Schick 1967).

Figure 1–8 Typical effects of urbanization on flow event hydrograph



Over a longer term, urbanization increases the area of impervious surfaces (parking lots, roads, and roofs) which increase runoff and peak flows by eliminating undeveloped land where infiltration can occur. Impacts of urbanization on stream ecosystems occur due to shifts in hydrology that alter stream habitats, such as fine sediment deposition, depletion of large wood, destruction of riparian vegetation, and significant water quality degradation from point and nonpoint pollution (Moscrip and Montgomery 1997). Baseflow in urban streams may be comprised primarily of wastewater discharges and irrigation return flows. Even low levels of urbanization (8% to 12% connected impervious area) impair stream ecosystems (Wang et al. 2001; Wang and Lyons 2003). However, effects may be mitigated by interspersing vegetated plots with impervious zones and maintaining riparian buffers along streams. An extensive review of literature about the effects of urbanization on stream ecosystems is provided by Paul and Meyer (2001).

(d) Mining activities

Mining activities have perhaps greater potential for damaging stream corridor resources than any other human endeavor (Macklin and Lewin 1997). Mines may be constructed above or below ground. Subsurface mines change hydrologic relationships, and in some cases, long reaches or entire streams may be diverted into abandoned underground mines. Drainage from subsurface mines often can be acidic and can contain elevated concentrations of heavy metals. Surface mines are sometimes constructed within channels or on flood plains immediately adjacent to channels, and changes in surface topography and channel volume are great enough to trigger large-scale channel instability or to transform lotic habitats into lentic habitats. Gravel removal from streams may result in changes in streambed type and morphology for long distances and times due to the diversion of coarse bed load from the stream corridor, complicating rehabilitation efforts (Brown 1998), and rendering spawning habitats unusable.

Many stream corridors continue to respond to disturbances created by hydraulic or dredge mining over a century ago. In other cases, watersheds have sustained drastic changes in topography, drainage networks, and vegetative cover due to extremely acidic or infertile soils that have been exposed by mining or disposal of mining wastes. Dispersal of heavy metals and radionuclides derived from mining or smelting is particularly detrimental (Macklin 1996).

(e) Exotic or invasive plants and animals

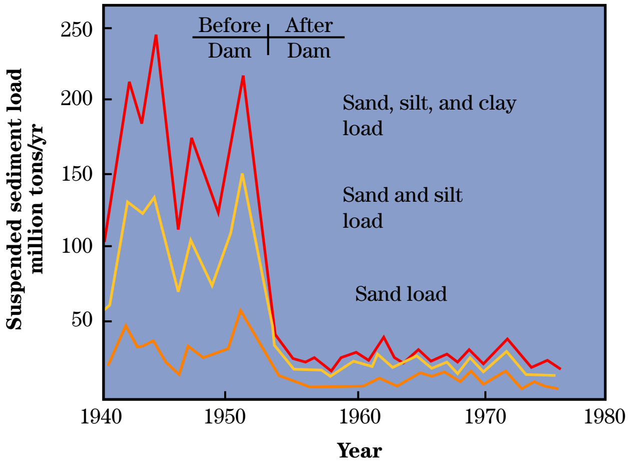
Exotic, or nonnative species, occur in many stream corridors, and management of these organisms is often a necessary component of rehabilitation or restoration projects. Invasive alien species are defined as nonnative organisms that cause, or have the potential to cause, harm to the environment, economy, or human health (Pimentel et al. 2000). Examples of invasive animals are zebra mussels and stocked game fish that supplant native species. These species compete with native species for niche resources, often leading to declining habitat quality and biodiversity. For example, the exotic vine, kudzu (*Pueraria lobata*), was imported from Asia in the nineteenth century and planted along stream corridors in the Southeast for erosion control. In recent decades, kudzu has hindered recovery of native riparian woody plants in stream corridors (Shields, Bowie, and Cooper 1995), and is viewed as a nuisance pest by forest managers. The exotic salt cedar (*Tamarix chinensis*) thrives in dammed rivers and stream corridors of the arid West and Midwest, excluding cottonwood, willow, and many other native riparian species (FISRWG 1998).

(f) Dams and diversions

Dam construction has affected all of the watersheds larger than about 2,000 square kilometers within the continental United States (Graf 1999). Dams typically moderate peak flows and trap sediments (fig. 1–9 (adapted from USACE 1994d)), but additional perturbations also occur depending on the operating conditions and site-specific variables. Grant, Schmidt, and Lewis (2003) reviewed existing information regarding downstream physical effects of dams and proposed a conceptual model based on sediment supply and the change in the frequency of sediment-transporting flows produced by the dam. Dams typically increase water depth and decrease velocity upstream, transforming lotic habitats to lentic conditions. Dams reduce peak flows downstream, resulting in narrower channels with more uniform flood plain vegetation. In some cases, braided channels may be transformed to single-thread forms. Bed material becomes more stable and interstitial voids fill with fines since flows high enough to flush gravels are less frequent. Water quality impacts include major changes in water temperature, turbidity, and nutrient levels. Dams also are a barrier to migration for aquatic species, as well as the flow of energy and materials, leading to fragmentation of habitat and ecological processes critical for sustaining aquatic species (Poff and Hart 2002). Dams can also block coarse sediment transport which, in some cases, results in channel incision downstream. Dams also reduce the delivery of large wood to downstream reaches.

Removing dams is an increasingly common practice, particularly where the dam is no longer needed, costs of maintenance and repair do not warrant continued operation, or environmental values upon removal exceed those provided by the dam. Dam removal projects create technical and political challenges, and the environmental effects may be negative, as well as positive. Of particular concern is the management of sediments stored by the dam, as this sediment may contain contaminants from the watershed. A review of information related to dam removal is provided by the Aspen Institute (2002), and the base of knowledge in this area is rapidly expanding. Other references addressing aspects of dam removal include Schuman (1995); Doyle and Shields (2000); Bednarek (2001); Grant (2001); Pizzuto (2002); and Doyle, Stanley, and Harbor (2003).

Figure 1–9 Effect of storage reservoir on downstream sediment transport (Missouri River average annual suspended sediment load at Omaha, NE)



By their very nature, water development projects such as dams and diversions alter the timing, duration, magnitude, and frequency of streamflow in a river system (Ward and Stanford 1979; Lillehammer, Brittain, and Saltveit 1984; Petts 1984; Gore and Petts 1989; Calow and Petts 1994; Church 1995; Ligon, Dietrich, and Trush 1995; Ward and Stanford 1995a, 1995b; and Stanford et al. 1996 for extensive treatments of this subject). Importantly, dams and diversions can substantially alter fisheries and riparian habitat along regulated stream reaches (Lane 1955a; Williams and Wolman 1984; Ligon, Dietrich, and Trush 1995; Montgomery and Buffington 1998; Buffington and Montgomery 1999; Shields, Knight, and Cooper 2000).

(g) Channel modification projects

Channel modifications are frequently implemented for flood control, drainage, erosion control, or to relocate channels for construction of various types of infrastructure. Changes in channel geometry can trigger significant fluvial response and usually require erosion control structures like weirs or revetments. Many stream management projects address physical or ecological damages produced by channelization projects constructed between 1950 and 1970 (Brookes 1988; Bolton and Shellberg 2001).

The USACE (1994d) ranks changes in the channel cross section by their potential for creating channel stability problems (from lowest to highest) as shown in table 1–3.

Generally speaking, the more dynamic a channel reach is before alteration, the more likely that changes in channel cross section will cause stability problems (USACE 1994d) (tables 1–4 and 1–5).

(h) Recreation

Stream corridors provide recreational opportunities such as swimming, boating, fishing, hiking, hunting, bird watching, and photography. The sensitivity of stream corridors to recreational use varies with soils, climate, topography, and intensity of use (FISRWG 1998). Intense foot or vehicle traffic may compact soils, destroy vegetation, and trigger flow concentration and erosion. Power boating can cause bank erosion due to wave wash, and accidental spills or waste discharges can degrade water quality. Fish and wildlife may be impacted by over harvesting or disturbance. Littering, noise, erosion, and vandalism degrade stream corridor aesthetics.

Table 1–3 Stability rankings for various channel cross-sectional changes

Stability Ranking (1 = low, 10 = high)	Stream cross-sectional change
1	Nonstructural flood control measures (flood-proofing structures, warning systems)
2	Levees set back clear of the meander belt
3	Levees within the meander belt
4	Off-channel detention basins
5	Upstream flood retention basins or reservoirs
6	Flood bypass channels
7	Clearing and snagging (removal of large woody debris or bank vegetation)
8	Enlarged cross section with the existing low-flow channel left intact
9	Channel widening
10	Channel deepening

Table 1–4 Typical features and stability problems associated with streams

Channel type	Typical features	Stability problems
Mountain torrents	Steep slopes Boulders Drops and chutes	Bed scour and degradation Potential for debris flows
Alluvial fans	Multiple channels Coarse deposits	Sudden channel shifts Deposition Degradation
Braided rivers	Interlacing channels Coarse sediments (usually) High bed load	Frequent shifts of main channel Scour and deposition
Arroyos	Infrequent flows Wide flat channels Flash floods High sediment loads	Potential for rapid changes in platform, profile, and cross section
Meandering rivers	Alternating bends Flat slopes Wide flood plains	Bank erosion Meander migration Scour and deposition
Modified streams	Previously channelized Altered base levels	Reduced activity Degradation and aggradation Bank erosion
Regulated rivers	Upstream reservoirs Irrigation diversions	Reduced activity Degradation below dams Lowered base level for tributaries Aggradation at tributary mouths
Deltas	Multiple channels Fine deposits	Channel shifts Deposition and extension
Underfit streams	Sinuous planform Low slope	Meander migration
Cohesive channels	Irregular or unusual planform	Variable

Table 1–5 Rating of channel modifications for effects on channel stability

Type of channel modification	Mountain torrent	Alluvial fan	Braided, multiple channel stream	Arroyo	Meandering stream	Modified stream	Regulated stream	Delta	Underfit stream	Cohesive stream
Nonstructural flood proofing, flood warning, evacuation	0	0	0	0	0	0	0	0	0	0
Levees set beyond stream meander belt	1	2	2	1	1	1	1	2	1	1
Levees set within stream meander belt or along bankline	2	5	5	4	3	3	2	4	2	2
Off-channel flood detention basin	2	3	3	3	2	2	2	2	1	1
Within-channel flood detention basin	4	5	5	5	4	4	3	4	2	2
Major flood storage reservoirs	3	4	4	4	3	3	2	3	1	1
Floodway, diversion, or bypass channels	4	5	5	5	4	4	4	5	3	3
Removal of bank vegetation or large wood (clearing and snagging)	6	6	5	5	7	7	5	5	5	5
Compound channel, low-flow pilot plus flooding berms	5	8	8	7	7	6	6	7	4	4
Significant channel widening	6	9	9	8	8	6	7	7	5	5
Significant channel widening and deepening	7	9	9	9	9	9	8	8	8	7
Significant channel widening, deepening, and straightening	8	10	10	10	10	8	9	9	7	8

Note: Qualitative rating of 1 (low) to 10 (high impact on stability)

654.0110 Summary of ecological principles to guide stream designs

Fluvial systems are dynamic. They change over time and in space in response to their hydrology and geomorphology, and the interactions of these physical processes with biotic communities (bacteria, plants, animals). To protect species, habitats, and water resources, managers must incorporate environmental features into stream project designs (Shields et al. 2003). Historically, engineered solutions to stream channel problems featured constrained physical systems. Today, resource managers and stream design engineers are seeking ways to modify tried and true designs to allow minimally constrained natural ecological processes to be restored. The following principles of stream restoration design incorporate ecological considerations to facilitate such modifications:

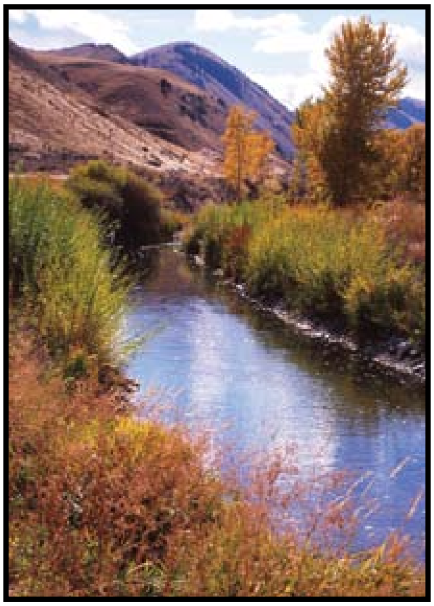
- Base designs on ecological principles, as well as physical ones. To the extent possible, restore or maintain the inherent complexities of stream corridors, ecological linkages, and their physical connections. For example:
    - — Incorporate native vegetation into design of flood control structures, revetments, levees, and other hard structures.
    - — Incorporate silvicultural treatments to maximize generation of trees, specifically for large wood recruitment.
    - — Incorporate livestock and/or recreational management regimes into stream design projects to protect restoration or conservation investments in riparian zones and sustain their functions.
    - — Remove hard structures no longer deemed necessary or functional in the watershed due to changes in the physical and ecological conditions.
    - — Work with partners such as USACE and the U.S. Bureau of Reclamation (USBR) to restore natural hydrologic regimes to the extent possible.
    - — Protect life and property.
- During the design process, integrate the disciplines of fluvial geomorphology, geology, hydrology, aquatic and riparian ecology, sedimentation engineering, and hydraulic and geotechnical engineering. If possible, collect baseline and post-implementation data to validate successful designs of innovative approaches to stream corridor restoration. Publish and distribute the information so that it can be used by other designers in the future.
- Design for site-specific response in a watershed-scale context. Consider factors affecting stream corridor processes at different spatial scales, from landscape to watershed to microhabitat, as well as factors that influence the long-term population status and dynamics of aquatic species and the community of species with which they interact. Seek technical advice regarding aquatic species from local experts and state fish and wildlife agencies.
- Consider ecological costs and values, as well as project and long-term maintenance costs of engineered solutions to channel problems. Projects that are compatible with the inherent tendencies of stream corridor systems tend to be more stable, require less maintenance, and are more ecologically productive than traditional engineered approaches (Brookes 1989). These advantages should be emphasized when determining design options.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 2 Goals, Objectives, and Risk



Issued August 2007

Cover photo: Setting quantifiable, realistic, and achievable goals and objectives is a critical early step in planning successful stream restorations.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 2 Goals, Objectives, and Risk

Contents

Tables

Figures

Chapter 2 Goals, Objectives, and Risk

654.0200 Purpose

The purpose of this chapter is to emphasize the need for the clear identification of the desired outcome or result of any action to restore or protect streams. Identification of the true nature and causes of stream problems is a critical step in the overall planning process and one which has been abbreviated or overlooked on many failed or poorly performing restorations.

The selection and evaluation of goals, as well as any design approach or treatment alternative must address risk or consequences of failure. This should be examined from both an ecological perspective, as well as a life and property standpoint. While risk is described at several points in this handbook, it is introduced in this chapter. Designing solutions is also an integral part of the overall planning process. The procedure for designing solutions is described in NEH654.04.

654.0201 Introduction

Conservationists are frequently faced with conditions along and in streams that are characterized as problems because certain functions are not being provided or simply because the overall character of the stream system has changed. It may be that the system is damaged and needs to be repaired or that a shift in perception of stream functions and values has occurred, spurring the need for some sort of action.

Understanding the true nature of stream problems is challenging because of the dynamic nature of streams, their seasonal changes, responses to disturbances, and their ability to recover. Recognizing the current condition of a stream, comparing it to historical conditions, and projecting its future conditions are, therefore, challenging; but, nonetheless, need to be documented and clearly understood to determine appropriate and achievable goals and objectives.

The goal of a stream restoration planning process is to formulate a plan that is feasible and effectively addresses the identified problems and goals of the restoration project without adversely affecting adjacent stream reaches or riparian areas.

The term stream restoration can be used to describe many different activities. Actions that support or lead to designed solutions are a critical part of the stream restoration process to assure that what is designed and implemented fits the goals and objectives of the job or project.

(a) Goals and objectives

The perceived success or failure of many stream restoration projects can be as much a function of the criteria selected as the design. Therefore, the importance of establishing achievable project objectives is critical. Once established, these objectives will delineate the data collection effort, methodologies for assessments, and finally the design itself. An interdisciplinary team is required since few people have all the skills necessary to conduct a successful stream restoration study and design. While the exact makeup of the team can vary, it should include engineering, geomorphological, and ecological expertise.

The team should also include the stakeholders. Stakeholders are the groups who may fund the project, affect the stream directly, or be affected by actions taken on the stream. A trained facilitator and interdisciplinary involvement may be needed to guide the development of goals and objectives and to assure that all stakeholders, problem identification issues, other opportunities, and constraints are fully recognized. Once agreement is reached on the alternatives to be pursued, the design process can proceed.

Generalities in objectives, such as *fixing the stream*, can lead to problems. Narrowing the objectives reduces ambiguity for the study team members. Objectives should be:

- specific
- realistic
- achievable
- measurable

Restoring streams to a given historical condition may be an objective. If this is the approach, care must be taken to ensure that physical or biological changes in the watershed have not prohibited a return to that historical condition. For example, the objective for an incised and widening stream in an urban watershed could be to restore it to support a sensitive fish species that was present before development. Changes in water quality and runoff patterns could make this an unattainable objective. Many restoration projects are actually environmental enhancement projects or rehabilitations, since it may not be feasible to return a system to an historical condition. Another of the principal reasons for this is that good, quantitative data on watershed and stream historical conditions is normally lacking. Restoration, therefore, becomes rehabilitation, since not all ecologically self-sustaining functions and values can be restored to the stream.

Clear objectives that are reachable, within the constraints and capabilities of the stream and its riparian area, will lead to better designs that perform as intended. Some objectives may, at first glance, appear to be realistic, but may need to be reformulated if preliminary design information indicates that either the costs will be too high, the intended results may not be achievable, or that boundary constraints may significantly alter or preclude the implementation of the final design.

Typical goals and objectives

Some typical goals for urban stream restoration and recovery are to:

- prevent streambank erosion on residential properties and protect infrastructure
- prevent flooding of residential properties caused by debris or sediment in the channel
- protect bridge abutments, bridges, and road crossings
- protect valuable agricultural land
- protect a municipal water supply (main source works and water quality)
- maintain or restore fish habitat
- maintain or restore water quality

Residential homeowners may be primarily interested in repairing eroded banks and removing debris or woody material blocking the channel to protect their yards, drainage pipes, septic systems, retaining walls, barns, and houses. A municipal water company may need to have a water main protected. Channel erosion may be causing headcutting of the channel, threatening bridge abutments or a road (fig. 2–1). Other stakeholders, including state and Federal agencies, may have primary interests in maintaining or improving aquatic habitat.

Further refinement of stakeholders' interests may produce more goals and better defined objectives such as:

- Maintain or rehabilitate environmental quality by designing and constructing stream restoration projects that:
  - look natural
  - function naturally with channels connected to flood plains
  - provide desirable stream and riparian habitat, including overhanging root cover and large woody material
  - reduce bank erosion
  - maintain water quality
  - are economical to design and build

- Protect infrastructure in channels and flood plains by designing and constructing stream restoration projects that:
  - do not increase flood profiles
  - do not migrate across flood plains
  - protect valuable riparian infrastructure
  - have a low risk of failure
  - do not send debris or woody material downstream to plug bridges and culverts
  - maintain water quality
  - are economical to design and build

In some cases, a compromise needs to be reached between goals for infrastructure protection and aquatic habitat. Sometimes these goals are incompatible, and sometimes they are mutually supportive. Some instances of incompatibilities are:

- An interest in having a project that can naturally evolve over time or rapidly change in response to large flow events, where the stability of riparian infrastructure requires a fixed and static bankline.
- Woody material can provide valuable habitat benefits, but can also increase flood profiles by plugging bridge openings.

Some instances of mutually supportive goals are:

- Large woody material is valuable for aquatic habitat and on some streams can help achieve channel stability.
- Natural streams with channels connected to flood plains can reduce tractive forces in the channel by dispersing and attenuating high velocity flows, thereby increasing channel stability.

Figure 2–1 Township road threatened by severe degradation of channel bed (Calhoun County, IL) (*Photos courtesy of Michael Hollow*)

(a) March 2003—Original concern about bank failure threatening road expanded to include rock riffle grade control structures to stabilize bed, reduce bank height, and improve aquatic habitat

(b) June 2003—2 months after treatment using rock riffle grade control structures to stabilize bed and gabion baskets to stabilize failing bank near road. Note water impounded in pool.

654.0202 NRCS Conservation Planning Process and stream restoration

A plan is a sequence of logical steps to reach a goal or objective. Most stream restoration projects consist of complex issues involving a number of people and ecological components. Using a multi-disciplinary planning team helps to identify and address many of the issues in a timely manner. The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Conservation Planning Process (CPP) follows policy written in the National Engineering Manual (NEM), Part 510, Planning.

The NRCS CPP is referenced because of the need for NRCS field conservationists to recognize how stream work fits into the overall CPP.

Prescribing stream corridor restoration design elements requires progression through and iteration of NRCS CPP steps (fig. 2–2 (USDA NRCS National Planning Procedures Handbook (NPPH), 2003b)). As part of this process, alternative resource management systems (RMS) are developed for the conservation management unit (CMU) or, in this case, the stream reach or stream corridor, and an RMS is selected by the client and then implemented. The nine-step process is listed in detail in table 2–1, with relevance to stream restoration. Although sequential in steps, iterations and cycling back to a previous step commonly occur in the planning process. Plans may result in complex solutions involving a balance of watershed, riparian, and instream actions. The actions may be combinations of management, as well as designed and implemented practices and techniques. The planning process may be rapid for simple projects and may require extensive time for complex projects involving many people and resource issues.

Stream solutions start with landowners or stakeholders requesting assistance with a stream-related problem. The problem may be streambank erosion, which may be controlled and simultaneously protect or enhance ecological functions and values of the stream and riparian area. However, the problem may be a much more serious and widespread condition of multiple reach or systemwide instability, requiring detailed planning and coordination with many landowners and stakeholders. The area of streambank of concern to a landowner is also part of the stream system and its watershed. The focus of the planning team must be on the whole system to determine the cause of the problem, formulate alternatives, and evaluate the effects alternatives may have on the rest of the stream system.

Although these steps are listed in sequential order, the process may require an interactive or sometimes iterative approach. For example, the preliminary design for a planned alternative may not fit the site or may otherwise result in unacceptable construction requirements or unintended or poor overall performance. Recycling back through some steps of the planning process may be required to develop a more suitable alternative for which a new design can be developed.

The formulation and selection of an alternative solution should give consideration to the potential problems and human resource availability. Information must be identified that could affect installation such as construction access, safety concerns, material availability, pollution control requirements, and local ordinances. Some of the potential problems a planner may identify are:

- permitting requirements (surveying, clearing, earth-moving, dredging, cultural resources)
- ownership/land rights
- site access (season, timing, and physical limitations)
- material availability (earth materials, plant materials)
- construction scheduling (season, environmental windows flow conditions)
- local ordinances
- tolerance for risk and uncertainty
- utilities (underground, overhead)
- pollution control (instream, parking areas, sediment control, chemical control)
- safety concerns (working on slopes, in water, around heavy equipment, using hand tools)
- threatened or endangered species

Figure 2–2 NRCS CPP showing the dynamic interaction between the steps

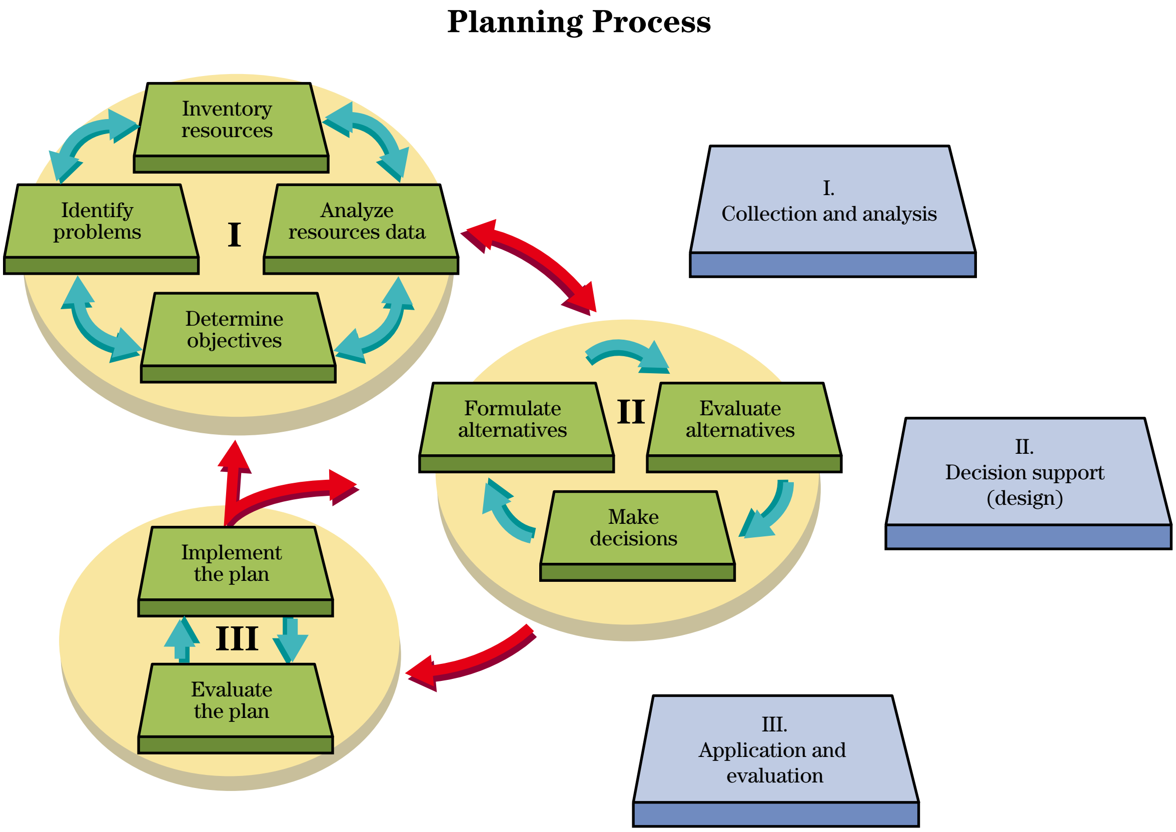


Table 2–1 Stream restoration planning process

Step no.*	Description	Generalized stream restoration planning step	NEH 654 chapter	Detailed stream restoration planning steps	Potential iteration of steps
Phase I—Collection and analysis (understanding the problems and opportunities)					
1	Identify problems and opportunities	Decide what stream characteristics need to be changed	1 2 4 17	Project identification: identify all • Stakeholders • Goals and objectives • Risks • Local vs. systemwide instabilities	Rigor of the assessment depends on the acceptable risk. As each element is addressed, use the information to confirm the initial assessments. It may be necessary to revisit the goals and objectives (may need to revisit step 2).
2	Determine objectives	Describe the desired physical, chemical, and biological changes in the stream			
3	Inventory resources	Study the stream to understand its primary physical processes, dominant impacts on water quality, and abundance and distribution of different biological populations	3 5 6 13 16 17	Assessment: assess the following at the watershed scale and at the site or reach scale: • Geomorphic condition (stream type) • Existing ecological conditions (riparian and instream) • Ecological and physical thresholds • Dominant physical and biological processes and constraints • Sediment budget and stability of existing conditions Acquire hydrologic data (watershed scale) Acquire hydraulic data (stream reach scale) Determine: • Why is the stream in its current condition • What is the ideal condition • What keeps it from naturally adjusting to the ideal condition	
4	Analyze resource data	Examine the collected information and decide what are the most important factors or processes that impact and influence the desired conditions in the stream			
Phase II—Decision support (understanding the solutions)					
5	Formulate alternatives	Determine which processes and factors can be changed, and decide if those changes are sustainable and self-reinforcing	4 5 6 7 8 9 10 11 12 13	Conduct the stability design Select practices or techniques for RMSs Select and design appropriate stabilization techniques • Cross section • Planform • Stabilization, soil bioengineering, integrated techniques • Profile, grade Conduct a sediment budget and stability assessment on the selected design, appropriate to design the practice, so it can be implemented	
6	Evaluate alternatives				
7	Make decisions				
Phase III—Application and evaluation (understanding the results)					
8	Implement the plan	Implement the selected changes to the stream system	15 16 17	Identify construction issues and impacts on design to fine-tune design and implementation Document maintenance and monitoring requirements: • Perform ongoing maintenance • Evaluate success and practice adaptive management	
9	Evaluate the plan	Modify the course of action as new information is collected and analyzed			

*NRCS Planning Procedures Handbook, Amendment No. 4, 180–VI–NPPH, March 2003

During the stream restoration planning process, information is gathered and decisions are made that will direct the design, determine the type of contract or agreement to use, and identify installation concerns. Decisions such as the extent of design needed are determined based on the complexity of the alternative selected, type of contract or agreement, availability of experienced staff to direct construction, and contractor experience.

An understanding of the different types of contracts and agreements is imperative during planning. Contract issues are described in more detail in NEH654.15. Once the planners know the available resources, they can select the type of contract or agreement. Project cost can determine the type of contracting procedure selected such as formal or informal (simplified) acquisition procedures. Funding may also dictate the selection of a particular type of contract. For example, labor may be provided by volunteer groups and the equipment acquired with an equipment rental contract, if funds are limited. A local sponsor may be able to do part or all of the work if they have the equipment, workforce, and experience.

During the planning process, installation must be considered when selecting alternative solutions. For example, complex solutions may require either experienced construction oversight to direct the work or a very detailed design package.

654.0203 Historic approaches for determining goals for stream restoration designs

Knowledge of the behavior of streams in relation to conditions in their watersheds before and during the historical period gives insights to effective watershed management. The design and restoration of streams is often guided by a desire to recover a lost condition. This historic basis requires asking to what standard or for what historical period we are designing. For example:

- What did a stream and its watershed look like at the time of European settlement?
- What did a stream and its watershed look like before the land use became what it is today?
- What did a stream and its watershed look like before the last big storm?
- What did the stream and its watershed look like before its condition became a concern?

The historical approach is not new. Some important earlier studies are by Gilbert (1914); Happ, Rittenhouse, and Dobson (1940); and Vita-Finzi (1969). A more recent, but classic, study using a large assortment of historical techniques for landscape reconstruction is that of Whitney (1995).

(a) Limitations of historical approaches

Goals for a stream restoration project are often determined by picking a point in the past from a photograph, writing, oral history, or from interpretation of landforms and attempt to put the stream back to that condition, or a desired point in time. However, things are not always as they seem. For example, a large Georgia swamp pronounced by authorities as primeval was shown to have been prime agricultural land in the 19th century that had been transformed to swamp by human action (Trimble 1970a). On the other hand, some Australian lakes and rivers commonly thought to have been radically transformed by human action were shown to have changed relatively little, and those changes may have had more natural than human causation (Finlayson and Brizga 1995).

Selecting a stream shape from a photograph and trying to replicate that shape ignores other factors that control the planform and other attributes of the stream and its corridor, including the riparian area. Photos of streams typically focus on crossings, easily accessible points, and cross sections. In many cases, usually little can be learned about the historical pattern and diversity of riparian vegetation from photographs at such locations.

Dynamic changes in timing, frequency and magnitude of flows, and sediment load and transport are also not revealed in photographs. The size, shape, and other physical characteristics of alluvial streams are a function of the types and quantities of sediment in the water and comprising the bed and banks, as well as the nature of the flow conditions. A photograph could easily show a transition phase between two relatively stable states, but may provide little understanding about the direction or magnitude of that change. Refer to NEH654 TS2 for an expanded description on the use of historic information for stream restoration design.

In a physical and possibly biological sense, streams are disturbance-driven systems. The current processes that can be observed in a stream channel were shaped by prior floods, sediment input and transport events, channel changes, vegetation changes, and species interactions. Although it is useful to think of a stream as having a most probable form, each of these extreme events resets or alters that form.

654.0204 Geomorphic approaches for determining goals for stream design

The geomorphic approach to stream restoration work encompasses a number of different activities including stabilizing unstable streambanks and channels, reconfiguring the planform of channelized or aggraded streams, restoring natural substrates and other habitat features, and even daylighting piped streams. Figure 2–3 illustrates a daylighting stream project showing a stream that formerly flowed through a pipe underground and was restored to a more natural condition. This work can be undertaken on a single stream reach or comprehensively over an entire watershed. The geomorphic approach to stream restoration work provides a way to meet management objectives of:

- protecting streamside property or structures from erosion or reducing sedimentation rates in a downstream reservoir or navigable waterway
- improving ecological conditions for aquatic or riparian life

Work undertaken as compensatory mitigation is included in this latter management objective. Regardless of the management objective, stream geomorphic restoration design and construction techniques strive

Figure 2–3 Daylighting stream project

to produce a stable stream that is natural in appearance to the untrained eye, with minimal detrimental environmental impacts.

A structured planning process is needed for stream work that:

- examines the physical, biological, and chemical processes in and around a stream to determine their hierarchy and interaction
- describes in what historic range of variability those processes functioned
- determines which processes could be modified to bring about desired results
- describes desired results and how long it would take to achieve them
- monitors the results of a modification to a stream to determine the level of success
- adapts future actions according to monitoring and evaluation results

Many stream management and modification practices fail because of oversimplification, application of approaches that are not designed for dynamic fluctuations in site conditions, and a general lack of understanding about how streams function, physically, biologically, and chemically. A goal might be that the number of adult salmon returning to a stream will be increased tenfold in the next 20 years. Until the amount of habitat in the stream and its utilization are described, there may be no way of knowing if these fisheries goals can be achieved.

In addition, physical processes of sediment delivery and transport and streamflow fluctuations create physical habitat units. The amount of flooding and interactions between floodwaters, riparian vegetation, and the shallow alluvial aquifer and hyporheic corridor often play a major role in nutrient redistribution in a stream. This can impact primary food sources and productivity. Until these issues are understood in relative importance to one another, determining if the goal is realistic or sustainable may not be possible.

Ideally, environmental investigations should be conducted in the planning stage, prior to formulating a stream restoration plan. Work proposed to control erosion or sedimentation should be substantially different in scope from work proposed to benefit aquatic life. For the former, environmental planning investigations should be focused on collecting information necessary to develop the optimal design that will meet the erosion and sedimentation control objectives. Designs should keep conditions as natural as possible, and construction practices should be used that minimize adverse environmental impacts to stream life during construction. In contrast, when the management objective is to improve ecological conditions for aquatic life, it is important for restoration planners to determine that a stream is biologically impaired and that degraded geomorphic conditions are, indeed, a principal stressor to aquatic life.

(a) Geomorphic analog or reference reach

An analog section of stream, sometimes called a reference reach, can also be used in establishing goals. In this technique, a section of the project stream or a neighboring stream is identified that is thought to function in a desired manner. The reference reach is measured, vegetation is analyzed, and biologic conditions are characterized, and these become the goals for the reach of stream that is deemed to be not functioning properly.

In cases where there have not been substantial changes in sediment supply and hydrologic character, stream reaches up or downstream of the degraded reach could provide an appropriate template for restoration design. This situation is of greatest potential applicability when the cause of channel degradation is from direct channel disturbance or riparian vegetation changes.

More insight is gained by this reference reach approach than the desired point-in-time method, but the technique has some limitations. Directly transferring the properties of one stream to another makes the assumption that the recent disturbance regimes have been similar. Also implicit in this technique is that analog sections are in the same geologic materials and have similar size watersheds, chemical budgets, sediment budgets and sediment particle size distributions, and biologic food chains and predator-prey relationships. The lack of similarity between reference reaches and the restoration stream reach may induce more uncertainty into the process for setting objectives.

Geologic conditions may be controlling stream behavior in the reference reach. These larger scale geologic controls often create stable stream conditions. Unfortunately, this stability is not necessarily transferable to the restoration stream section that is under the influence of different geologic conditions. The limitations of this approach are addressed in more detail in NEH654.09.

654.0205 Ecosystem approaches for determining goals for stream design

Prioritization of stream restoration work should first characterize the existing ecosystem condition, identify stressors, and then prioritize among these stressors. Stream restoration plans should be formulated to focus effort on correcting major stressors. To restore aquatic life, degraded stream conditions should be restored only if these conditions are a priority stressor for aquatic life and will not likely self-correct in a timely manner without intervention.

Several degraded conditions may be harmful to aquatic life. These include constructed fish blockages, upstream migrating headcuts, streams confined in underground pipes, streams confined by concrete, and recently maintained or channelized streams in earthen channels. These stream conditions should generally be considered priority candidates for stream restoration work, since remediation of the condition would likely benefit aquatic life.

The ecologic approach to stream restoration work may provide the greatest benefit to aquatic life in a short reach, but the results could benefit aquatic life over a much greater length of the stream system. When degraded conditions are widespread, the restoration work should be strategically targeted at local reaches that can eventually produce widespread improvement to benefit aquatic life, or work would need to be undertaken on a large scale. Table 2–2 shows likely impact scales for various stream problems.

Two opportunities where localized restoration work benefits aquatic life over a much greater length of stream are where a structure obstructs the upstream passage of aquatic life (fig. 2–4) and when a downstream change in base level causes a rapid upstream migrating headcut (fig. 2–5).

Fish blockages prevent upstream movement of fish and other aquatic organisms that are unable to pass through or over them. Following natural or human-caused events that result in depletion of aquatic species upstream of the blockage, populations occurring downstream may be unable to reoccupy upstream habitat when conditions improve. Also, following downstream migration, migratory aquatic species may be unable to return upstream of the blockage and cannot survive otherwise suitable habitat. However, it should be noted that fish blockages may be desirable if they are preventing the upstream movement of an unwanted invasive aquatic organism.

Diversion of water flow for irrigation, municipal and industrial water supplies, and recreation can have extreme consequences for aquatic habitat and riparian vegetation along the stream where water is diverted. The degree of impact from these diversions depends on state laws and regulations on instream flow conditions and water rights. In the past, some streams have been totally dewatered due to diversions, resulting in total loss of aquatic habitat. In the past 20 years, many irrigation diversions have installed fish screens with return flows that prevent fish from being diverted into ditches or irrigation fields.

Table 2–2 Situations in which ecologic restoration projects in a stream reach would have a high likelihood of benefiting aquatic life

Stream reach problem	Likely scale of impact
Constructed fish blockage in stream system naturally lacking fish blockages	Watershed
Rapidly upstream migrating headcut	Watershed
Piped stream	Stream reach
Concrete stream channel	Stream reach
Earthen stream channel recently channelized or maintained	Stream reach
Water diversions causing flows too low for fish passage or rearing	Stream reach

Figure 2–4 Fish blockage in stream

Figure 2–5 Upstream migrating headcut; smaller tributaries will also cut into fields, triggering gully erosion

Headcuts proceeding upstream can destabilize streams over a very large area, altering the relationship between the stream and its flood plain, drying out flood plain wetlands, and generating large volumes of sediment that can be harmful to aquatic life. Headcuts are also often fish blockages.

Two degraded geomorphic conditions that present restoration opportunities to improve conditions locally are piped streams and streams with concrete channels (fig. 2–6). When streams are piped or lined with concrete, habitat complexity is completely lost, and flow conditions are often severely altered. Water velocities are greatly increased during high-flow events, while the channels may run nearly dry at other times. Additionally, flow between the stream and ground water underlying the stream (the hyporheic habitat) is prevented, severely restricting the nutrient processing functions that the stream and its aquatic life would otherwise perform. Daylighting piped streams is the restoration of a stream's planform and normally involves substantial design efforts, especially in built-up areas. Removing concrete channel boundaries and restoring a stable planform may be the only way to restore functions to these streams. In either case, a first step is to begin to reconnect riparian areas and people to the streams. In the case of piped streams, the starting point is to gain awareness of what the stream once was and what it can be with daylighting. For concrete-lined channels, reconnecting can start with establishment of green areas and managed riparian areas along the channel.

Channelized streams with earthen channels (fig. 2–7) present unique challenges for restoration. The simplified substrate and depth conditions of the channelized stream constitute a loss in habitat quality for stream life.

Stream channelization is common in regions of the country where large areas of wetlands have been lost (fig. 2–8 (U.S. Fish and Wildlife Service (USFWS))). In these areas, opportunities to restore flood plain wetlands should be investigated as a way to contribute to stream ecosystem restoration. Generally, the self-restoration potential of lost wetlands in absence of intervention is low.

Although excessive sediment in streams is the principal stressor to aquatic life nationwide, restoration projects may not always benefit aquatic life. Excessive sediment, while not desirable, is not typically damaging to all stream aquatic life, as are some other stressors, such as highly degraded water quality and severe

Figure 2–6 Stream encased by concrete channel

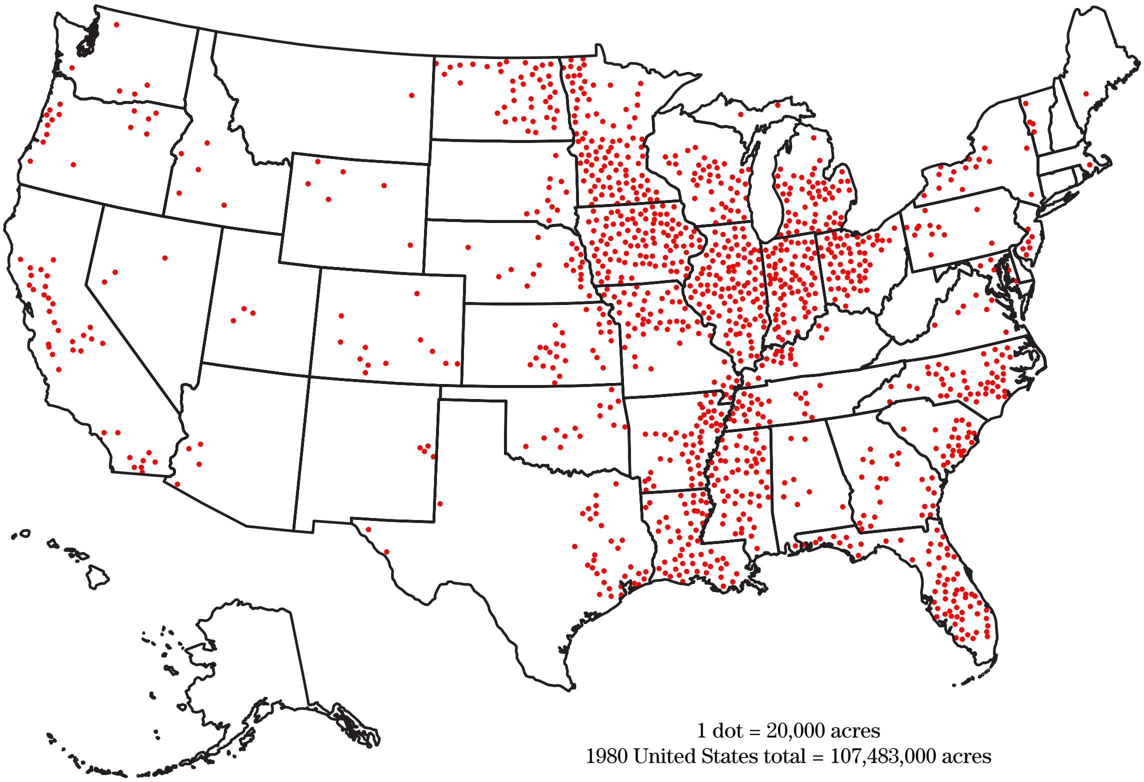
Figure 2–7 Channelized stream (lower left); former natural stream has been assimilated into the regional artificial drainage network

alterations in flows. The impacts of excess erosion and sedimentation impact primarily sediment-intolerant species such as:

- aquatic insect larvae in riffles
- fish that spawn on coarse substrates
- fish that eat insects of coarse substrate bottom habitat
- aquatic organisms that eat submerged aquatic plants

Excessive sediment damages some highly valued aquatic organisms such as many species of trout. Sediment-tolerant organisms, however, may thrive if no other stressors are present. Systemwide strategies may be needed to reduce watershed sediment production. The USDA Agriculture Research Service (ARS), NRCS, and U.S. Army Corps of Engineers (USACE) have undertaken projects to demonstrate such systemwide sedimentation/erosion control strategies in northern Mississippi (Demonstration Erosion Control project).

Figure 2–8 Regions of the country where channelized streams would likely be associated with historic lost wetlands



654.0206 Rural stream restoration

The primary task in most rural situations is to protect an identified resource. Stream restoration in rural areas is often undertaken as a result of an individual landowner request at a specific site where there is no organized effort to restore a larger stream segment. While it may be legitimately questioned whether stream restoration can be accomplished on such a small scale, there are many opportunities to address local conditions and begin the process of education with a long-term goal of restoration on a larger scale. The problems or symptoms leading to the request can be analyzed and documented to determine the feasibility and probable effects of a local solution. The analysis will then conclude whether appropriate action can be taken to offset negative treatment effects and then assess the risk of action or inaction. The time and expense of large-scale studies and data collection may not be justified by a single request from an individual or a small group of individuals. However, in many cases, individual goals and objectives can be achieved by careful problem identification, root cause analysis, and appropriate application of restoration techniques. At the very least, a determination of no feasible action at the individual scale is far superior to an inappropriate attempt at a solution that may have negative impacts at the larger scale.

(a) Issues

Typical rural requests fall into two broad categories: protecting property or restoring and maintaining channel capacity. Both types of requests normally relate to one or more specific problems centered on the loss of tangible property due to bank erosion, excess bed-load deposits, excess woody material, or increased runoff exceeding channel capacity and, therefore, resulting in increased flooding or channel adjustments. The desired condition in these instances is simply to protect what is being damaged: crops, cropland, public roads, utilities, private roads, bridges, and levees. Unfortunately, the problem is seldom as isolated as the landowner's goal of protecting a resource.

The landowner objectives or goals must first be related to an immediate cause and a root cause before a treatment recommendation can be determined. Table 2–3 shows how the most common primary goals relate to problems, immediate causes, root causes, and solutions.

Where possible, it is preferable to address the root cause of the problem. Realistic goals must take into account the accurate assessment of the root cause of the problem. The first task is to broaden the landowner's concept of stream dynamics from merely patching a problem to understanding why the problem exists. Often asking about other current or past stream related problems will lead to a productive discussion about the landowner's longer term goals and objectives. And just as important, it will give the designer insight into the overall stream's behavior and state of equilibrium.

As an example, slope failure affecting an access road may be the problem, but there may also be a problem maintaining a stream crossing or keeping the large logjams out of the channel. Investigation may lead to the conclusion that the channel is degrading, causing the stream crossing to be undermined. The same incision process is then causing excessive slope failure as the bank height increases, resulting in channel widening and large mature trees being undercut and falling into the channel. The landowner may now understand that to patch the slope failure threatening the access road may be futile unless the incision problem is first addressed. The goal of protecting the access road has been broadened to address the cause of the problem. By halting the channel incision on this reach of stream, the landowner's access road can be protected. The stream then can be improved by moving it towards equilibrium, and the aquatic value and aesthetic qualities enhanced.

The task of addressing the immediate problem will remain the landowner's objective, but the method of attaining the goal must address the larger issue of channel instability by treating the root cause of the problem. A decision will then need to be made regarding the scope, risk, and cost analysis of all the proposed treatment alternatives. Before discussing alternatives, explore the secondary goals and objectives of the landowner. The requests are almost always generated by one of the primary objectives, but some landowners will also be interested in such secondary benefits such as aesthetics, aquatic habitat, wildlife habitat, or water quality.

Table 2–3 Common streambank problems, causes, and solutions

Primary goal	Problem	Immediate cause	Root cause	Solution
Protect property: cropland, forestland, residential land Infrastructure: roads, bridges, utilities, levees	Lateral migration	Excess energy/ increased velocity	Steepened gradient or increased flow	Reduce energy gradient by reducing slope with grade control or re-meandering stream. Increases in flow regime will require watershed treatment and/or temporary storage to reduce discharge
		Inadequate riparian vegetation	Clearing and/or removal of mature vegetation	Restore riparian vegetation and buffer area. Additional treatment (toe protection) may be needed during establishment period
		Channel obstruction	Woody material, landslide has reduced channel capacity at site forcing flow around obstruction	Remove obstruction to restore channel capacity
		Unstable channel planform	Normal lateral migration, channelization or modifications have created small radius bend(s)	Modify channel geometry to conform to natural channel geometry relationships of stable channels. Typically with radius of curvature/bankfull width ratio greater than 2.0
		Excessive bed-load deposition	Excessive erosion upstream generating more bed load than channel can transport. May be result of channel incision and widening upstream of problem. May be aggravated by channel widening, resulting in excessive width depth ratios. May also be depositional area created at delta above confluence with larger stream or reservoir	Find and treat sources generating excessive bed load. Channel may then need to have stable cross section and planform reestablished at problem reach. Attempts to modify channel to transport bed load through the problem reach are only successful in moving the problem downstream
	Slope failure	Critical bank height exceeded	Channel incision has created bank height that exceeds soil strength to resist failure	Stabilize bed to prevent additional incision, and raise bed elevation to restore bank heights that are less than critical height. An alternative after halting incision is to slope banks to an angle that is stable for the materials and heights
			Banks are over steepened by lateral erosion at the toe of the bank resulting in slope failure	Stop lateral erosion at the toe. Refer to causes of lateral migration to insure root cause is addressed
		Geotechnical problems	Banks have internal geotechnical problems resulting in bank failure only indirectly effected by streamflow (seeps, springs, weeps, differing soil materials)	Address the geotechnical problem before attempting any other solution. Consult with appropriate technical personnel for assistance

Table 2–3 Common streambank problems, causes, and solutions—Continued

Primary goal	Problem	Immediate cause	Root cause	Solution
Restore or maintain channel capacity	Bed-load accumulation	Excessive upstream sources	Large bank failures/escarpments or bed degradation contributing excessive bed load	Identify and make appropriate treatment to reduce bed-load contributions
		Reduced velocity in reach resulting in deposition of bed-load material	Change in slope or backwater effects from channel obstruction downstream reservoir or confluence with another stream	May be no effective practical solution without detailed project analysis and major project activity to reduce bed load
	Multiple or frequent logjams	Logjams restrict flow, resulting in loss of channel capacity and increased flooding or bank scour near obstruction	Introduction of woody material from logging, clearing ,or high mortality rate of mature trees upstream of problem, resulting in logjams at site	Locate source, and address problem by removing potential for excessive woody material in channel
			Excessive slope failure upstream causing large woody material from riparian zone to enter channel	Address problem of slope failure upstream of problem. Refer to causes of slope failure to ensure root cause is addressed
	Increased runoff/ flooding	Land use changes in watershed such as urbanization or intensified agricultural use	Change in flow regime resulting in increased peaks or extended durations initiating changes in channel morphology	Make watershed modifications to restore natural flow regime. Alternative is to allow channel morphology to adjust naturally, or make carefully planned adjustments to changes in flow regime

Fortunately, effective treatment to address the immediate problem will usually have positive impacts on these secondary goals if the root causes of the problems are addressed and the stream segment is brought back to a state of near equilibrium. However, by first identifying the secondary concerns, the level of improvement can be enhanced with appropriate design, construction, and operation and maintenance of treatment measures.

(b) Scale

After the root cause has been identified, the scale or scope of the solution must be determined. The question is, "Is this a local instability problem or a systemic problem?" If the problem is local, an individual landowner or cooperation between two or more landowners can implement the needed solutions. However, if it is a systemwide failure, rarely can the rural stream restoration project expand to the watershed level without a local organization to sponsor the project. Figures 2–9, 2–10, and 2–11 illustrate a systemwide stream stability problem, and figure 2–12 shows an example of a local stability problem treated with a grade control structure and stream barbs.

The question then becomes, "Is there a solution that can be implemented by the landowner?" If not, the only answers may either be to expand landowner involvement or abandon the project until the required area of treatment can be addressed.

Fortunately, many areas of the country have a grid of roads, culverts, and bridges that effectively confine many of the channel instability problems to segments between road crossings. Many times, even a systemwide failure may have some solutions or treatments available by working complete segments between these manmade stable points. The root cause again will indicate the extent or scale required to implement a satisfactory solution.

654.0207 Developing watersheds

Public officials are faced with ever-increasing liability pertaining to public safety, public infrastructure, property, and other forms of investment. As rural watersheds transform to urban, municipal governments must accommodate growth by annexing and zoning additional land parcels. Preparation for subsequent development of subdivisions and other construction may include an inventory of streams and other sensitive sites to assess the impact of additional runoff from impervious cover. Other planning measures include updating or revising the comprehensive plan, development codes, ordinances, and other protective measures. Rural communities and areas in the urban fringe undergoing transformation may not have technical or human resources to develop comprehensive plans, ordinances, or to carry out special studies. Others, however, play an active role in planning and guiding development.

In these newly urbanizing areas, as well as areas already urbanized, stream restoration can be viewed as a capital improvement because of the amount of public expenditure involved with working in and around streams. Measures are available to municipal and county governments to minimize future impacts on streams, as well as to protect improvements made along the stream. State legislation grants municipal home rule authority, enabling local jurisdictions to enact and codify ordinances. These legal instruments are used to further protect community assets, which include streams.

The U.S. Environmental Protection Service (EPA) Office of Water compiled a collection of municipal ordinances from various local governments throughout the country. These ordinances were collected as part of a larger partnership effort with organizations, such as the International City Municipal Association (*http://www.icma.org*), American Water Works Association, and others, as a template for those charged with making decisions concerning growth and environmental protection. These ordinances also address aquatic buffers, erosion and sediment control, open space development, stormwater control operations and maintenance, illicit discharges, and post construction controls.

Figure 2–9 Systemwide instability. Heavy bed load from upstream erosion exceeds this stream's capacity to carry bed load. The root cause is channelization and urbanization, resulting in loss of channel capacity as midchannel bars form. (Sugar Creek, McLean County, IL)

Figure 2–10 Systemwide instability. Very heavy bed-load deposits have filled original channel, forcing stream to move laterally into finer grained bank materials. This is an example of an alluvial or bed-load-driven stream. (Sexton Creek, Alexander County, IL)

Figure 2–11 Systemwide downcutting induced by channelization project downstream. Additional landowners must become involved to address the root cause of channel incision to stabilize the entire degrading reach. This is an example of a threshold or flow-driven stream. (Hurricane Creek, Jefferson County, IL)

Figure 2–12 Local instability problem above a township bridge. This channel became misaligned with the bridge opening due to lateral migration. The treatment includes stream barbs and a rock riffle grade control structure to protect against possible degradation as a result of shortening the channel during realignment. (Bay Creek, Pike County, IL)

654.0208 Urban stream restoration

The challenges of working to restore physical and biological functions and values in urban or developed streams and their watersheds focus on hydrologic characteristics that no longer fit a natural stream, as well as the obvious limitations provided by physical and legal boundary constraints. To accurately understand the objectives and risks of stream restoration in a developed watershed both the social complexity, as well as the biophysical complexity of the landscape, must be understood (fig. 2–13). Stakeholder goals and objectives must also be clearly defined and the community's interests prioritized. Implementing any successful project also requires that risks be understood mutually by the community, as well as the planners and designers.

Understanding the temporal and spatial scales of stream processes, channel evolution process, and linkages between flow and sediment movement and channel dynamics is essential in any stream restoration project. Understanding these interrelationships will be incomplete, however, without a dynamic watershed context. Recognizing that many developed watersheds are, in fact, actively developing is essential to implementing a successful stream restoration project.

Figure 2–13 Developed area (urban or suburban)

How streams and their watersheds change over time must be clearly understood. It is important to recognize, at the time of observation, where the channel exits in the space-time continuum of its dynamic equilibrium with the water and sediment of its watershed. Failure to do so can result in the implementation of a stream restoration project which is neither in harmony with the land management objectives of the community nor meets the biophysical needs of the resource.

(a) Issues

The issues and interests of landowners within developed watersheds often are similar to those in rural watersheds. These issues and interests often include loss of property, fish and wildlife habitat, recreational opportunities, risk of flooding, and aesthetics. However, this difference in residence time, so to speak, significantly affects all steps in planning a stream restoration project in an urban area.

The human community affects ecological processes and is also affected by the implementation of a stream restoration project. Fully engaging the community in the planning process to identify issues and interests encourages people to look beyond their own backyards and to identify ways to integrate the complex facets of a given project.

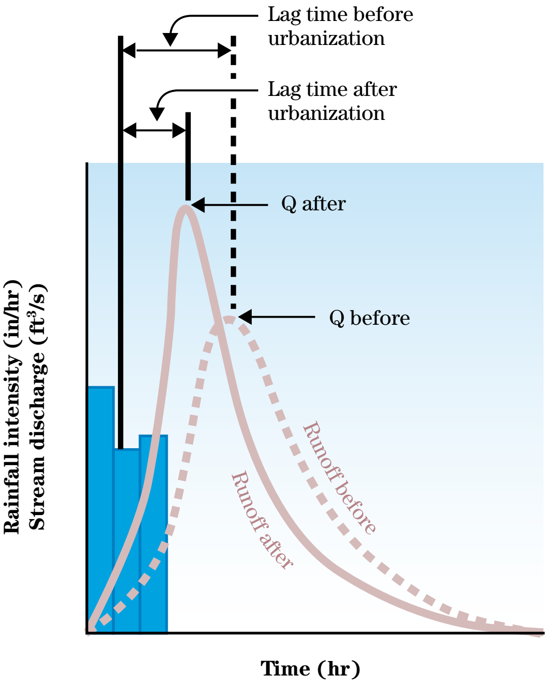
The scale of the project, degree to which the stakeholders wish to participate, and in some cases, the resource issues being evaluated will determine the amount of public participation. An issues and interests meeting has two principal objectives:

- All stakeholders can identify the issues and interests that they feel are important, both as related to the specific project resources and to the area as a whole. These include the natural resources of the area, as well as the social and economic resources of the local community. This allows all members of the community who choose to participate to have a voice in the resource conservation decisionmaking process. By doing so, it creates a way for stakeholders to communicate, explore different perspectives, and see the project in a larger context than might otherwise be possible.
- Stakeholders attending the meeting(s) can participate equally in a collaborative process

to identify the project objectives and focus. The goal is to design and implement a technically sound stream restoration plan that meets the needs of the ecosystem and is in harmony with the resource management objectives of the community and the respective local, state, and Federal agencies. This meeting establishes common threads and common ground for stakeholders and creates a way for their dialogue to be translated into action by implementing an achievable plan to conserve, protect, manage, or rehabilitate the stream corridor resources.

It is of paramount importance to recognize how changes in land use affect watershed hydrology and sediment regime. Urban development produces more impervious surface area, subsurface drains, land grading, and stormwater conveyance systems. The effects of increased imperviousness and the subsequent disconnect of the water infiltration and water storage capacity of the watershed soils and ground water result in a distinct shift of the streamflow hydrograph to the left, as shown in figure 2–14 (Federal Interagency Stream Restoration Working Group (FISRWG) 1998). Both the rising limb and recessional limb of the hydrograph have an increase in slope with a higher peak discharge and a decreased lag time between the onset of a particular storm event and peak streamflows. How this changed and changing hydrology affects the morphology and stability of urban streams and channels must be understood, recognizing that regional curves of typical stream dimensions for various drainage area sizes may not be usable at all.

Figure 2–14 Comparison of hydrographs before and after urbanization



Increased flows in urban watersheds often result in channel incision. In addition, the clear-water discharge associated with present day storm drainage systems results not only in increased streamflows, but also results in streamflows with a higher capacity to transport sediment. The process of incision often results in the simplification of the streambed topography. The pools shorten in length, become shallower, and pool slope is steepened. Riffles become more extensive and steeper.

The process of incision and resulting change in stream morphology operate in a negative feedback loop, perpetuating instability and loss of habitat within the stream. Consider the equation for stream power:

$$\phi = \gamma Q S \qquad \text{(eq. 2–1)}$$

where:

ϕ = stream power (ft-lb/s-ft)
γ = specific weight of water (lb/ft^3)
Q = discharge (ft^3/s)
S = slope (ft/ft)

As shown in figure 2–15, development within a watershed results in an increase in stream Q during a storm event. An increase in Q results in a direct increase in stream power. The increase in stream discharge and, thus, in stream power translates to an increased ability to transport sediment. The channel must adjust (incise) to accommodate the increased flows now generated by its watershed.

Incision tends to decrease bed topography, thereby increasing channel slope. An increase in channel slope results in a direct increase in stream power. Again, the increase in stream power translates to an increased capacity to transport sediment, which is expressed as incision. Figure 2–15 illustrates the relationship between changes within a developed or a developing watershed, relative to incision and loss of habitat, with respect to the variables of the stream power equation.

An often overlooked and misunderstood risk associated with stream restoration in urbanizing or developed watersheds is the acceptance of the project by the community. It is important for the resource professional, both the planner and designer, to recognize that the community is not only one of the resources affected by the project but also one of the resources which affects the project. A stream restoration project, which is technically sound from a biophysical perspective, but not in harmony with the resource management objectives of the community, may also be considered a failure.

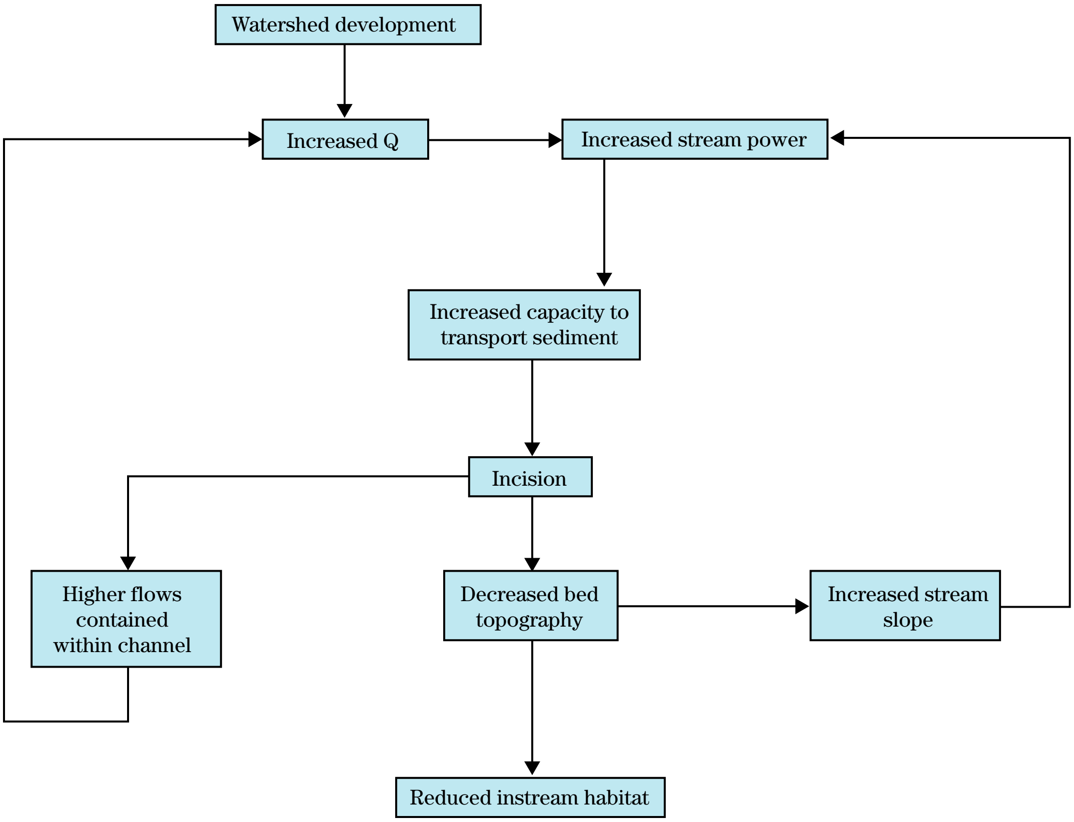
Case study 8 of this handbook, Copper Mine Brook, provides some limited risk analysis for an urban stream restoration project involving concerns about infrastructure, as well as biological and physical stream processes.

(b) Scale

In a rural watershed, the entire stream reach (say, 12 meander wavelengths) may be located on the property of a single landowner who has resided on the property for the past 25 years. The description of the issues and interests of the landowner, relative to the temporal and spatial scales of the channel instability, is comprehensible for the landowner. The landowner has witnessed the evolution of the channel and has a stake in its entire reach.

Conversely, in a developed watershed, that same reach of stream may be home to 30 different property owners who have an average residence time of approximately 5 years. The discussion of issues and interests

Figure 2–15 Potential effects of urban development in a watershed



expands accordingly, and the description of the spatial and temporal scales of the channel process may not be as relevant to these landowners. The perspective of each landowner rarely extends beyond the adjoining properties if it extends beyond their individual property. In addition, their perspective of the channel and its associated processes, on average, do not extend beyond 5 years. They own only a portion of the channel and have been witness to its evolution for only a short period of time.

654.0209 Constraints

Constraints limit the possible actions. Determining project constraints is just as important as establishing objectives. There is a feedback loop between constraints and project goals and objectives. Constraints can be natural anthropogenic. Examples of natural constraints include:

- mountains that limit channel planform
- bedrock outcrops that limit or control channel grade
- water quantity that limits the aquatic species that can use a channel

Examples of anthropogenic constraints include:

- flood plain development or land use that limits channel planform
- tolerance for risk of project failure
- endangered species or regulatory concerns that helps defines acceptable treatment practices

Anthropogenic constraints are particularly common in urban flood plains and include rights-of-way, highways and bridges, utility crossings, buildings, archeological and historical sites, and cemeteries.

Another common concern is contaminated sediment in the streambed or banks. To ensure that these polluted sediments stay in place, it may be necessary to stabilize the banks, preventing the natural channel migration process.

Technical and nontechnical issues affect the feasibility of any stream restoration project. Technical constraints are generally reasons why a particular treatment recommendation cannot function or meet the landowner objective. Nontechnical constraints are generally reasons why the treatment recommendation will not be implemented.

(a) Technical constraints

Data availability—In most rural situations, the existing data are sparse and general in nature. Typically, information is limited to existing aerial photography, topographic maps, soils maps, and local knowledge. The information from these sources is invaluable, especially historical photography that can be used to determine changes in planform, land use changes, lateral migration, and some bed features such as point bars and central bars.

Additional data collection at these rural sites is usually limited, as the scale of the project will not justify large data collection expenses. If more data are needed than can be collected locally, the technical constraint may then be the lack of sufficient data to make a recommendation or to design a treatment. This constraint must be balanced with the experience and judgment of the designer, as it is unlikely that any project will have all the data the designer would like to have available.

Number of landowners—Another technical constraint enters when the scale of the project requirements exceeds the level of interest. In other words, effective treatment requires work on several properties and there is not the interest or the resources available to implement a solution. The technical decision will then quickly be reduced to answering questions about long- and short-term feasibility and risks. Questions to be asked include:

- Is there a treatment that can be effectively applied within the scope of the project area?
- Would the proposed solution have negative impacts on stream stability on a larger scale?
- Will the effect of upstream or downstream instability threaten the implementation or planned life of the treatment?

If these questions cannot be answered satisfactorily, the treatment is not technically sound and should not be implemented.

Experienced designer(s)—The lack of sufficient data and the lack of justification to devote resources to data collection make experience and professional judgment extremely critical in these rural settings. It becomes essential that the designer investigating these sites has the knowledge, time, and experience to gather basic field information and make sound observations of stream characteristics and behavior both at the site, as well as upstream and downstream, for a considerable distance, before making any treatment recommendation. The investigation must be thorough enough to make sound judgments about the stage of channel evolution in the project reach, sediment transport efficiency, bed-load transport capability, bank materials, presence of geotechnical concerns, planform geometry, geomorphic bankfull dimensions, and incision. Local data are not widespread in the form of reference reach data or localized regional curve information to determine the normal or expected size, shape, and slope of a stable channel in the local physiohydrological region. Therefore, until and unless these resources are developed locally, the designer will need to rely on professional judgment to apply appropriate technical information from other regions and base recommendations on experience gained from similar applications.

Availability of materials, equipment, and labor—For any solution to be implemented, it must be feasible to construct with materials and equipment readily available. Many stream restoration projects are in areas where access is difficult. These types of questions should be asked before finalizing a recommendation:

- Is there access for the necessary equipment to get to the site?
- Is there room for the equipment to operate safely at the site?
- Is the right kind of equipment available locally?
- Will construction be done from the land or bank side or the streamside?
- What kind of environmental damage is likely?
- Will there be damage to roads, lawns, or fences that must be considered?
- Is there access to get materials to the site?
- Are required materials readily available?
- Will access be available for repair or maintenance?
- Are skilled and experienced contractors available?
- Is the labor pool locally restricted during the time of installation?
- Are volunteers available, and can they perform the work?

(b) Nontechnical constraints

Costs—Economic constraints are often the most obvious constraints. In rural areas, the cost may easily exceed the value of the resource to be protected. In many circumstances, protecting rural land may not have a favorable cost/benefit analysis unless other factors, such as improvement to water quality, aesthetics, and habitat enhancements, make the project viable. Landowners may not value these secondary benefits enough to make the project economically attractive. Therefore, a large portion of rural projects often include protection of roads, bridges, utilities, and access points. For this reason, some areas or projects may qualify for financial assistance from Federal, state, or local funding sources to provide landowners an incentive to apply stream restoration practices that would not be economically feasible if the landowner were to bear all costs.

Regulations—Regulatory constraints may also impact the project design and feasibility. All projects are subject to review by regulatory authorities under Section 404 of the Clean Water Act (33 U.S.C. 1344), Section 10 of the Rivers and Harbors Act (33 U.S.C. 403), State Section 401 Water Quality Certification, and Section 106 of the National Historic Preservation Act. Most areas also have state and local regulations that must be met. Become familiar with all the regulatory guidelines in your project area before completing final designs to be submitted to permitting agencies. NEH 654.17 provides additional information and consideration regarding permitting requirements.

Aesthetics—Aesthetic or societal constraints may also affect planning in rural settings, although usually to a lesser degree than in an urban project. By addressing the root cause of the identified problem, the stream segment can be stabilized, and the damage caused by previous erosion or construction activities will be restored through natural regeneration. In settings and locations where natural regeneration is permissible, substantial cost savings can make a project economically viable. In areas with adequate seed supply and fertile soils, sites can naturally revegetate during the first growing season. Figure 2–16 shows a project site on Kickapoo Creek in Illinois, where the banks were revegetated naturally. Some locations will require the restoration of all disturbed or eroded areas with vegetation due to aesthetic, societal, or regulatory requirements.

654.0210 Risk, consequences, and uncertainty

Evaluating risk, consequences, and uncertainty help designers and stakeholders make decisions on what design choices to make. Such measures of probability are described in many texts and handbooks (Fripp, Fripp, and Fripp 2003). Risk is the probability of some event happening. Uncertainty describes the level of error in estimates of risk and consequences. Examples of these are:

- *Risk*—There is a 50 percent chance a 2-year storm will occur each year.
- *Consequences*—If the 2-year storm occurs, the following series of consequences could happen:
  - The streambank could erode 5 feet.
  - Part of a state highway will slide into the river.
  - Motorists could be killed and highway repairs would be expensive.
- *Uncertainty*—Tools to predict the discharge and velocities from various frequency storms are commonly used. Given a certain frequency storm, present tools to evaluate the certainty of the bank eroding with resultant damages are not that accurate or precise.

The analysis of both short- and long-term benefits must consider the risk factor of the proposed treatment alternative. The concept of risk is mentioned here because of its relevance in defining realistic goals for stream restoration.

In rural settings, the risk factor is normally somewhat lower than in an urban setting. If the stream restoration project fails, the consequences are often much greater in a heavily developed area than in an undeveloped area. At the same time, a rural setting can have a high risk factor when infrastructure, such as roads, bridges and buildings, is involved. Generally, the more risk involved in a potential failure, the more caution should be taken in the recommendation and design. This risk assessment should always be considered and discussed with the landowner so that all parties are aware of the level of risk taken. In a low-risk location where only moderate damage may occur, many

Figure 2–16 Project site where banks were vegetated naturally (Kickapoo Creek, IL)

(a) December 2000—lateral bank affecting adjacent cropland

(b) April, 2001—5 months after installation of stream barbs. No shaping or seeding of banks was included in project. Eroding banks will be allowed to vegetate naturally.

(c) September 2001—10 months after installation of stream barbs. Eroding banks have sloughed to stable angle and revegetated.

landowners are willing to accept possible damage that would need some repair, rather than accept substantial cost increases to lower the potential damage. As the riparian corridor matures, a well-designed stream restoration project becomes more stable over time. The greatest risk of damage normally occurs in the period immediately after installation.

More often than not, as a result of increased infrastructure, as well as compromised ecosystem health, the risks of action or inaction tend to be higher in a developed watershed than in a rural watershed. The risks associated with any one particular project vary based on the scope and scale of the subject stream reach and watershed. Although the risks associated with stream restoration are often interrelated, they can be related to the objectives for the social and biological communities.

Different approaches to achieving a given objective may involve varying degrees of risk to public safety, natural resources, property, or infrastructure. They may also offer varying certainties for success. These risks and the probability for success must be weighed against other project considerations when selecting and prioritizing projects. Table 2–4 shows an interpreted range of qualified risks for selected instream treatment techniques.

In any stream project, the “do nothing” alternative should be evaluated. This is also referred to as the “future without action” alternative. However, even this apparently simple approach should not be considered casually. Allowing an unstable condition to continue can have significant detrimental consequences from both a physical, as well as an ecological perspective.

Table 2–4 Potential range of qualified risks for selected instream treatment techniques*

Technique	Risk to habitat	Risk of channel change	Risk to infrastructure, property, or public safety	Uncertainty of technique	Probability of success
Boulder clusters	Low	Low to moderate	Low	High	Moderate
Channel modification	High	High	Low to high	High	Low to high
Drop structures	Low to moderate	Moderate	Low to high	Low	Moderate to high
Fish passage restoration	Low to high	Low	Low to moderate	Low	High
Instream sediment detention basins	Moderate to high	Low to moderate	Moderate to high	High	Low to high
Large wood and logjams	Low	Moderate	Moderate to high	Moderate to high	Moderate
Side channel/off-channel habitat restoration	Low	Low to moderate	Low	Low	High

* Derived from Stream Habitat Restoration Guidelines, September 2004; Washington Department of Fish and Wildlife, U.S. Fish and Wildlife Service, and Washington Department of Ecology: *http://wdfw.wa.gov/hab/ahg/shrg/*

654.0211 Conclusion

The accurate identification and prioritization of the issues and interests of the land user or community is crucial in planning and designing a stream restoration project. Objectives or goals that are preconceived or defined unilaterally for a restoration project often result in failed projects or projects that do not perform properly or meet expectations. Detailed designs, based on poorly formulated goals and objectives, will not normally meet expectations of the restoration. Time and resources should only be expended on detailed designs if the objectives are specific, realistic, achievable, and measurable.

Objectives of a restoration should be as specific as possible, with the resulting conditions clearly described in terms that stakeholders understand. Improving the environment would be a poorly stated objective, without any other description of what will be different with the project in place.

Objectives should be realistic and achievable. Early optimism during project planning should be tempered by what can actually be done. For example, restoration of a cold-water fishery in a stream that has been severely altered by urbanization and watershed changes may not be achievable, even though it is a noble goal. The temperature regime of the stream, both before and after restoration, should be thoroughly understood. Another example might be the desire to restore a stream to an historical condition, but the current watershed conditions differ significantly. It may not be possible to restore all of those historical functions and values to the system, but a few could actually be restored.

Objectives should be measurable. Subjective goals, such as improve water quality, may seem to be good, but should be further refined to state exactly what changes in water quality parameters are the desired outcomes of the restoration. Monitoring of the before and after conditions will reveal exactly how much change has been achieved or to what degree the desired functions and values have been restored to the stream.

The selection of goals and objectives must take into consideration the risk associated with the current, as well as the proposed project condition. This risk must be evaluated from both an ecologic, as well as a life and property prospective. In addition to the risk of the project, the uncertainty associated with the design approach and the probability of success should be taken into account. The evaluation of risk and uncertainty may force a revision of the goals and objectives.

The restoration design should include a balanced approach between structural and management elements. For example, stabilizing streambanks should include not only bank stabilization practices, but also riparian practices to manage cattle crossing (fencing), access to water (designed stream crossing), and grazing management. The final plan and design for the restoration should consider ways to meet the goals and objectives of the stakeholder(s), as well as to benefit or improve water quality, fish habitat, and riparian habitat.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654 Stream Restoration Design
National Engineering Handbook

Chapter 3 Site Assessment and Investigation

Issued August 2007

Cover photo: Characterizing the physical, chemical, and biological conditions of a stream involves sampling and the use of assessment tools.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 3 Site Assessment and Investigation

Contents

Tables

Figures

Chapter 3 Site Assessment and Investigation

654.0300 Purpose

This chapter describes procedures for assessing watershed and site conditions. Stream system inventory and assessment techniques are identified and compared. Information is provided on stream stability, as well as geological and biological assessments. A description of the uses, advantages, and disadvantages of various geomorphic stream classification systems is also provided. Finally, this chapter addresses fluvial processes and geologic issues related to ecological function, as well as stream design.

The description in this chapter of assessment requirements and methods focuses on stream systems. A stream system consists of a watershed and ground water component that contributes discharge to the system and a flood plain area that is directly connected to a fluvial channel. In a natural setting, a channel is sized by nature and associated with discharge and sediment loading from upland areas, as well as earth materials in the channel. Other upland influences include anthropogenic changes in rainfall runoff characteristics such as occur with land use change and change in sediment supply. Sediment changes can be associated with land use change and, also, with dam construction. In addition, the system might be influenced by downstream factors such as a bridge, dam, or the confluence of another stream or river.

654.0301 Introduction

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) is increasingly providing technical guidance to organizations and individuals who are actively restoring rivers and streams degraded by extreme storm events, as well as human activities. Stream restoration is an interdisciplinary, comprehensive effort that focuses on reversing past damages and assisting nature to restore partial or complete functioning of a stream system.

Watershed hydrologic, hydraulic, geomorphic, and biological processes affect streams, and designers should have an understanding of these basic principles to work in streams. NEH 653 (Stream Corridor Restoration: Principles, Processes, and Practices) provides fundamental information on streams and their corridors, as well as the basics of how to plan stream corridor restorations (Federal Interagency Stream Restoration Working Group (FISRWG) 1998).

A stream inventory and assessment is needed to provide the process-based framework to define past and present watershed dynamics, develop integrated solutions, and assess the consequences and success of restoration activities. This assessment generally includes data collection, field investigations, and a determination of the equilibrium stage of the system or portions of the system. A channel is considered in dynamic equilibrium when the prevailing flow and sediment regimes do not lead to aggradation or degradation or to changes in the channel cross-sectional geometry over the medium to long term. Data collection and assessment forms the foundation for analysis and design and is an essential first step in the design process, whether planning the treatment of a single reach or attempting to develop a comprehensive plan for an entire watershed (FISRWG 1998). Refer also to the National Water Quality Monitoring Handbook, NEH 600 (part 1) and NEH 651 (part 2, draft).

A multidisciplinary investigation is typically performed to assess prior, existing, and future stream system conditions; to better understand the dominant processes acting in a watershed; to identify information and resource needs; and to aid in the selection and design of project alternatives. Key factors that should always be considered are spatial and temporal influences on the system or portion of the system of interest. Numerous methods are available to investigate and assess stream systems. None of these methods are perfect and vary considerably in the information they provide, information they require, the spatial and temporal scales they consider, and the complexity, expertise, and resources required to use each method. Many of these methods, together with factors associated with their use, are briefly described in this chapter. A compilation of numerous inventory and assessment techniques (USDA NRCS 2001c) is presented in NEH654 TS3A, along with a table that describes the principal features and applicability of each method.

(a) Stream system assessment

Planning for stream system projects includes a systematic investigation of past, existing, and future conditions in the system. A complete analysis requires a team experienced in stream geomorphology, geology, hydrology, ecology, and stream hydraulics. The purpose of this investigation is to:

- identify the dominant fluvial processes in the stream system
- identify the equilibrium state of the system or portion of the system of interest
- determine if there is a problem. If so, is it an anthropogenic problem, a problem associated with the equilibrium state of the system, an existing or potential problem associated with past, current, or future land use, flood plain or riparian zone changes, or a combination of factors
- identify the factors that influence the issues of concern, as well as potential mitigation strategies

Knowledge of dominant processes allows prediction of the proposed project's impact on stream geomorphology, potential changes in the equilibrium of the system, and the impact the natural processes will have on the functionality of the project. The equilibrium state of various stream reaches and the changes occurring in the stream system should be accurately assessed. This assessment is the foundation for understanding future changes in the system and how alternative management, design, or mitigation strategies will work. Solutions are developed to address the goals and objectives of the project. These solutions might be self-sustaining, or require periodic maintenance, or the solutions are meant only to be temporary. In some cases, the best solution might be a river rules concept that simply provides adequate space for the stream to adjust to change.

Many perceived or actual stream problems are associated with a change in sediment supply within the system; change in sediment transport capacity or competency; change in bank erodibility, usually resulting from vegetation removal; or a combination of these factors. Potential causes of these changes are many. They might be due to localized stream modification such as a new culvert or bridge crossing, flood plain modification, or a more systemwide change. They might be due to urbanization, increased impermeable surface area, altered drainage, increased runoff, more discharge, larger peaks, and more frequent high flows. Biological and ecological impacts are sometimes associated with other factors such as changes in water chemistry, changes in low flow regimes, or changes in vegetation on the banks, flood plain and riparian zones. Assessment of these factors is presented later in this chapter.

Bank and meander migration, scour, and deposition are natural stream processes that might be exhibited by high quality streams that are in dynamic equilibrium. Natural meander migration rates vary across hydrophysiographic areas, so that a particular rate may or may not constitute a problem. Major events or significant perturbations may cause a stream to make rapid adjustments to move toward or depart from a state of equilibrium. In some areas, very small rates, perhaps a fraction of a foot per year, might signal a problem, while in other areas many feet of movement in a single event might be normal.

Often, any adjustment is viewed as a problem because it causes an unwanted impact on anthropogenic land use or structures. In these cases, the bank is often hardened. This treatment creates a temporary solution for the human concern, but, in some situations, actually makes the stream more prone to moving out of equilibrium because an additional constraint has been added to the system. Therefore, it is important to recognize that short-term changes in sediment storage, channel shape, and planform are both inevitable and acceptable in natural channels with unprotected banks. A key to preventing problems or to developing self-sustaining solutions is to provide the channel system with adequate space and time for adjustment.

A range of conditions exists for a stable channel, and some stable processes may appear unstable. Specifically, many large river systems have a stable state characterized by low gradient alluvial channels with active channel migration zones. Mistakes have been made in the past due to the lack of recognition of this key process (Wohl 2000; Reid and Dunne 1996).

Stream evaluations can be performed at various levels. The appropriate level of detail depends on the status of the study, the perceived significance of potential problems, the scale of the project, risks, and the resources available. A unique approach of using aerial videography and Geographic Information System (GIS) technology to assess stream stability is described in NEH654 TS3B.

Basic information requirements

Comprehensive evaluations of stream systems can require both extensive resources and extensive expertise across a wide range of disciplines. It is important to have adequate expertise and to identify and address the most important issues. For example, it is not uncommon for assessments to focus on hydrology and hydraulics. While both might be vitally important in developing an appropriate solution, the most critical basic information is first-hand knowledge of the stream system and an assessment of the past, current, and future equilibrium state of the stream system. This often requires an assessment of sediment supply and transport.

(b) Initial stream characterization: flow duration

U.S. Geological Survey (USGS) topographic contour maps may be a first source of information on some important flow characteristics of streams, but the blueline streams may lack the detail to decide which streams need protection (Leopold, Wolman, and Miller 1964; Hansen 2001). Delineating stream networks using the contour crenulations (indentations) with some field verification can improve the identification and location of streams on maps, resulting in better awareness and management of small streams (Strahler 1957).

Perennial and intermittent stream types flow for extended periods beyond storm events. Under normal circumstances, perennial streams typically flow all year. Intermittent streams cease flow during parts of the year. Ephemeral channels primarily flow in response to storm events, but normally do not flow for extended periods afterward. Physical and biological indicators of flow duration and channel response to flow are also useful to help characterize a stream when flow data are not available.

Streams may be classified according to their flow conditions (table 3–1 (Hansen 2001)). The presence of a defined channel may be the best indicator to separate perennial and intermittent streams from ephemeral channels.

Small streams are seldom identified on contour maps beyond indentations in the contours, so they may go unnoticed if field evaluations do not follow office plan-

Table 3–1 Field criteria used for characterizing streamflow conditions

Criteria	Streams classified by flow duration characteristics		
	Perennial	**Intermittent**	**Ephemeral**
Channel	Defined	Defined	Not defined
Flow duration (est.)	Almost always	Extended, but interrupted	Stormflow only
Bed water level	Above channel	Near channel surface	Below channel
Aquatic insects	Present	Few, if any	None
Material movement	Present	Present, less obvious	Lacking or limited
Channel materials	Scoured, flow sorted	Scoured or flow sorted	Mostly soil materials
Organic material	No organic buildup	Lacks organic buildup	Organic buildup

ning. Stream and water quality protection goals may be difficult to achieve if the watershed streams and their connection and impact on the project area are not well defined.

For larger areas, stream detail can be digitized from topographic maps. Flow networks can also be estimated from digital elevation models (DEM) or triangulated integrated networks (TIN), which can be developed from digital topographic contours with flow routing methods using GIS software. If detailed digital elevation data are available, 10-square-mile data are preferred over 30-square-mile data, and noninteger elevations are preferred. Light Detection and Ranging (LIDAR) imagery, if available, may also be used to identify stream systems in great detail. Substantial editing of computer-generated stream networks may be needed to verify streams according to the contour crenulations.

Unusual flow patterns and paths can complicate stream type identification. Perennial streams may be interrupted as surface flow travels underground in coarse substrates, crevices, or through debris deposited in landslides. In karst topography, perennial streams may appear from underground flow networks, and substantial surface runoff may enter ground water directly through sinkholes and other solutioned features in karst limestone.

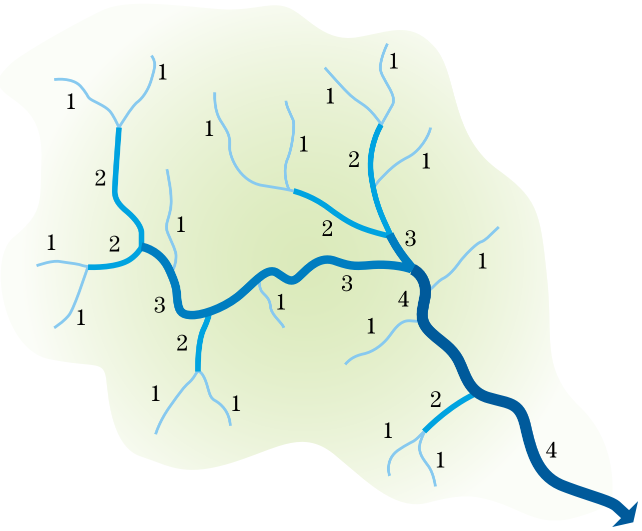
Soil types and plant species are not listed specifically for determining stream types, but the presence of hydric soils, hydrophytic plant species, or associated hydrologic indicators may be important in determining stream types (U.S. Army Corps of Engineers (USACE) 1987). Hydric soil indicators adjacent to streams include gleyed color and mottling and can be used to help estimate depth to the permanent water table or saturation zone. Plant species and rooting adaptations common to high moisture conditions may provide additional information.

(c) Initial stream characterization: stream orders

Identification of the stream network and stream orders (Strahler 1957) can be done through analysis of 1:24,000 scale topographic quadrangle maps (Leopold, Wolman, and Miller 1964), digital orthophotoquads (DOQ), or DEM. First-order streams are identified as the unbranched channels that drain from headwater areas and develop in the uppermost topographic depressions, where two or more contour crenulations (notches or indentations) align and point upslope. These first-order streams may, in fact, be field ditches, gullies, or ephemeral gullies. The combination of two streams of the same order forms the next higher order (fig. 3–1). The density and pattern of the streams may vary with drainage size, geology, landform, and type of stream channel.

The use of stream orders is a valuable quick reference and has been used to correlate information. However, it does have limitations. Since the intersection of a channel with a lower order does not raise the order of a stream, a long, skinny basin may be classified with much lower order streams than a wider, but shorter drainage basin. As a result, stream order comparisons work best when the comparison is within a single drainage basin.

Figure 3–1 Stream orders in a watershed may be useful in understanding flow conditions, setting goals and objectives, and provide preliminary information for design of solutions.



654.0302 Preliminary investigation

Ward and Trimble (2004) recommend that a preliminary investigation be conducted to provide sufficient information to design the study; select analytical methods, models, and procedures; and prepare an estimate of fund requirements to conduct the assessment. The purpose of the study is to:

- assemble and evaluate existing data
- obtain as much information as necessary
- develop a scope of work
- identify data requirements, data deficiencies, and cost resource requirements
- identify system boundaries and boundary conditions
- prepare a preliminary diagram of the physical system
- identify issues that restrict or inhibit the ability to conduct the study or need further study
- use USGS gage data or other records, where available, to assist in analysis of high flows and channel-forming events
- identify biological and ecological assets and concerns

654.0303 Reconnaissance

A reconnaissance of the site should always be done. Careful planning and advance preparation is critical. Practitioners should obtain background information by reading reports or previous studies. It is also valuable to obtain available topographic maps and aerial photographs and collect climate, soils, geology, and land use information. Especially useful will be maps, photographs, and surveys from different years in the same location, to indicate changes in the watershed and stream. It is important to talk to people familiar with the location and communicate with local, state, and Federal agencies to determine if there are ongoing or recently completed studies in the region.

Much of the data can be assembled in the office by reviewing old reports, maps, and aerial photos. Historical data are used to identify trends, provide information on rates of landform change in the watershed, and help determine land use impacts on current conditions. The examination and review of geologic information, local historical accounts, historic channel thalweg and cross section information, FEMA maps, biological monitoring, hydrologic models, watershed development and land use patterns, and aerial photographs can be useful in this assessment. Recent gage data should be reviewed to determine if current conditions might be the result of a recent extreme event, rather than long-term or systematic instabilities.

Prior to a site visit, it is recommended that the field team prepare a checklist of needed equipment and materials. The team should prepare written descriptions of each task to be performed, and make sure each reconnaissance team member is aware of the objectives, as well as their assigned tasks. It is useful to consider things that might go wrong and prepare contingency plans before going to the field. This is particularly important if electronic equipment is being used to document findings or take measurements.

For safety and logistical reasons, field work is best accomplished by teams of at least two people. Field work, particularly in urban areas, may raise significant health and safety issues, including crime, needles, and exposure to raw sewage and waterborne pathogens such as hepatitis.

654.0304 Detailed field investigation

Following the preliminary investigation, a detailed field investigation is performed to describe the geomorphological landforms of study reaches and to identify potentially destabilizing factors. This effort is often coupled with an identification of potential treatments or projects. This is based on field-gathered evidence of erosion, sediment storage, and deposition in the individual reaches. It is critical that experienced personnel conduct this effort. It is recommended that as a minimum the team consist of a biologist who is familiar with characteristics of aquatic and riparian habitat of the study area; a scientist or engineer who is experienced in stream geomorphology and sediment transport; and engineer(s) experienced in hydraulics, hydrology, design, and construction practices.

Inspections at bridge crossings should be treated with caution, since bridges are frequently placed at constrictions or at bedrock outcrops. These locations may not be characteristic of the stream as a whole. However, valuable indicators of stream stability can be observed at bridges and other points where infrastructure crosses the stream. Field assessments are best made during low-water conditions and during the dormant season when banks are not covered with vegetation and can be more readily examined. However, it is important to recognize that conditions may be different at high flows. In assessing streams in the field, it is important to keep in mind that a channel typically has four degrees of freedom: width, depth, slope, and planform.

Basic information on how to conduct field investigations to collect data for a channel stability assessment is contained in the following publications: EM 1110–2–4000 (USACE 1995c); EM 1110–2–1418 (USACE 1994d); and Thorne (1998). Biedenharn, Elliott, and Watson (1997) contains a detailed description of field equipment and features to look for in the field. The collection of field data can be aided with the use of field assessment data sheets, which should be adapted to the specific study needs. Guidance for carrying out detailed reconnaissance surveys is given in Downs and Thorne (1996); Thorne, Simon, and Allen (1996); and Thorne (1998). Example field assessment data sheets are provided in appendices B and C of Copeland et al. (2001).

Generally, the following basic information should be collected:

- descriptions of the watershed development and land use, flood plain characteristics, channel planform, and stream gradient
- assessment of historical conditions—this can be obtained with interviews of knowledgeable landowners. Anecdotal testimony, however, may result in some exaggeration of historical conditions, but multiple sources will help to provide accuracy
- measurements of low-flow and bankfull channel dimensions and channel slope in critical reaches and identification of terraces and active flood plains
- characterization of the channel bed—determine if it is bedrock, erodible cohesive material, armored, or unconsolidated alluvium. Determine the gradation of any armor layer and collect bed material samples of the substrate.
- descriptions of river bank profiles, bank materials, and evidence of bank instability
- descriptions and locations of point bars, pools, riffles, bed instability and evidence of sedimentation processes
- observations of response to channel alterations, and evidence of stream recovery
- descriptions of channel debris, woody material, and bed and bank vegetation
- preliminary stream restoration alternatives should be identified so information can be gathered on possible constraints such as access, utilities, and staging areas.
- photographic records of critical stream and watershed characteristics

There are many possible indicators of the equilibrium state of a stream system. A range of field indicators within a watershed is shown in table 3–2, reproduced from Copeland et al. (2001). These indicators are not absolutes, and items listed as possible indicators of instability may occur in natural or stable streams. Usually, no single indicator will accurately identify the cause of a problem or the equilibrium state of the system. A weight of evidence approach should be used, and it is important that those conducting the field assessment be experienced in the accurate interpretation of stream reconnaissance results.

It is also important to recognize the possible pitfalls of field assessments. These include observer bias, temporal limitations, and spatial limitations. Issues related to observer bias can be partially overcome with the consistent use of trained personnel. This practice will minimize relative differences between observations. Temporal bias can be minimized by examination of historical records, but these may be incomplete. Having the field team walk a continuous reach of stream can reduce spatial bias. Field investigation should extend both upstream and downstream of the project reach and, ideally, should be conducted during different seasons.

Table 3–2 Possible field indicators of river stability/instability

Evidence of degradation	Terraces (abandoned flood plains) Perched channels or tributaries Headcuts and nickpoints Exposed pipe crossings Suspended culvert outfalls and ditches Undercut bridge piers Exposed or "air" tree roots Leaning trees (hockey stick trunks) Narrow/deep channel Banks undercut, both sides Armored bed Hydrophytic vegetation located high on bank Points of diversion for irrigation have been moved upstream Failed revetments due to undercutting
Evidence of aggradation	Buried structures such as culverts and outfalls Reduced bridge clearance Presence of midchannel bars Outlet of tributaries buried in sediment Sediment deposition in flood plain Buried vegetation Channel bed above the flood plain elevation (perched) Significant backwater in tributaries Uniform sediment deposition across the channel Hydrophobic vegetation located low on bank or dead in flood plain
Evidence of stability	Vegetated bars and banks Limited bank erosion Older bridges, culverts, and outfalls with bottom elevations at or near grade Mouth of tributaries at or near existing main stem stream grade No exposed pipeline crossings, bridge footings, or abutments

During field work, it is important to locate and observe both stable and unstable areas within the study reach. By observing the areas with the worst problems, the upper limits of erosion, sedimentation, and flooding can be established. It is equally important to visit reaches of the system where these problems are absent or not as severe. This approach will provide an envelope of values associated with the study area and better describe the variability and physical characteristics of the stream reach.

The information gathered in the reconnaissance and detailed field investigations should be used to divide the channel into geomorphologically similar reaches. When establishing reach limits, consideration should be given to differences in channel slope, tributary locations, presence of geologic controls, planform changes, location of channel control structures (grade control structures, dams, culverts, low-water crossings), changes in bed-material size, major sediment sources (mines, construction activities, sediment laden tributaries), instream gravel mining, maintenance dredging, changes in channel evolution type, and other significant hydrologic or geomorphic changes. Initial reach limits may be made early during the field investigation, but may be refined following more detailed analyses. The choice of an assessment technique should be made with consideration of the study goals. An example of some basic assessments is shown in table 3–3 from Copeland et al. (2001).

Table 3–3 Reach condition assessment

Condition	Bed	Bank
Stable	The channel bed is as close to a stable condition as can be expected in a natural stream. The reach exhibits few signs of or minimal rates of local bed scour or deposition	The channel banks are as close to a stable condition as can be expected in a natural stream and appear to have a low potential to erode. Banks are predominantly covered with extensive vegetation, boulders, or bedrock formations. Local bank erosion is within an allowable rate of change
Moderately stable	The channel bed in the reach is in a moderately stable condition. However, the reach may be in transition. Bed aggradation or degradation occurs at a low rate of change. Moderate to high rates of local bed scour or deposition occur (rapid aggradation immediately above and scour immediately below a minor debris blockage, such as a single tree blocking the channel	The channel banks in the reach are in a moderately stable condition and exhibit medium erodibility. Banks are partially vegetated with moderately erodible soils. Typically, parallel flows do not result in bank erosion. The reach may be in transition. Banks exhibit moderate local bank erosion that does not appear to be spreading (in an otherwise stable reach, a single section of the bank could fall into the stream and result in local, moderate bank erosion)
Unstable	The channel bed in the reach is unstable. The bed is undergoing widespread bed aggradation or degradation at a moderate rate. Moderate scour occurs, and many of the pools are filled with loose sediment	The channel banks in the reach are predominantly unstable. Banks are experiencing widespread erosion at a moderate rate. Channel banks are undergoing local bank erosion at a high rate of change and where the erosion is not likely to be self healing
Very unstable	The channel bed in the reach is in a very unstable condition. Typically the channel shows no signs of approaching equilibrium with the current shape and planform. The bed is undergoing widespread aggradation or degradation at a high rate. Reaches are severely scoured, and all of the pools are filled with loose sediment	The channel banks in the reach exhibit high erodibility and do not have any controls that restrict extensive changes in planform or shape. Riparian root masses are not present to slow rapid bank retreat. Any parallel or impinging flows will cause extensive bank erosion. Reaches have near vertical to overhanging banks

At the conclusion of a field investigation, channel stability in each reach is summarized. General classification techniques are descriptions based primarily on observation and can be useful both in compiling observations and in communicating with stakeholders. Channel typing is an elementary level of stream classification that uses generic terms. Many techniques are available, and they range in complexity and required effort. The channel description may include parameters such as channel and flood plain geometry, bed and bank material, planform, vegetation, bedforms, evidence of aggradation or degradation, and grade control.

Geomorphic channel classification involves the selection of a classification system and categorizing a channel based on factors and measurements such as dominant mode of sediment transport, entrenchment ratio, and sinuosity. Some of the most widely used classification systems are described in chapter 2 of EM 1110–2–1418 (USACE 1994d) and in the FISRWG (1998). Streams can also be classified by their biota, habitat conditions, baseflow levels, and direct measures of water quality.

In summary, data obtained during the field investigation and historical data collection can be used to determine the target stream type in terms of boundary sediments, riparian vegetation, and meander patterns. In many cases, the type and density of bank vegetation will be different from that present in the reference reaches due to ecological, aesthetic, and recreational objectives. It is important that target vegetation is identified prior to channel design because it influences flow resistance. Otherwise, the stability of the restored channel could be affected.

Examples of useful tools for organizing and analyzing stream geomorphology data are the STREAM toolbox developed by the Ohio Department of Natural Resources (NEH654.10) and a streambank inventory and evaluation spreadsheet developed by Illinois NRCS that is described in NEH654 TS3C. This information also describes stream stability and equilibrium, along with a channel evolution model as background material. A detailed procedure for data collection and analysis is presented to better understand the dynamics of a target stream. Another useful tool is Stream Channel Reference Sites: An Illustrated Guide to Field Techniques (Harrelson, Rawlins, and Potyondy 1994). This publication helps in organizing and guiding field assessments and stream measurements.

(a) Geologic assessment

Geologic factors can often be complex, yet they are the foundation of the stream system. Studying both the surface and subsurface geologic conditions is fundamental to a complete understanding of the stream's morphology.

This process should begin with a study of the available geologic maps that are available at a variety of scales from both state agencies and the USGS. Geologic maps generally show whether the materials in a valley are consolidated or unconsolidated, and they indicate the parent material both underlying the stream channel and in the watershed above it. This information can be used to estimate engineering properties and erodibility of the parent material and streambanks, type and amount of sediment available for transport, and potential materials for armoring. It is critical to verify this information in the field.

The engineering properties of the parent material and its resistance to erosion can have significant effects on the morphology and stability of a stream. Where bedrock hard points are part of the streambed, downward migration is limited, and the cross-sectional flow area must be accommodated by lateral erosion. Alternately, if bedrock hard points occur in a streambank, lateral migration is limited, and the cross-sectional flow area will be accommodated by downcutting.

Determining the type and amount of sediment available for transport within the watershed is an important part of the design process. In areas of high erosion rates, significant amounts of sediment can be delivered to the channel, and the quantity and particle-size distribution must be considered. For example, sparsely vegetated desert conditions can contribute enough sediment during rare, but high flows to overwhelm the stream completely. Badland conditions, such as those in the Dakotas, can form in soft, unvegetated shales, and also contribute significant amounts of sediment.

The geology can vary significantly even across small reaches, and its effects can be different depending on the location within the stream system. Different aspects of the geology may be important depending on whether the stream is in the erosional reaches near the headwaters, in the transporting portion of the mid-stream reaches, or in the depositional reaches near the lower end of the channel system.

Changes that have occurred at the site through geologic time must also be considered. The tectonic history, climatic changes such as ice ages, and other surficial processes are reflected in the current morphology of the stream channel. For example, faults can create soft zones in otherwise hard bedrock that will be more susceptible to erosion and channel development. In addition, the materials in the streambanks are a reflection of the stream's former positions within the landscape (upland, hillslope, fan, terrace, valley bottom, delta) and its previous erosional and depositional history.

In most of North America, the climate has changed drastically since the end of the Pleistocene Epoch, about 100,000 years ago. The climate was significantly wetter, runoff was generally higher, and glacial meltwater carved huge channels still in evidence today. Paleochannels that formed during that time have not experienced significant changes in areas with no active tectonic forces. For example, the Missouri River in northern Montana was pushed south from its original channel by continental glaciers during the last ice age. The Milk River, a much smaller system, now flows through this old channel, appearing to be underfit to the higher flow conditions that formed it.

The channels that were formed during higher flows are composed of coarser grained materials. They are overlain by finer grained materials deposited by today's lesser flows. This situation can be highly susceptible to erosion, but might not be considered without knowledge of the paleoenvironment. In particular, fines and sand can be washed out of gravel deposits during bankfull flows, especially on outside curves. This can undermine the streambank, creating an overhanging condition that fails under its own weight. Finer materials above may be cohesive, exhibiting increased shear strength, but once undermined, will fail and add sediment to the stream.

Coarser grained deposits provide higher resistance to flow than fine-grained deposits. Gravelly stream channels are considered to have formed from lateral accretion, or the extension of gravel bars, and finer textured deposits are considered to have formed from vertical accretion.

Some geologic conditions promote higher bank stability. For example, preconsolidated glacial till and wind-deposited loess both create stable bank configurations, even with high, vertical banks. Peat that is formed in marshy conditions also may form a stable, vertical streambank, if it is not interlayered with other materials.

In general, geologic conditions play an important role in the development of the stream morphology. These conditions should always be thoroughly considered in an interdisciplinary stream study.

(b) Biological assessment

Watersheds are complex systems that integrate many factors. For this reason, a select group of indicators is often examined to infer watershed condition. For instance, instream habitat features, such as riffles, can be used to assess fish productivity potential. The U.S. Environmental Protection Agency (EPA) reviewed stream assessment protocols that range from subjective, visual-based protocols to objective, quantitative assessments that are time consuming measurement-based methods (EPA 2004). Some protocols provide unique approaches or particularly useful methods to address aspects of stream assessment and mitigation. For instance, the Eastern Kentucky Stream Assessment Protocol from the USACE Louisville District, incorporates a wealth of biological data into the calibration of the stream assessment method and integrates biotic and abiotic factors of fluvial systems in eastern Kentucky. The Integrated Streambank Protection Guidelines from the Washington Department of Fish and Wildlife (WDFW) (2003) uses a series of sequential or hierarchic matrices to aid practitioners in selection of practices to treat eroding streambanks (EPA 2004).

Like the canary in the mine, the health of indicator species can be used to reflect the general health and well being of a riparian system and watershed. A somewhat unique example of an indicator species is riparian bats (NEH654 TS3D).

Biotic indicators

Biotic indicators are widely used to assess water quality. Biotic indicators are effective in assessing both past and present human activities on the watershed. While numerous biotic indicators exist, two common practices are briefly described here: the Index of Biotic

Integrity (IBI) and the Ephemeroptera, Plecoptera, and Trichoptera (EPT) Index.

The IBI uses fish surveys to assess human effects on a stream and its watershed. The EPT Index uses benthic macroinvertebrates, such as stoneflies, mayflies, and caddisflies, as indicators to assess land use and water quality within a watershed.

The presence, relative abundance, and diversity of aquatic macroinvertebrates may also be direct or indirect indicators of the surface water regime (Water Quality Field Guide, SCS–TP–160; and Water Quality Indicators Guide, SCS–TP–161). Rocks, sediment, and leaf accumulations can be searched in riffle and pool areas, since they are normally the first and last areas to dry up. The presence of a variety of species from the orders Plecoptera (stoneflies), Ephemeroptera (mayflies), Trichoptera (caddisflies), Coleoptera (aquatic beetles), Diptera (cranefly), and others suggest persistent flow. Intermittent streams generally lack macroinvertebrates, though occasionally, a few early successional species can invade and dominate that niche during wet periods. With no persistent flowing water, pools, or saturation, ephemeral channels normally do not have aquatic insects. The presence of other organisms, such as freshwater mussels, crayfish, or snails, may be helpful when compiling evidence to determine stream type.

Biotic factors, particularly characteristics of stream biota, have been used with great success to evaluate watershed conditions and are one of the oldest approaches to assess water quality. However, biotic indicators have disadvantages in comparison to other indicators. Biotic indicators are not as visible as habitat indicators. For example, a stream habitat feature, such as a sloughing bank and the resulting increase in sediment, is more easily documented than the subtler effect of sediment on biotic communities in the stream.

IBI—The IBI was developed to help resource managers sample, evaluate, and describe the condition of small warm-water streams in central Illinois and Indiana (Karr 1981). The IBI became popular for assessing warm-water streams throughout the United States. Karr and his colleagues explored the sampling protocol and effectiveness in several different regions and on different types of streams. As the IBI became widely used, different versions were developed for different regions and ecosystems. The original version had 12 metrics that reflected fish species richness and composition, number and abundance of species, trophic organization and function, reproductive behavior, fish abundance, and condition of individual fish. The metrics were scored and summed to arrive at an index ranging from 60 (best) to 12 (worst). Newer versions generally retain most of the original metrics, but some have been modified to improve sensitivity to environmental degradation in a particular region or type of stream. The IBI has also been tailored to reflect differences in fish species within a region, and in other types of ecosystems such as estuaries, impoundments, and natural lakes.

Fish are useful in measuring degradation for many reasons:

- Fish are sensitive to a wide array of stresses.
- Fish integrate adverse effects of activities in the watershed.
- Fish are long lived. Their populations show effects of reproductive failure and mortality in many age groups, thereby providing a long-term record of environmental stressors.

To develop an IBI, a 30-foot-wide stream typically requires a four-person team (fig. 3–2). The team samples in an upstream direction using a seine or electroshocker to sample the stream.

Figure 3–2 To develop the IBI, fish samples are collected by means of seines or electroshocking devices.

A state permit is often required for fish collection. Federal permits from the National Oceanic and Atmospheric Association National Marine Fisheries Service (NOAA Fisheries Service) and/or U.S. Fish and Wildlife Service (USFWS) may be required for fish collection, as well. While techniques for fish sampling vary, some studies use a 300-foot stream length. Others may use species-area curves to determine the stream sample length. For detailed information on sampling techniques and development and analysis of an IBI, see the NRCS National Biology Handbook (NHB), part 190.

Both left and right banks of the stream are sampled, taking care to include all stream habitats such as riffles, pools, runs, snags, undercuts, and deadfalls. Stunned or seined fish are netted and placed in buckets until the end of sampling. At the end of the section, the team pauses and allows the water to clear. The team then returns downstream to the starting point, repeating the sampling procedure along the way. Once back at the starting point, all fish are identified by species, counted, and measured. Sores and fish anomalies are also noted. In general, fish species identification requires a trained biologist or person familiar with fish assemblages in the area. Data are recorded, and fish that can not be identified are preserved and sent to a laboratory for analysis. Fish are then returned to the stream after completion of sampling and data recording. IBI scores are determined in the office, using 10 to 12 metrics tailored for the area. An example of the metrics and a brief description are presented in table 3–4 (North Carolina Department of Environment and Natural Resources (NCDENR) 1997).

The example metrics shown in table 3–4 are from piedmont streams. Metrics are tailored to a particular region and are generally available through state departments of water quality.

Table 3–4 Example of metrics used to construct an IBI in Piedmont streams

Metric	Description
Number of fish species and individuals	The total number of species and individuals supported by the stream will decrease with environmental degradation
Number of darters	Darters are sensitive to environmental degradation. Darter habitats may be degraded as the result of sedimentation, and channelization
Number of species of sunfish	These species are particularly sensitive to sediment filling pools and loss of instream cover
Number of species of suckers	Suckers are intolerant of chemical and habitat degradation, and because they are long lived and provide a multiyear perspective
Number of intolerant species	Intolerant species are most affected by stream degradation, and therefore would disappear by the time a stream is rated as fair
Percentage of tolerant species	Tolerant species are present in moderate number, but become dominant as stream degrades
Percentage of omnivores (plant eaters), insectivores (insect eaters), and piscivores (fish eaters)	These are the trophic groups. The trophic groups describe what the fish species eats and where it is in the food web. Deviations from what is expected are noted. For example, the cause of a great number of omnivores than insectivores is nutrient enrichment
Percentage of diseased fish	Skeletal anomalies, fin damage, disease, and tumors increase with stream degradation
Percentage of species with multiple age groups	Determines reproductive success of the fish populations

EPT—Benthic macroinvertebrates are small stream-inhabiting creatures that are large enough to be seen with the naked eye. They spend all or part of their life cycle in or on the stream bottom. The name benthic macroinvertebrate means bottom-dwelling (benthic) small organisms without backbones (invertebrate). Since benthic macroinvertebrates do not move about like fish, they provide an indicator of what has affected the immediate area where they are found. Benthic macroinvertebrates have adapted to life in a stream, using all habitat niches. For example, some are adapted to higher velocity portions of the stream, some live below the bottom of the stream, some crawl for food, while others let the food come to them. Healthy streams can have several hundred kinds of benthic macroinvertebrates.

The EPT Index is named for three orders of aquatic insects that are common in the benthic macroinvertebrate community: Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). The EPT Index is based on the premise that high-quality streams usually have the greatest species richness. Many aquatic insect species are intolerant of pollutants and are not found in polluted waters. The greater the pollution, the lower the species richness expected, as only a few species are pollutant tolerant. Some basic identification features of stoneflies, mayflies, and caddisflies are shown in figure 3–3. The common mayfly is up to 1 inch in length (without tail), and has three distinct fuzzy or threadlike tails, and green, brown, gray, but usually black color. Mayflies have variable tolerance to pollution, but are usually considered to inhabit cleaner waters. The common stonefly measures less than 1 inch in length (without tail), and has two wings, two sets of branched gills between the underside of the body, and yellow to brown color. The stonefly is not tolerant to low levels of dissolved oxygen and therefore prefers cold, swift-moving streams. Stoneflies are an important source of food for trout. The streamlined, flat body of stonefly nymphs enables them to move about the streambed in rapid currents. The caddisfly (which resembles a caterpillar) has a soft, wormlike body, a hard covering on the head, and yellow or brown, but usually green color. Larvae build hollow cases that either carry or attach to small rocks. Cases are built from sand, twigs, small stones, crushed shells, or rolled leaves, and are used for protection and pupation. Caddisflies have a large range of tolerance to pollution. Note that identification of many species is straightforward, while others require microscopic identification, requiring expert assistance.

Figure 3–3 Aquatic insects

Common mayfly, Ephemeroptera group

Common stonefly, Plecopetera group

Caddisfly, Trichoptera group

Features of an EPT Index—The EPT Index method uses a rapid sampling technique for determining between-site differences in water quality or for watershed studies with a large number of sites, and emergency sampling where it is desirable to rapidly assess the effects of spills and unusual discharges. The EPT Index should not be used in areas that naturally are known to have low EPT species richness (either inherent or human induced) or in areas where more pollution-tolerant groups are of interest.

The EPT Index is a versatile index because of certain characteristics of benthic macroinvertebrates. Benthic macroinvertebrates are sensitive to stress, both natural and human induced. When their environment is affected either by human or natural causes, the population will change, leading to an impaired or imbalanced community. Much like the canary in the coal mine, the response of aquatic insects gives an early warning of possible harm to a water body. Because many aquatic insects spend their entire lives within aquatic systems, they show the effects of physical habitat alteration, point and nonpoint contaminants, and cumulative pollutants over their life cycle. Other important features of aquatic insects are that they:

- are found in all aquatic environments
- exhibit diversity and are sensitive to pollution
- display a wide range of responses to pollution
- are less mobile than many other groups of organisms (fish)
- are often of easily collectible size

Like all biotic indices, the EPT Index can be used when chemical and physical measurements of a complex mixture of pollutants are not feasible. Moreover, these aquatic insects show responses to a wide array of potential pollutants and are sensitive to both short- and long-term conditions affecting water quality.

Collecting samples to construct an EPT Index—Benthic macroinvertebrates are collected using a variety of methods. The suite of sample collection techniques described consists of the kick-net sample, sweep-net sample, leaf pack sample, and visual collections (EPA 1999b). These techniques are aimed at sampling the favorite habitats and food sources of the aquatic insects. Stream food resources are larger organic matter particles in leaf litter and large woody material; smaller organic matter particles in suspended materials and sediments; and diatoms, algae, and other materials growing on rocks, wood, and plants; and prey (Hauer and Lambert 1996).

Each macroinvertebrate occupies a certain niche according to its feeding group: shredders, collector-gatherers, scrapers, filterers, or predators. Shredders prefer to feed on larger particles of organic matter such as leaves and twigs, in turn churning these into smaller organic matter that can be fed upon by collector-gatherers. Collector-gatherers feed on small particles of organic matter in or on the bottom of the stream. Scrapers feed on diatoms and algae that are attached to underwater surfaces. Filterers feed by straining small organic matter particles out of the water. Filters can be fanlike appendages on the insect's body or built externally by the insect to resemble little underwater nets.

Predators feed on other macroinvertebrates. In healthy streams, all feeding groups are present. Stream impairment may be indicated when one or more feeding groups are missing from a stream. In general, stoneflies are predators, mayflies are scrapers or collectors, and caddisflies are scrapers, collectors, or shredders. The ratio and number of these macroinvertebrates change with the stream food resources and human impacts and, therefore, can be used as a tool for assessing the ecological status of the biotic community and the water quality.

The kick sample is conducted using a rectangular section of window screening attached between two poles. The net is positioned on the stream floor, downstream of the sampler. One person holds onto the net. The other person disturbs the stream bottom upstream of the net and kicks the invertebrates present into the net. Invertebrates collected on the net are washed into a bucket. A long-handled triangular net is also used to disrupt and sweep areas under banks, root masses, and mud banks. Netted invertebrates are washed into a bucket. This procedure collects mayflies and caddisflies which prefer low-current environments. Leaf packs in the stream, snags, sticks, and small logs are examined and macroinvertebrates separated into a bucket. In general, shredders such as the caddisflies prefer these environments. A final visual search of upturned rocks, cobbles, and logs is conducted to collect adhering macroinvertebrates. For example, rocks in low current areas harbor stoneflies. Macroinvertebrates are separated or picked from the bucket samples with forceps and placed in vials containing ethanol for later classification and counting.

Macroinvertebrates usually require identification in the laboratory by a trained biologist. However, community watch group volunteers, teachers, and students can be trained to make basic identifications of the three groups used in the EPT Index. The NRCS Stream Visual Assessment Protocol (SVAP) also uses aquatic insects to assess stream condition (USDA NRCS 1999b).

EPT Index score development—The EPT Index is the total number of distinct taxa within the groups Ephemeroptera, Plecoptera, and Trichoptera. For example, if five species of Ephemeroptera (mayflies), five Plecoptera (stoneflies), and two Trichoptera (caddisflies) are found at a site, the total number of EPT taxa and Index would equal 12. The EPT Index is then compared to values on an EPT rating chart that has been developed for that particular region. Many state water quality departments are a good source of information on how to develop a rating chart for a particular ecoregion. The EPT Index increases with improving water quality; that is, there should be a greater number of EPT insect taxa in cleaner water. Ratings are tailored to account for differences in species pollution tolerance between regions. Table 3–5 (modified from NCDENR 1997) shows an example of EPT criteria developed for the Southern Piedmont of North Carolina. In this example, a site with an EPT Index of 12 would have a rating of fair.

The EPT Index can be used to directly assess the cumulative effects of all activities in the watershed. These results allow establishment of baseline or reference conditions for watersheds to characterize their overall condition, identify potential nonpoint and point source pollutants, target resource efforts in impaired watersheds, and evaluate the effectiveness of pollution control measures.

Beavers and beaver management

Beavers were among the most widely distributed mammals in North America, and they were eliminated from much of their range by the late 1800s because of unregulated trapping. Beavers eat the leaves, inner bark, and twigs of aspen, alder, birch, cottonwoods, willows, and other deciduous trees. Conifers such as fir and pine are eaten occasionally. They also eat shrubs, ferns, aquatic plants, grasses, and crops such as corn and soybeans. Beaver dams are created by mud, rocks, and whatever other materials are available to the beaver.

Beaver dams create backwaters that flood areas upstream. This provides protection from predators, access to a food supply and their dens, and wet areas that promote the growth of their favorite foods. Because this backwater may also flood roads, fields and other land, much interest has been placed on beaver management. Beaver management involves trapping and relocation (Tippie 2003); installing flow devices to encourage dam building at more desirable locations (Lisle 2004); and using pond levelers to control water depth and reduce flooding (Snohomish County Public Works 2004; Cooperative Extension Service, Clemson University 1994).

Table 3–5 Example of EPT index ranges and their corresponding water quality ratings for southern Piedmont, NC

Rating	Excellent	Good	Good-fair	Fair	Poor
EPT	>27	21–27	14–20	7–13	0–6

654.0305 Stream classification systems

This description of stream classification systems is designed to help users understand the variety of different systems and their relationship to channel stability, basin geomorphology, riparian and aquatic ecosystems, and watershed condition. Its goal is to help stream professionals recognize how the effectiveness and longevity of riparian restoration activities are related to basic stream classification techniques. Readers can learn the basic terminology of each classification system and acquire sufficient background to communicate with peers and producers about the differing systems. While many other techniques exist, four stream classification methods are presented in this chapter. These are listed in table 3–6. The descriptions provided herein attempt to promote an understanding of the strengths, weaknesses, and limitations of the presented systems.

(a) Overview of stream classification systems

Stream classification systems have been in use in their simplistic forms for at least a hundred years (Davis 1909). Much of the basis for modern stream classification systems, however, began in the 1950s and 1960s with work by Leopold and Wolman (1957), Lane (1957), and Schumm (1963).

River and stream systems are dynamic and continually respond to changes in sediment load, hydrology, and form. Under the current watershed conditions, stream classification systems help users understand the present and expected future status of a stream system. The strengths and weaknesses of these classification systems are described, but the description does not compare one system with another.

Four different types of classification systems are presented in this chapter. The Framework and Integrated Guide includes a listing of classification and mapping criteria. The channel evolution model (CEM) is an example of a system based on nonstable processes. The Montgomery and Buffington system is based on defining channel processes, and the Rosgen system is a classification of the current status of the channel. Each of these classification systems was designed to address a specific set of practical requirements by its developers and as a result, each has specific application areas in which it is strongest and weakest. No one system works for all situations, and professionals working in the field of stream restoration are well advised to match the appropriate classification system to the problem at hand.

Table 3–6 Stream classification systems

Stream classification	**Full name**	**Basis**
USDA Forest Service aquatic framework	Framework of Aquatic Ecological Units, and Integrated Resource Inventory Training Guide	Consistency of classification criteria
Schumm, Harvey, Watson, and Simon	Channel evolution model (CEM)	Channel response
Montgomery and Buffington	Classification of Channel Reach Morphology for Mountain Streams in the Pacific Northwest	Channel processes
Rosgen classification	Classification of Natural Rivers	Current channel condition

(b) USDA Forest Service: Framework of aquatic ecological units and the Integrated Resource Inventory Training Guide

The USDA Forest Service developed an aquatic framework (Maxwell et al. 1995) that contains standard terms and classification criteria for aquatic systems and their linkages to terrestrial systems at all spatial scales. Its purpose is to ensure consistency in classifying and mapping aquatic systems, and therefore, enhance the analysis of aquatic systems to reflect their varied forms and functions. The Forest Service has also developed the Integrated Resource Inventory Training Guide, Chapter 3, Common Water Unit (USDA Forest Service 1997a) that has tables of the classification criteria based on the aquatic framework (tables 3–7 and 3–8 (Frissell et al. 1986; Montgomery and Buffington 1993a; Paustian et al. 1992; and Rosgen 1994, USDA Forest Service 1997a). Major stream types are defined by channel entrenchment, shape, and sinuosity.

Potential NRCS use of the framework will primarily be as a guide for data collection and field mapping of stream reaches. The framework does not include estimates of what the next evolutionary phase of a stream might be. The stream reach classifications of Frissell et al. (1986), Montgomery and Buffington (1993a), Paustian et al. (1992), and Rosgen (1994) are based on a group of common geomorphic factors that are included in the framework. For use in classification, the most helpful sections of the framework are valley segments and their subdivision, stream reaches. Stream reaches are defined as uniform in flow and channel morphology and have discrete patterns of aquatic habitats and fluvial processes. A small set of stream reaches is nested within any valley segment.

Strengths

The aquatic framework contains a listing of mapping and classification criteria that are used in several stream classification systems. With the collection of the stream attributes, the user could assign a channel type to a reach in several systems. If the reach is classified in several systems, this method has the advan-

Table 3–7 Defining criteria for classifying stream reach types

Variable	Description
Channel pattern	The plan view of the stream reach. Geomorphic controls and sediment transport regimes create straight, sinuous, meandering, tortuous, braided, and anastamosing channels. Sinuosity is used to describe the overall channel pattern. Sinuosity is the length of the active channel divided by the length of the valley. This attribute is map and photo interpreted
Channel entrenchment	The degree to which the stream is incised into the landscape. This criterion indicates how well floods are contained by a stream channel. It is the width of the flood-prone area divided by the width of the active, or bankfull, stream channel. The flood-prone area is the width of the valley floor at a level corresponding to twice the maximum bankfull depth of the channel. This attribute is field observed
Bank stability	Can be reduced by natural events (floods, fire, landslides) or human disturbances (grazing, logging, roads) that change runoff amounts, sediment loads, and bank vegetation Vegetated–stable. Bank is vegetated with no evidence of active erosion or sloughing and no tension fractures Vegetated–unstable. Bank is vegetated, but tension fractures exist at the top of the bank Unvegetated–stable. Bank is not vegetated, but is composed of bedrock or stable boulders or cobbles Unvegetated–unstable. Bank is not vegetated and is composed of bare gravel, sand, silt, or clay, or a matrix of cobbles and these finer particles
Woody material	Large woody material usually improves habitat complexity and quality in a stream reach, often forming pools. All pieces of large woody material that span the channel or lie totally or partially within it are counted
Temperature	Reflects both the seasonal change in net radiation and the daily changes in air temperatures. It is affected by flow velocity and depth and ground water inflow

tage of compounding the individual system strengths. This method includes some stream health attributes that could be used to diagnose the condition of the stream reach against a reference healthy stream reach. The system is being used by the USDA Forest Service for mapping of aquatic systems, and data already collected would be available for National forests.

Weaknesses

The aquatic framework classification does not have specific recommendations to determine evolutionary trends for each type of stream reach.

Table 3–8 Stream type classes, modifiers, and bed structures

Class	Channel entrenchment	Width-to-depth ratio	Sinuosity	Description
A	<1.4	>12	<1.2	Straight, steep, entrenched, narrow stream
B	1.4–2.2	>12	>1.2	Moderately sinuous, moderately sloped, moderately entrenched stream
C	>2.2	>40	>1.4	Meandering, low-gradient alluvial stream with broad flood plain
D	n/a	40	n/a	Braided, wide, multiple streams with many bars and eroding bank
DA	>4.0	<40	Variable	Anastomosing, flat, narrow multiple streams with stable banks
E	>2.2	<12	>1.5	Tortuous, narrow stream with broad flood plain and stable banks
F	<1.4	>12	>1.4	Meandering, low-gradient, wide, entrenched stream with eroding banks

Modifiers

Materials		Slope	
1	Bedrock	h	Hydraulic (over 10%)
2	Boulder (over 256 mm)	a	Aggressive (4.0–9.9%)
3	Cobble (64–256 mm)	b	Balanced (1.5–3.9%)
4	Gravel (2–64 mm)	c	Cumulative (0.5–1.4%)
5	Sand (0.062–3 mm)	f	Flat (under 0.5%)
6	Silt/clay (under 0.062 mm)		

Bed structure

PR	Pool-riffle (alternating pools and riffles)
PB	Plane-bed (lacking distinct bedforms)
SP	Step-pool (alternating pools and vertical steps)
C	Cascade (tumbling flow over disorganized large rocks)

(c) Channel evolution model

During the 1960s, several stream channels in northern Mississippi were channelized to control out-of-bank flooding. Major incision of the channel (down cutting) occurred from the late 1960s through the 1980s. Subsequently, a geomorphic study was conducted on several of the streams, and the investigations identified a sequence of steps through which all the channels had evolved. This channel evolution model (CEM) describes a predictable sequence of change in a disturbed channel system that was characterized as moving from reach types I through V (fig. 3–4a and table 3–9 (Schumm, Harvey, and Watson 1981)).

The model was developed by Schumm, Harvey, and Watson (1981) from investigating three unstable, channelized watersheds in northern Mississippi: Pigeon Roost Creek, Oaklimiter Creek, and Tippah River. The streams in these watersheds have mainly cohesive bank soils. The increased slope of the constructed channels started a process of significant down cutting after the channelization was completed. Starting at the oversteepened reach, the five types of channel reaches generally can be seen going downstream. In Schumm, Harvey, and Watson (1981), the series of five channel reach types as identified for Oaklimiter Creek can be characterized as shown in table 3–9.

Additional information was obtained from a study on Hotophia Creek Watershed in 1987. This study refined the CEM by introducing a ratio for critical bank height to bank height for each channel type. If the bank height (h) exceeds the critical bank height (h_c), gravity failure is imminent. For Type I, $h < h_c$; for Type II, $h > h_c$; for Type III, $h > h_c$; for Type IV, $h \sim h_c$; and for Type V, $h < h_c$.

A modification to this model was proposed by Simon (1989). This is the CEM that is most typically preferred. The modification by Simon included an extra step to account for channel modification and is perhaps more widely recognized. It is shown in figure 3–4b. The Simon model identifies six stages through which a stream progresses when subjected to destabilizing influences such as the urbanization described earlier in this chapter. Each of these stages is referred to as a class.

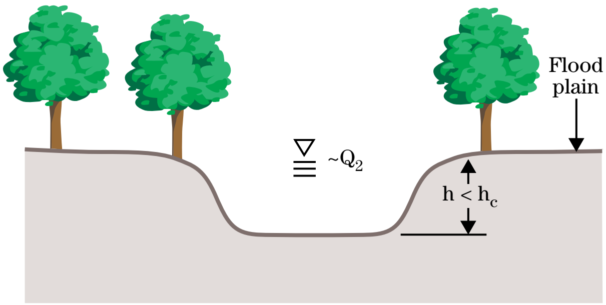
In the Simon (1989) model, class I is the natural channel before modification; class II represents the stream channel morphology directly after human activity such as channel straightening. This class is the new stage added by Simon.

Table 3–9 Characteristics of channel reaches using the CEM (see fig. 3–4a)

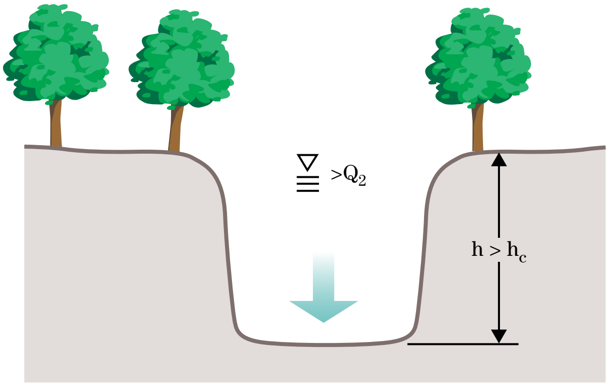
Types in a downstream direction	Sediment storage	Shape	Location and stability	Width-to-depth ratio (F)
Type I	Very little or none	AU ≈ shaped	Upstream of active nickpoints, have oversteepened slopes	Highly variable 4.0–7.0
Type II	Variable	Steep vertical channel banks and increased depth	Immediately downstream of active nickpoints, degrading	30–4.0
Type III	1.5–2.0 ft	Banks failing	Active channel widening and degrading	≈5.0
Type IV	2.5–3.5 ft	Low water sinuous thalweg	Reduced rate of active channel widening, aggrading, beginning of quasi-equilibrium	≈6.0
Type V	Up to 6 ft	Alternate bars	Aggrading, quasi-equilibrium	>8

Figure 3–4a Schumm, Harvey, and Watson (1981) schematic cross sections and longitudinal profile of an incised stream showing features of the five classes of the CEM

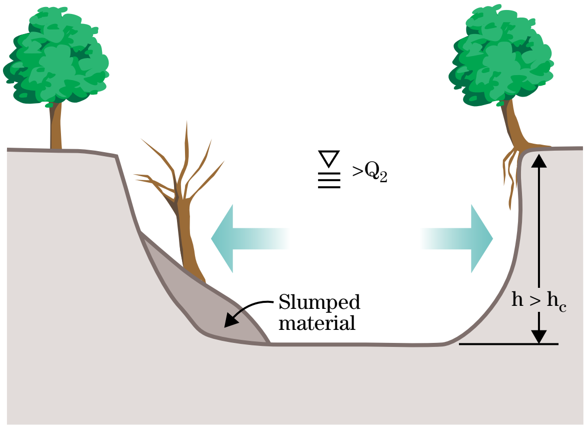
Type I–Stable



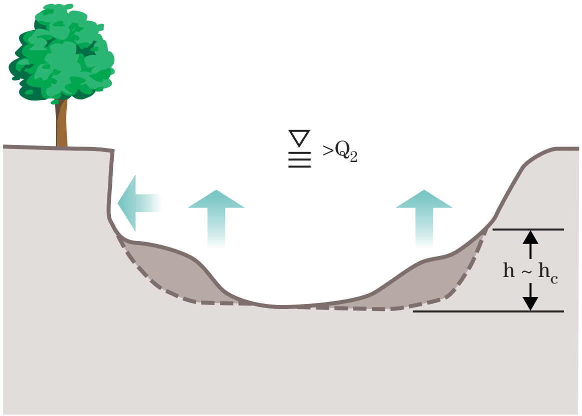
Type II–Incision



Type III–Widening



Type IV–Depostion/stabilizing



Type V–Quasi-equilibrium stable

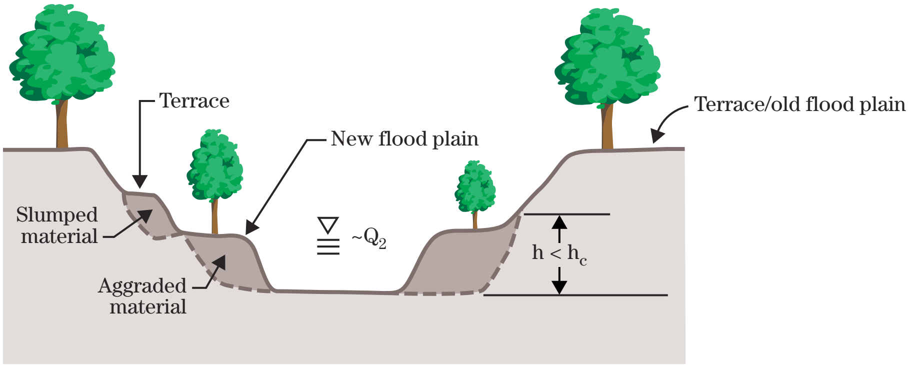
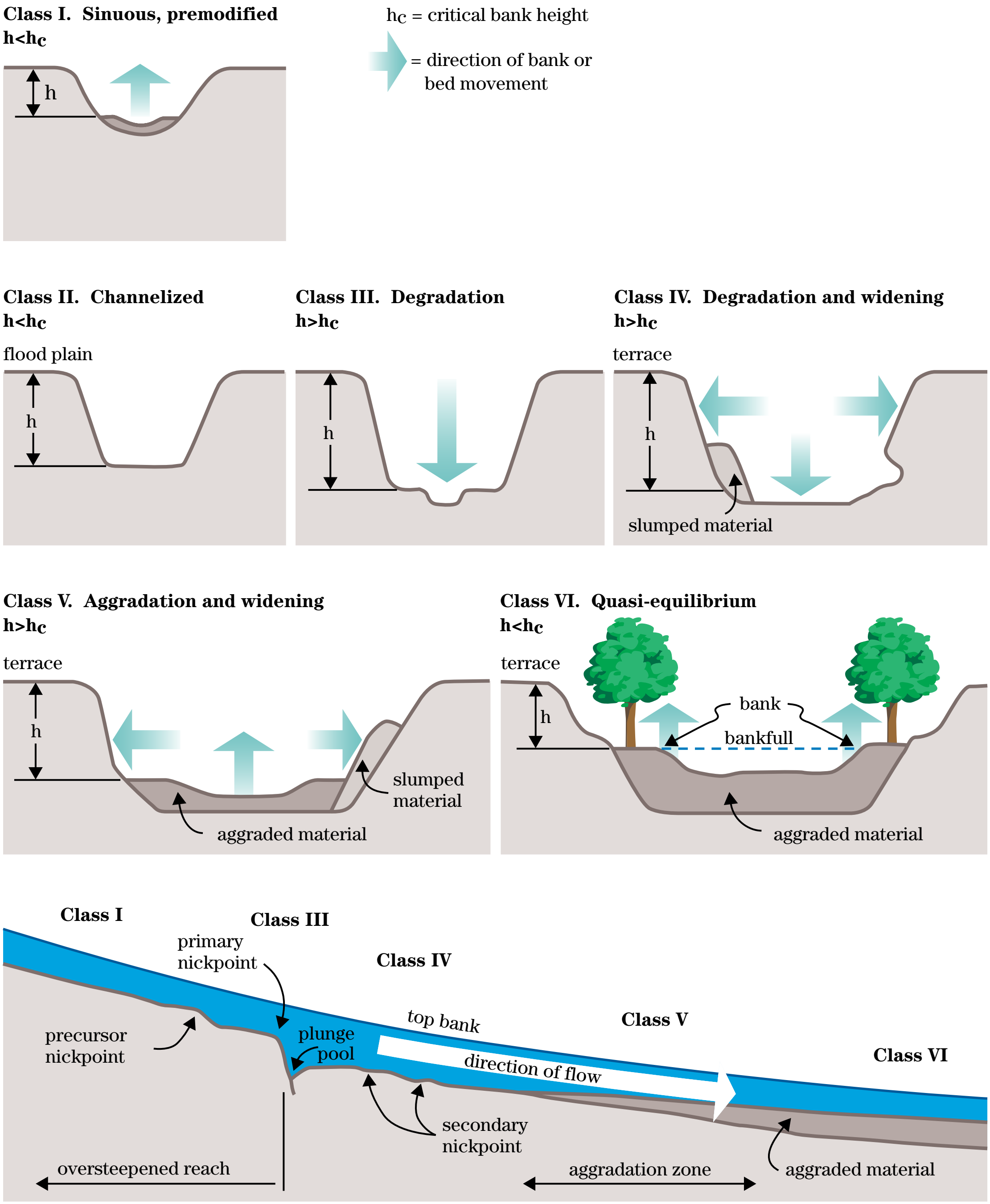


Figure 3–4b Simon (1989) schematic cross sections and longitudinal profile of an incised stream showing features of the five classes of the CEM



Class I. Sinuous, premodified
$h<h_c$

Class II. Channelized
$h<h_c$

Class III. Degradation
$h>h_c$

Class IV. Degradation and widening
$h>h_c$

Class V. Aggradation and widening
$h>h_c$

Class VI. Quasi-equilibrium
$h<h_c$

Class III is then the first sign of an instability problem, with evidence of downcutting or degradation in the channel bottom. Class III of the Simon 1989 model corresponds to Type II of the Schumm, Harvey, and Watson (1981) model.

As the bottom of the channel changes elevation, support for the banks is removed and the streambanks slump, creating a widening channel shape (class IV of the Simon 1989 model). It corresponds to Type III of the Schumm, Harvey, and Watson (1981) model.

At some point, a new equilibrium is being approached. The sediments from the slumped banks begin to form new, vegetated flood plains at a lower elevation (class V) and a smaller, natural channel within the new banks. It corresponds to Type IV of the Schumm et al. 1981 model. The new stream equilibrium (class VI) has abandoned the former flood plain and created a new one at the lower elevation (FISRWG 1998). This new stream equilibrium corresponds to the Type V of the Schumm et al. 1981 model.

Typical streams will exhibit several of the classes defined in the Simon CEM, depending on the location in the stream relative to the disturbance. The last part of figure 3–4b illustrates a nickpoint: the head of an active erosion event in the stream channel, working its way upstream. Class I describes the state of the stream well above the nickpoint where the effects of the disturbance are not yet in evidence. Progressing downstream, this figure illustrates the primary nickpoint (class III), and varying stages of bank instability in the wake of the nickpoint (classes IV and V). If enough time has passed since the disturbance, conditions farther downstream will approach class VI.

Strengths

The CEM was developed to help predict the changes a channel makes going through the process of headcutting. The CEM is based on geomorphic measurements of a reach of the channel system both upstream and downstream of a headcut. As a result, it is most accurate in its descriptions of what the next stage will be for the disturbed channel. The CEM is most valuable when verified for the watershed of interest. The CEM provides the kind of condition and trend information that is useful for shareholders and engineers to choose and design practices that are most cost-effective and have a greater probability of success. This model provides a means of segregating stream reaches into those requiring lesser or greater intervention to achieve a stable condition. For example, at Simon (1989) model class III (degradation), achieving a successful restoration is likely to be expensive, if at all possible. On the other hand, at class V (aggrading and widening), little effort may be required other than revegetation to speed the recovery process.

Weaknesses

Both the Simon (1989) and the Schumm, Harvey, and Watson (1981) models require a geomorphic study to determine reach stability values. It only applies in watersheds with degraded channels, and it works best in watersheds with fairly uniform soils and geology. Therefore, it is not as useful in systems with highly variable soils, grade, or planform control. The model has three assumptions that may limit its broad application:

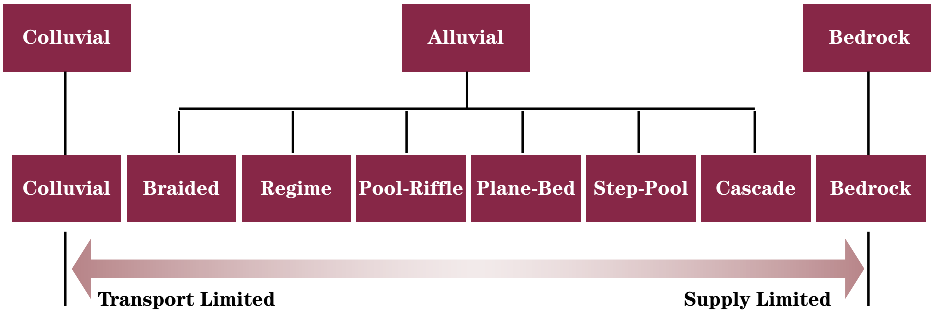
- channel base level will not change
- channel is formed in alluvial material that permits all types of channel adjustment
- land use of the watershed will not change greatly

(d) Montgomery and Buffington classification system

The Montgomery and Buffington (1993a) system classifies channel reach morphology for forested mountain streams. The authors emphasize that there are very distinct differences between mountain channels and their lowland counterparts. Most of the field observations used to develop their system were made in Washington, Oregon, and Alaska. The persistence of significant quantities of large woody material in these mountain channel systems makes the current application of this classification system somewhat regional and unique. Further testing has definite potential to validate its application to other mountainous regions of the country. The morphological processes described by the authors may serve as a template for developing other regional classification systems.

Mountain streams can be categorized into erosional (sediment supply source), transporting, and depositional reaches (fig. 3–5). Montgomery and Buffington have expanded this process-based concept to include a number of channel types in each of the three geo-

Figure 3–5 Montgomery and Buffington stream classification system



	Braided	Regime	Pool-Riffle	Plane-Bed	Step-Pool	Cascade	Bedrock	Colluvial
Typical Bed Material	Variable	Sand	Gravel	Gravel, cobble	Cobble, boulder	Boulder	N/A	Variable
Bedform Pattern	Laterally oscillary	Multi-layered	Laterally oscillary	None	Vertically oscillary	None	•	Variable
Reach Type	Response	Response	Response	Response	Transport	Transport	Transport	Source
Dominant Roughness Elements	Bedforms (bars, pools)	Sinuosity, bedforms (dunes, ripples, bars) banks	Bedforms (bars, pools), grains, LWD, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, LWD, banks	Grains, banks	Boundaries (bed & banks)	Grains, LWD
Dominant Sediment Sources	Fluvial, bank failure, debris flow	Fluvial, bank failure, inactive channel	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Hillslope, debris flow
Sediment Storage Elements	Overbank, bedforms	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, inactive channel	Bedforms	Lee & stoss sides of flow obstructions	•	Bed
Typical Slope (m/m)	$S < 0.03$	$S < 0.001$	$0.001 < S$ and $S < 0.02$	$0.01 < S$ and $S < 0.03$	$0.03 < S$ and $S < 0.08$	$0.08 < S$ and $S < 0.30$	Variable	$S > 0.20$
Typical Confinement	Unconfined	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Pool Spacing (Channel Widths)	Variable	5 to 7	5 to 7	none	1 to 4	< 1	Variable	Variable

morphic zones (Montgomery and Buffington 1993a; Montgomery and Buffington 1997).

A net reach response is dependent on the size and amount of sediment available to transport compared to the reach's hydraulic transport capacity. Reaches with more sediment supply than sediment transport capacity are erosional or source reaches. These reach types usually occur in the headwaters of mountain streams. Some length of midreach stream tends to achieve a balance between sediment load and transport capacity. These reaches are identified as transport reaches. These middle stream transport reaches may be relatively short in some stream systems and quite long in others, depending on the relative balance of sediment supply and size compared to transport capacity. Middle stream reaches tend to exhibit a net long-term balance between aggradation and degradation which is inherent in most definitions of stream stability. A net, long-term sediment balance within a stream reach may not necessarily translate to stream stability because of extreme fluctuations in sediment load and continuous change instream geometry. Finally, the lower end of mountain stream systems are typically depositional reaches due to a reduction in transport capacity as stream gradients are reduced. These depositional reaches are also identified as response reaches.

Many variables other than sediment supply and transport capacity influence channel characteristics. Important geometric properties of stream channels include width, depth, and alignment. Hydraulic properties include slope, roughness characteristics, hydraulic radius, discharge, velocity, velocity distribution, turbulence, fluid properties, and uniformity of discharge. Other geomorphic factors include grain size of suspended sediment and bedload material, frequency of island occurrence, bar types and numbers, and especially the influence of debris flows and the occurrence of large woody material in forested mountain streams.

The Montgomery and Buffington classification system identifies eight distinct channel types (fig. 3–5). The bedrock channel type can occur in a number of positions on the stream profile, although it is more likely to occur on steeper slopes. The colluvial and bedrock stream reach types are normally associated with the headwater portion of a stream system, but they are quite different in morphologic characteristics. Source channels can be further divided into hillslope (flatter hill or mountain tops), hollow (transitional slopes) and colluvial (steeper sloped) channels. The further division of source channels primarily reflects the position of the channel in the headwater profile and has some implication on the relative amount of sediment load that can be anticipated from each type. The colluvial channels are normally the highest yielding source channel type in the watershed system because they contain significantly more sediment than the stream has capacity to transport. Sediment size (boulders, cobble) may be an important transport factor that may limit sediment loads from source channels in headwater streams.

Under certain circumstances, bedrock channels may also temporarily serve as source channels. Bedrock channels are often associated with headwater stream reaches, but they may also occur in the lower gradient portion of the watershed as well. With respect to sediment, bedrock channels are normally opposite of colluvial channels in that transport capacity significantly exceeds sediment supply. Simply stated, most of the available sediment has been removed down to bedrock. However, the sudden introduction of a sediment source such as a debris flow may temporarily cause a bedrock channel to take on the morphologic characteristics of a colluvial channel. The bedrock channel will ultimately return to its bedrock morphology once the temporary sediment source is removed. The time required to revert back to a bedrock morphology will depend primarily on the volume of the sediment obstruction and the particle size of the material to be transported.

Because the hydraulic capacity of bedrock channels normally exceeds available sediment supply, bedrock stream reaches are categorized as transport reaches. The remaining five channel classes are alluvial reach types. They include the cascade, step-pool, plane-bed, pool-riffle, and dune-ripple classes. Sediment in cascade channels is predominantly supply limited resulting in excess transport capacity. These channels occur on steep slopes that result in high rates of energy dissipation, and flows tend to be continuously in the supercritical range. Channel bed material will typically consist of boulders and cobbles since any finer material will have been mobilized and transported downstream. Much of the turbulent energy in cascade channels is dissipated in converging and diverging flows over and around large boulders and other trapped debris or obstructions.

Step-pool channels are also found in transport reaches, and they occur on steeper slopes, exhibit coarse bed material, and have low to moderate width to depth ratios. Step-pool channels, like cascade channels, are characterized as sediment supply limited with excess transport capacity. The primary distinction is that flow regime in step-pool channels is alternately supercritical in the steeper areas with subcritical flow and energy dissipation occurring in the pool areas. The bedrock, cascade, and step-pool stream reach types are all found in transport reaches.

The three remaining Montgomery and Buffington channel types (plane-bed, pool-riffle, and dune-ripple) are also alluvial channel types, but they fall into the response group. Plane-bed channels include channel reaches described as glides, riffles, and rapids. They typically occur on slopes intermediate between step-pool and pool-riffle channels. Plane-bed channels are usually described as armored bed surfaces. Streambed armoring indicates a lack of bedload transport capacity for larger particle or material sizes ,while finer suspended sediments have been readily transported through plane-bed reaches. Depending on sediment size distribution and discharge, plane-bed channels may exhibit either supply or transport limited morphologies.

Pool-riffle stream reaches are also response reaches. The bed of pool-riffle channels tends to be stable over time even though the bed material is mobilized by intermediate and larger flow events. Bars may develop in pool-riffle systems with high width to depth ratios and where the channel gradients are less than about 0.02 foot per foot. Like the plane-bed channels, sediment transport can be either supply limited or transport limited at various discharges. When sediment bars occur in pool-riffle systems, it is an indication that the composite flow regime is transport limited.

The dune-ripple channel is the third response channel type. A mobilized bed even at low flows characterizes the dune-ripple channel reach. They are typically low gradient, sand bed channels. Channel bed material can easily be put into suspension, but the combined sediment load is almost always greater than the available transport capacity. The bed material is constantly being shifted and moved short distances at all flows, but the overall lack of transport capacity compared to total sediment load results in the dune-riffle channel being transport limited.

Another key concept of the Montgomery and Buffington classification system is the recognition and categorization of a number of forced channel morphologies. A forced channel morphology can result from debris flows, geological barriers, bedrock outcrops, and especially from large woody material (LWM) in the Pacific Northwest. In small channels, trees tend to remain where they fall. Where the dominant trees tend to be longer than the channel is wide, woody material can create a sudden and long lasting constraint to the local stream morphology resulting in a forced stream type. On small mountain streams, LWM may dominate channel morphology by stream blockages that may exist for decades or even centuries.

In larger streams where the stream channel tends to be wider than the dominant tree heights, the LWM is typically mobilized and transported downstream. On these larger rivers, hydraulic processes dominate the impact of LWM on channel morphology. During large floods, LWM may be deposited on bar tops during the hydrograph recession, which may leave the impression that the LWM in the stream system has had little impact on channel morphology. Nevertheless, logjams influence channel pattern and flood plain processes in large forest channels through bank cutting or protection, channel unit and side development, and forcing channel avulsions (Bryant 1980; Nakamura and Swanson 1993; Abbe and Montgomery 1996).

LWM can be characterized as a random variable that creates many forced stream morphologies in Northwest streams. In addition to the impact of LWM on Pacific Northwest streams, there are a variety of other changes that can be anticipated. Montgomery and Buffington describe the array of potential channel changes as:

> *In response to changes in sediment supply or discharge, a channel may widen or deepen; change its slope through aggradation, degradation, or modified sinuosity; alter bedforms or particle size, thereby changing the frictional resistance of the bed; or alter the thickness of the active transport layer defined by the depth of channel scour. Drawing on both theory and empirical evidence, previous researchers developed conceptual models of channel response to changes in sediment load and discharge (Montgomery and Buffington 1998).*

Montgomery and Buffington have created a number of conceptual models of channel response supported by hydraulic geometry. Most of the documented experiences were associated with changes in sediment supply and/or transport capacity. Quantitative measurements of total sediment load including both bedload and suspended sediment are difficult and expensive to obtain. Hydraulic transport capacity is easier to obtain, but the accuracy and data format may not fit sediment modeling needs. For a more detailed description of the hydraulic geometry relationships and experiences with predicted changes and validated responses, see Montgomery and Buffington (1998).

Montgomery and Buffington acknowledge some merit to coarse scale classification systems for general planning purposes, but offer a cautionary note regarding the use of classification systems as a substitute for careful field evaluations of complex morphologic issues. Their cautionary note in its entirety is:

> *Channel classification cannot substitute for focused observation and clear thinking about channel processes. Channels are complex systems that need to be interpreted within their local and historical context. Classification simply provides one of a variety of tools that can be applied to particular problems—it is not a panacea. Classifications that highlight specific aspects of the linkages between channel networks and watershed processes are likely to be most useful, but careless application of any channel classification may prove misleading; no classification can substitute for an alert, intelligent, well-trained observer. Nonetheless, it is difficult to fully understand a channel reach without reference of the context defined by its bed morphology, confinement, position in the network, and disturbance history.*

Strengths
The Montgomery and Buffington stream classification system is a geomorphic process-based system that is strongly influenced by extensive experience on mountain streams, especially in the Pacific Northwest and Alaska. This classification system does an excellent job of identifying the morphologic differences in the mountain streams where it was developed. The process-based components of the system can be expected to work well in other mountainous regions, as well. The classification system aids the user in identifying source, transport and response (erosional, transport, and depositional) reaches. Regional variations with the classification system are more likely to occur with forced stream morphologies, especially those resulting from the presence of an abundance of LWM. There is clear reason to test the applicability of this classification system to other mountainous regions across the country, recognizing that the concept of forced stream morphologies may vary significantly.

Weaknesses
The nonfluvial geomorphologist initially may have difficulty applying the classification system with consistent results. The documentation in the past was developed within and written for the scientific community. As with many other systems, the procedure is not readily applied without study or training. However, with field experience, a practitioner should be able to define the nine stream classes identified by Montgomery and Buffington.

(e) Rosgen classification system

The Rosgen Classification of Natural Rivers was developed over 30 years of extensive fieldwork and observations of river systems across North America.

The Rosgen classification system tends to rely on field-measured parameters and is more experience-based than some of the other classification procedures described in this document. Rosgen's classification measures are based on channel dimensions measured at bankfull discharge, also known as channel forming flow. The complete Rosgen system is intended to provide both stream reach classification and guidance for potential restoration. The system includes the addition of a number of practical physical parameters that can be measured in the stream or from photographs and USGS topographic maps depending on the level of classification desired. Use of this method requires fundamental training and experience using this geomorphic method. Not only is a strong background in geomorphology, hydrology, and engineering required, but also an ability to implement the design in the field. The application of the classification system as part of a detailed design process is described in detail in NEH654.11.

The first version of Rosgen's current classification system was published in 1985. The system has continued to evolve with Rosgen (1994) and in Applied River Morphology (Rosgen 1996). The Rosgen system categorizes or classifies an individual stream reach, rather than an entire stream system. The key to the classification system is shown in fig. 3–6. Rosgen (1994) best describes the description of appropriate reach length as follows:

> *The morphological variables can and do change even in short distances along a river channel, due to such influences of change as geology and tributaries. Therefore, the morphological description level incorporates field measurements from selected reaches, so that the stream channel types used here apply only to individual reaches of channel. Data from individual reaches are not averaged over entire basins to describe stream systems. A category may apply to a reach (of) only a few tens of meters or may be applicable to a reach of several kilometers.*

Rosgen (1994, 1996) identifies four levels of detail in stream classification and assessment. This document primarily concentrates on levels I and II stream classifications. Each successive level provides a more detailed or finer definition of the dimension, pattern, and profile of the stream reach being classified.

Level I stream classification

Level 1 is a general characterization of the stream reach being classified. Level I stream classification is based on geomorphic features that can be interpreted from aerial photography, topographic maps, geologic maps, and a strong individual familiarity with the stream systems and land forms within the watershed of interest (Rosgen 1996).

Level I stream classifications are intended to be preliminary in nature. Level I classification makes use of readily available published information and relies on experience and judgment to the extent possible. The first four delineative criteria for levels I and II classifications are the same, but vary greatly in the intensity of required data. The four required channel characteristics for a level I determination are the number of channels, entrenchment ratio, width-to-depth ratio, and sinuosity. For a level I determination, the four channel characteristics often can be determined using a coarse scale with suitable landform maps.

As a minimum, level I classification requires a judgmental estimate of entrenchment (slight, moderate, or entrenched) based on prior knowledge of the stream system or experienced visual field observations. The specified ranges for width-to-depth ratio are fairly broad with break points at less than 12, 12 to 40, and greater than 40. In level I classification, the width-to-depth ratio is often viewed in terms of the stream reach being described as narrow and deep or flat and wide. With a minimum of experience, judgments of width-to-depth ratio with visual observations are relatively easy in all but borderline cases. The purpose of a level I classification is to designate the eight basic Rosgen stream types of A, B, C, D, DA, E, F, and G. These eight stream types are described in detail in Rosgen (1996).

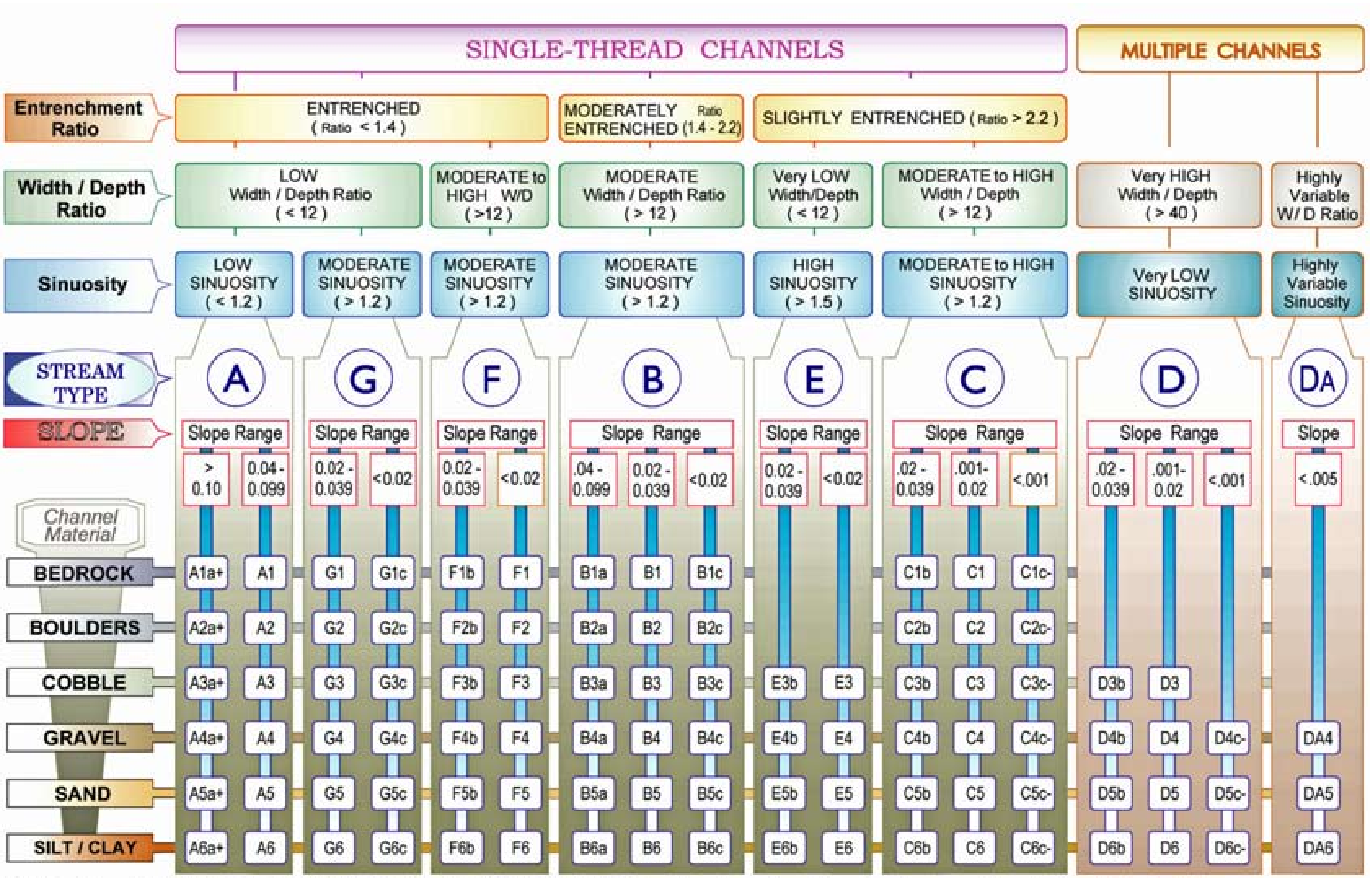
In practice, a level I classification can also include preliminary visual field estimates of bed material (a level II characteristic). An experienced practitioner can differentiate visually between a C channel with a sand bed (C5) and a C channel with a gravel bed (C4) in all but borderline cases. Channel water surface profile slope at bankfull stage (a level II characteristic) is not required to make a level I classification. However, a channel slope measurement from a USGS quadrangle map may be useful in preliminary planning to differentiate between channel types likely to occur on steep slopes versus channel types more likely to occur on flatter slopes. Estimates of channel slope are also useful in characterizing the general stream and valley system morphology.

Level I classification and any additional observations should be clearly identified as preliminary estimates that will have to be supported by actual field measurements in level II classification. Level I classifications can be useful for general discussion purposes, broad inventories, and coarse planning applications. Level I classifications are never suitable for use in the final design of stream restoration activities.

Level II stream classification

Level II stream classification requires actual field measurements and higher resolution landform mapping to delineate the more detailed and defensible stream classifications. The first four delineative criteria in level II classification are the same as were used for level I classification. The difference is that the number of channels, entrenchment ratio, width-to-depth ratio, and sinuosity must be accurately measured in the field for a level II classification.

Figure 3–6 Key to the Rosgen stream classification system



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Level II classification requires physical measurement of a number of associated parameters not required in level I including hydraulic characteristics. The hydraulic geometry portion of Rosgen's Classification of Natural Streams is strongly influenced by the early work of Leopold and Maddock (1953) and the work of Leopold, Wolman, and Miller (1964). This work identified eight interdependent hydraulic variables that could be used to characterize stream morphology. The variables are discharge, velocity, channel width, channel depth, channel slope, sediment size, sediment load, and roughness of channel materials.

Leopold, Wolman, and Miller (1964) recognized that a change in any one of these interdependent variables would produce resultant and often compensating changes in the other seven variables. The compensating effect is not uniform for all variables. For example, an increase in channel width will produce proportional, but inverse reduction in mean channel depth since, in many cases, bankfull channel area tends to remain relatively constant. For the same example, corresponding variables such as velocity and discharge may only exhibit minor reductions in magnitude. Rosgen has both directly and indirectly incorporated a number of the hydraulic geometry relationships into his criteria.

Two key field determinations are critical for obtaining accurate information for use in level II classifications. The first is that the elevation of the bankfull flow must be accurately determined, since it is directly linked to many other parameters. The term bankfull as used by Rosgen can be very confusing to the new practitioner who may visualize the common definition of bankfull as the elevation where water first begins to spill out of the channel banks and onto the flood plain. Rosgen uses the Dunne and Leopold (1978) definition of bankfull:

> *The bankfull stage corresponds to the discharge at which channel maintenance is the most effective; that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of the channels.*

The bankfull discharge and resultant elevation has a typical recurrence interval range of 1.0 to 3.0 years on an annualized frequency curve with a predominance of values occurring in the 1.2- to 1.8-year range. For channel types C, D, DA, and E which are only slightly entrenched, the lay definition of bankfull and the Dunne and Leopold definition are very similar. For the B channel type which is moderately entrenched or the A, F, and G channel types that are entrenched, the Rosgen bankfull is at an elevation well below the top of the banks. A number of good field indicators can be used as reliable indicators such as the top of point bars, a break in bank slope, and the presence of certain riparian vegetative species, which vary by region. An accumulation of indicators aids the practitioner in physically identifying the Dunne and Leopold bankfull elevation in the field. With proper training and concerted practice, individual determinations of bankfull tend to be consistent. Bankfull determinations are not necessary for the general level I classifications, but are a key element for the detailed level II determinations. For a more complete description of bankfull discharge, refer to NEH654.05.

The second important concept in determining level II classifications is entrenchment ratio. Entrenchment or channel incision is basic to geomorphic and geologic literature. Rosgen has established a useful working definition that helps define the relative degree of entrenchment. Rosgen defines entrenchment ratio as the width of the flood-prone area at an elevation twice the maximum bankfull depth, divided by the bankfull width (flood-prone width/bankfull width). Based on Rosgen's database, a total depth equal to twice the maximum bankfull depth constituted a major flood with an approximate recurrence interval of 50 years. Some stream professionals question the validity of this hypothesis. Rosgen defines the total width at two times the maximum bankfull depth as the flood-prone width. Regions outside of the area covered by the database may vary significantly from the flood-prone width/bankfull width relationship established by Rosgen. The procedures for making the necessary field measurements are listed in Rosgen (1996). This reference emphasizes the importance of an accurate determination of the bankfull elevation, since entrenchment ratio and several other parameters are directly related to the bankfull elevation. Important issues and concerns regarding the identification of bankfull indices is addressed in NEH654.05.

The concept of entrenchment ratio is an empirical relationship. Although Rosgen's database includes information from locations across the United States and Canada, some concern remains that this relationship needs to be evaluated on a national basis and that some regional modifications may be appropriate. The current version of Rosgen's Classification of Natural Rivers is presented in hierarchal form in the book, Applied River Morphology. The determinations of six hierarchal parameters are required to make a complete level II classification of a stream reach.

1. Number of channels—On the surface, this appears to be a simple determination that could be made from field observation or the use of current photographs and maps. However, by definition, there must be three active channels at the bankfull elevation to be considered a multiple-thread channel. Therefore, a bankfull determination is required to verify that there are actually three or more active channels at the bankfull stage. Multiple active channels (three or more), where they are verified to exist, identify the stream reach as either a D or DA classification. All other channels are considered to be single-thread channels.
2. Entrenchment ratio is defined as the width at an elevation twice the maximum bankfull depth divided by the bankfull width. The importance of an accurate determination of the bankfull elevation as it applies to this and other parameters has been described previously. Concerns have been expressed that regional variations in this parameter may be required. Geology, slope, vegetation, and other factors may also influence this parameter.
3. Width-to-depth ratio is defined as the width measured at the bankfull elevation divided by the mean depth of the bankfull channel. The magnitude of the parameter depends on an accurate determination of the bankfull elevation.
4. Sinuosity is defined as the ratio of stream length at the bankfull stage to valley length. Sinuosity can best be measured in the field, but it is a time-consuming measurement. Streams with smaller channels and with extensive canopy cover will likely require field measurements to obtain the needed accuracy. For larger streams and streams with limited canopy cover, sinuosity can also be successfully measured using alternative sources such as recent aerial photography with sufficient resolution. A scale of 1/660 (8 in/mi) is preferred; however, a scale of 1/1,320 (4 in/mi) usually gives acceptable precision for larger open-canopy stream channels. Sinuosity can be measured off USGS 7 1/2-minute quadrangle sheets, but this is not suitable for a level II classification. The scale of the 7 1/2-minute quadrangle sheets (2.64 in/mi or 1 in = 2,000 ft), the age of the quadrangle photo base, and the limited detail used in defining the stream channel on the quadrangle are all concerns that limit the utility of using USGS quadrangle sheets for determining level II sinuosity.

   At this point, a level II basic classification, A through E, of the stream reach can be obtained. The difference between the levels I and II classification is that the criteria have been validated with actual field measurements. In actual practice, level II classification is rarely terminated at this point. The remaining delineation criteria for a complete level II classification are:

5. Channel material is a determination of the surface particles that make up both the bed and bank material within the bankfull channel. The Rosgen classification procedure uses a modified version of the Wolman (1954) pebble count procedure for the determination of surface particle sizes. A number of cross sections selected to represent the distribution of pools and riffles within the reach to be classified are sampled using the pebble count procedure. Although the parameter being defined is channel bed material, each cross section is surveyed using equally spaced stations up to the bankfull elevation. Since each data point is counted equally in the process, the procedure is normally heavily weighted toward channel bed material, especially on wide shallow channels. For specific details on making a modified Wolman pebble count, refer to Rosgen (1996). Although exceptions are noted for bimodal particle size distributions, generally the D_{50} particle size determined from the modified Wolman pebble count procedure is used to classify the channel bed and bank materials up to the bankfull elevation. Rosgen's first channel material class based on a field determination is bedrock. The five remaining material classes are based on the D_{50} particle size of the streambed and bank material up to the bankfull stage as determined

from pebble count information. The six Rosgen material classes, including bedrock are:

- bedrock
- boulder—greater than 256 millimeters (10 in)
- cobble—64 to 256 millimeters (2.5 to 10 in)
- gravel—2 to 64 millimeters (0.08 to 2.5 in)
- sand—0.062 to 2.0 millimeters
- silt/clay—less than 0.062 millimeters

The channel material makes up the left-hand side of the Rosgen classification matrix. Pebble counts are more appropriate for boulder, cobble, and gravel bedded streams. Other protocols may need to be developed for sampling fine-grained bed and bank material (sand, silt, and clay).

Classification of sediment into particle-size classes is arbitrary, with class breaks frequently based upon standard sieve sizes. It should be pointed out that the class size breaks and most of the descriptive terms used by Rosgen were derived from the Udden-Wentworth classification system used by geologists (Wentworth 1922). This system employs different size breaks and some differing terminology from the particle size classification systems used by NRCS engineers (Unified Soil Classification System, American Society for Testing and Materials International (ASTM) D2487) or NRCS soil scientists (USDA soil texture classification system).

6. Slope is the local slope of the bankfull water surface within the reach that is being classified. Water surface slope is typically measured over a length equivalent to 20 bankfull channel widths or a minimum of two meander wavelengths. For applications in level II or higher, measurements of the actual water surface on both pool and riffle sections is also a requirement. Ephemeral streams may require the use of computed water surface profiles with sufficient cross section data to define the pool-riffle sequence.

The field determination of the bed material as defined provides the criteria to make a complete level II determination such as A3, which is an A channel with cobble bed material. If the slope of the local water surface profile is outside of the normal slope range for an A3 channel (0.040–0.099), the channel can be further described based on a slope subscript. An example would be an A3a+ which describes an A channel with cobble bed material on a slope greater than 10 percent. Some channel types such as B and C channels may have slope variations that are greater than normal (+) or less than normal (–).

Level III and IV assessments

Levels I and II are the levels of classification that characterize and describe stream types. Although detailed descriptions of levels III assessment and IV validation are not included here, it is useful to understand their scope. Levels I and II are a classification of the current status of the stream reach based on two distinct levels of data acquisition. Level III assessment is used to evaluate stream condition and its departure from the optimum or potential condition. Level III data are necessary to quantify numerous parameters (sediment load, bedload, bank erosion) that more clearly define trends and expected long-term changes in the current stream status. Level III data are critical as a basis for restoration designs and installation. Level IV is the validation level where the parameters of stream function are monitored over time to either validate a stream's status or the success of a restoration activity.

Management interpretations

Rosgen (1996) provides examples of how stream classification can be related to numerous NRCS activities. Stream type can be related to expected impacts due to disturbance, recovery potential, sediment supply, streambank erosion potential, and the potential for vegetation to control the dominant channel influence. Rosgen's database may not be completely representative of all regions of the country, and all final decisions should be supported by a field assessment. This method requires field data that represent local stream morphology.

Strengths

The Rosgen classification system is currently the most widely used of the four systems addressed in this document. While initially applied regionally, the method has been used nationally and internationally. Levels I and II stream classifications have found acceptance among a variety of disciplines. The greatest value of

Rosgen's classification system is in the establishment of a common language for communication among the associated stream disciplines. For example, a geologist in Alaska can talk to a biologist in Florida regarding a (C5) stream type and both will have a common frame of reference.

Rosgen's procedures go beyond levels I and II stream classifications. They are linked to design procedures and criteria for a wide range of stream restoration activities. Rosgen's levels III and IV procedures appeal to disciplines that do not have professional backgrounds in stream mechanics and geomorphology, but have a strong desire to do a better job in stream restoration activities. This may be considered as a strength or weakness depending on the competence of the individual(s) using the procedures.

Weaknesses

Combining silt/clay as a similar channel material is inconsistent with the general erosion, stability, and structural integrity characteristics of the two materials. Additional data on silt and clay channels from across the country may resolve this issue. The type B stream classification has been criticized as a catch all category. It represents the only stream type between slightly entrenched and entrenched. It also covers the largest slope range of any of the stream types with a slope range from <0.020 to 0.099. Additional data may warrant additional breakdown of the B stream type.

Other weaknesses are the lack of an upper limit on the width-to-depth ratio for C stream types, and the requirement of three active channels at bankfull for the classification of D stream types.

Levels I and II classifications describe the current condition of the stream reach, but does not address time variability issues such as the rate of entrenchment or rate of lateral migration. A number of time variability issues such as rates of aggradation or degradation and lateral migration are addressed in level III assessment and level IV validation.

Beyond levels I and II stream classifications, there is an often-expressed concern among geomorphologists and stream mechanics engineers that the overly enthusiastic novice in stream restoration may attempt projects that are beyond their technical capabilities. There may be a tendency by well-meaning users to overlook the need for interdisciplinary input. Another concern is that a stepwise procedure may mask the ability of an inexperienced user to fully understand the interrelationship between the watershed and channel processes.

Although Rosgen (1994, 1996) empirically derived boundary values for geomorphic predictors in his classification system, users should be aware that local calibration is very important to determine a tighter range of values more applicable to a given geographic area. Local calibration is even more important if a significant number of projects using the system are planned, or many streams in a project fall on the cusp of classification boundaries. Further, local calibration may highlight elements of the Rosgen classification system as better, more geomorphically significant descriptors of local stream systems than others.

Detailed information concerning the application of the Rosgen stream classification technique is provided in NEH654 TS3E. Design guidance is included in NEH654.11.

654.0306 Conclusion

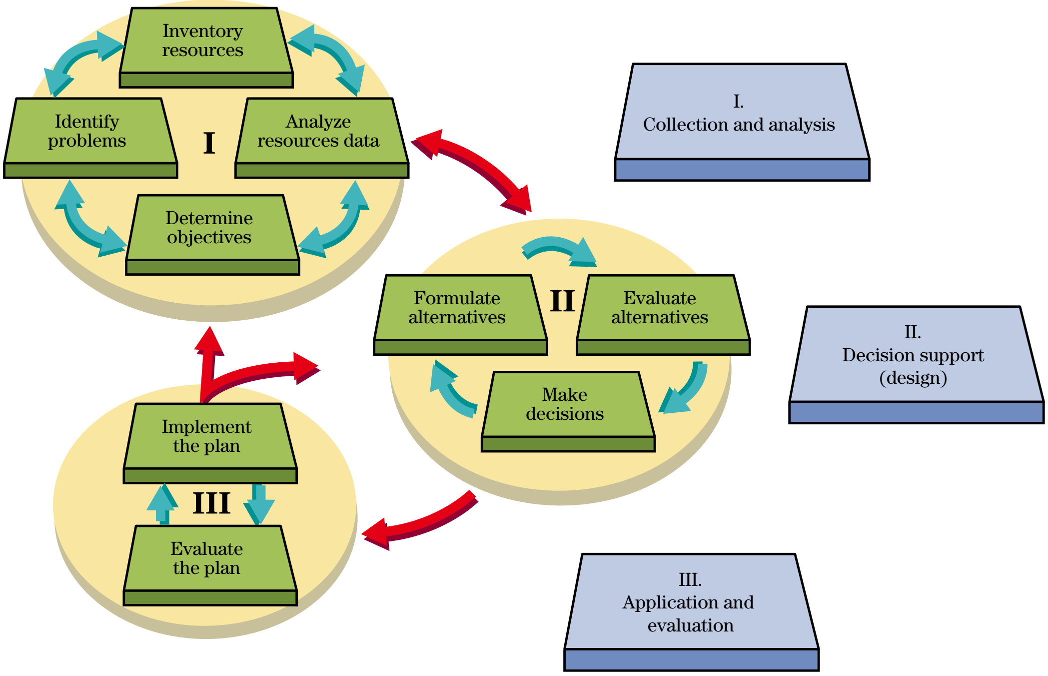
This chapter briefly summarized procedures for watershed assessments and site investigations. Stream system inventory and assessment techniques were identified and compared. Information was provided on stream stability, as well as geological and biological assessments. The uses, advantages, and disadvantages of various geomorphic stream classification systems were also described. This chapter addressed fluvial processes and broader geologic issues related to ecological function, as well as stream design and behavior.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654 Stream Restoration Design
National Engineering Handbook

Chapter 4 Stream Restoration Design Process



Issued August 2007

Cover illustration: Design of solutions for stream problems is a part of the restoration planning process. Designs translate the desired changes into the stream and riparian zone. Changes to the design may cause goals and objectives to be reevaluated, as the planning process may be iterative.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 4 Stream Restoration Design Process

Contents

Tables

Figures

Chapter 4 Stream Restoration Design Process

654.0401 Purpose

The purpose of this chapter is to provide an overview of the process for designing stream restoration solutions. The design process is integrated with the overall planning process. To design a solution means to fit it into the landscape, into the stream system, so that the result meets the goals and objectives of the plan. Solutions may range from no action to management and simple removal of perturbations, to site-specific practices, to riparian corridor and watershed-scale restoration systems.

Often, solutions to stream problems (fig. 4–1) are suggested at the time that they are identified, such as: “My streambank is eroding. We need to put rock riprap on it.” It could be that the problem merits that response. It could also be that the nature of the bank erosion problem is more complex and may be related to a general instability of the stream system. An interdisciplinary, onsite analysis is critical to the development and success of any designed solution or system.

The design of a solution to a stream problem must address the goals and objectives developed from the planning process. Once a solution is agreed upon, the design process determines the feasibility of the solution and whether goals or objectives must be revised or whether a different designed solution should be pursued. A cookbook design procedure is not recommended since each project and each design will have differing goals and objectives, physical or biological constraints, and jurisdictional requirements and constraints.

This chapter provides an integration of the conservation planning process (CPP) with stream restoration design concepts and provides the foundation for using the tools and procedures in the following chapters. Note that design of stream restoration solutions may include a wide range of design elements, from management practices to structural practices, the selection of which depends on the nature of each individual project.

654.0402 Introduction

Planning actions to fix stream problems can be a complex process. This is due to the interactions between possibly many stakeholders: people who affect or are affected by the stream problems and any potential solutions. How streams are supposed to look and function are ideals that vary from one person to another. Philosophies and approaches to stream restoration abound: restore to what conditions or functions?

This chapter overviews the process for developing designs to solve stream problems. There are many steps in the overall process (NEH654.02). Some steps may be accomplished quickly, while others may require lengthy analysis, data gathering (NEH654.03), or discussion with stakeholders, depending on the magnitude and complexity of the problems, as well as constraints posed by boundary conditions, funding, attitudes, or local requirements (fig. 4–2). Problems that are localized and involve only a single land user may be planned and designed rapidly. Designs must also address environmental and ecological factors, as well as satisfy the immediate stream restoration need. Streams in urban areas present unique challenges for restoration (fig. 4–3).

Figure 4–1 Severe bank erosion along the Connecticut River eroded cornfield and resulted in excessive sediment in the river

Appropriate and effective stream solutions can only be designed when the goals and objectives of the planned solutions are clear, realistic, and adequately formulated. NEH654.02 focuses on the importance of identifying the goals and objectives of any proposed stream action that will drive the design approaches. It also expands on the concept of risk associated with stream solutions—the risk of failure of the implemented design elements, the risk of creating ecological imbalances, as well as the risk of not achieving the intended results.

The importance of collecting the right information to assess the nature of the temporal, physical, and biological nature of the problem are addressed in NEH654.03. The information collected will also facilitate the design process and form the basis for making assessments of the overall success of the project after implementation.

This chapter introduces an overall design procedure, which is an integral part of the planning process for stream design. The purposes of stream designs can range from simply conveying water to restoring self-sustaining ecological functions and values to the stream corridor. The design process may be iterative, in that the initial design may require cycling back through some of the planning steps, making decisions, possibly modifying goals and objectives, and redesigning alternatives. Stream designs may include a variety of solutions ranging from upland watershed and riparian area management practices that may be needed, large-scale reconstructions of entire stream reaches, localized applications that can involve earth materials, live and inert plant materials, and manufactured materials.

Figure 4–2 How streams are supposed to look and function are ideals that vary from one person to another.

Figure 4–3 Lined channels may be necessary, based on boundary constraints, drainage needs (discharge capacity), and maintenance costs.

654.0403 The CPP for stream design

The design and management of streams must address the myriad of resource concerns, as well as client objectives, to support near- and instream stabilization activities in a sustained manner. In general, prescribing the treatment for a stream is based on the site or reach conditions including historic and reference stream corridor information and objectives of the decision-making client, as well as stakeholders who influence the client. This important issue was first addressed in NEH654.02.

Stream restoration is defined here as one or more conservation practices used to overcome resource impairments and accomplished the identified purposes based on client objectives for a conservation management unit (CMU) containing, in whole or part, the stream corridor needing treatment.

A stream corridor includes the stream and extends in cross section from the channel's bankfull level towards the upland (perpendicular to the direction of streamflow) to a point on the landscape where channel-related surface and/or soil moisture no longer influence the plant community. Figure 4–4 illustrates an idealized cross section of a stream corridor (modified from Stanford and Ward 1992).

This description encompasses moisture influenced land on both sides of a channel. The length of a stream corridor is typically a sinuous band that follows both sides of the channel from the headwaters to the mouth of the stream system. Depending on channel conditions (stream order, channel evolution model (CEM) stage, bankfull width, degree of incision, and flood plain characteristics), the width of this longitudinal band fluctuates with corresponding influences on the kind and composition of riparian vegetation within the band. In mountainous areas, changing elevations along the stream corridor determine riparian community composition because of the varying cold-hardiness capacity of individual plants. Also in effect are cross-sectional variations in microclimate and soils, which influence the kind and mix of riparian species. Stream corridor soils are typically not a single soil series, but a complex of named soil series and taxadjuncts. Taxadjuncts are soils closely associated with a named series that differ somewhat in one or more soil characteristics, which may further complicate the planning process.

Table 4–1 lists and figure 4–5 illustrates the steps in the Natural Resources Conservation Service (NRCS) CPP. This was described in NEH654.02. Detailed information about each of these steps is provided in the NRCS National Planning Procedures Handbook (NPPH) (USDA NRCS 2003b). These steps are applied for each CMU on a client's planning unit. An important aspect of the planning process is how the proposed stream restoration practice(s) will interact and work compatibly with other practices in the resource management system (RMS) to address all pertinent resource concerns in achieving resource quality criteria (refer to Section III of the local NRCS Field Office Technical Guide (FOTG), available for each county at *http://www.nrcs.usda.gov/Technical/efotg/*).

Figure 4–4 Cross-sectional view of a generalized stream corridor segment. Biota may reside in all dimensions (riparian, inchannel, hyporheic and/or ground water zone). Inundation and desiccation of the blue shaded area occurs as the amplitude of the discharge increases and decreases under a natural flow regime. Sd designates sediment deposition sites, and Se is a site of bank erosion. The solid line is the thalweg, and the broken lines indicate the different directions of flow and materials among inchannel, hyporheic, and ground water zones.

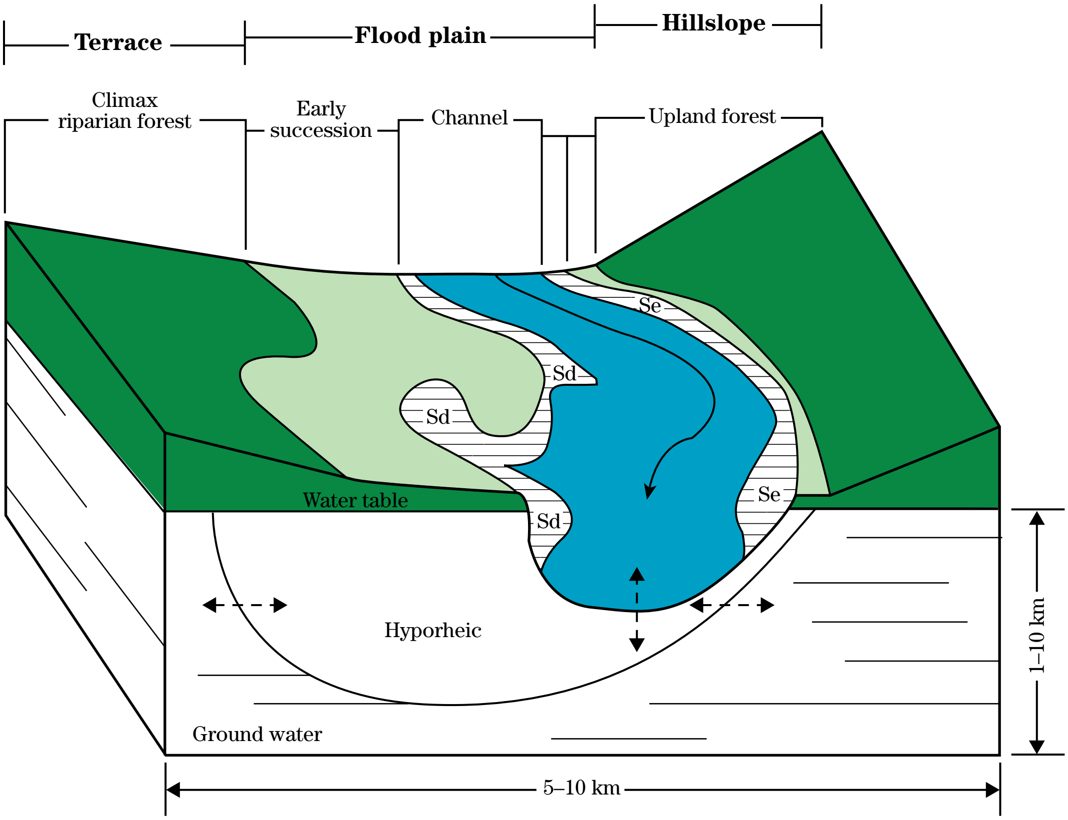


Table 4–1 Steps in the NRCS CPP

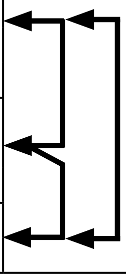
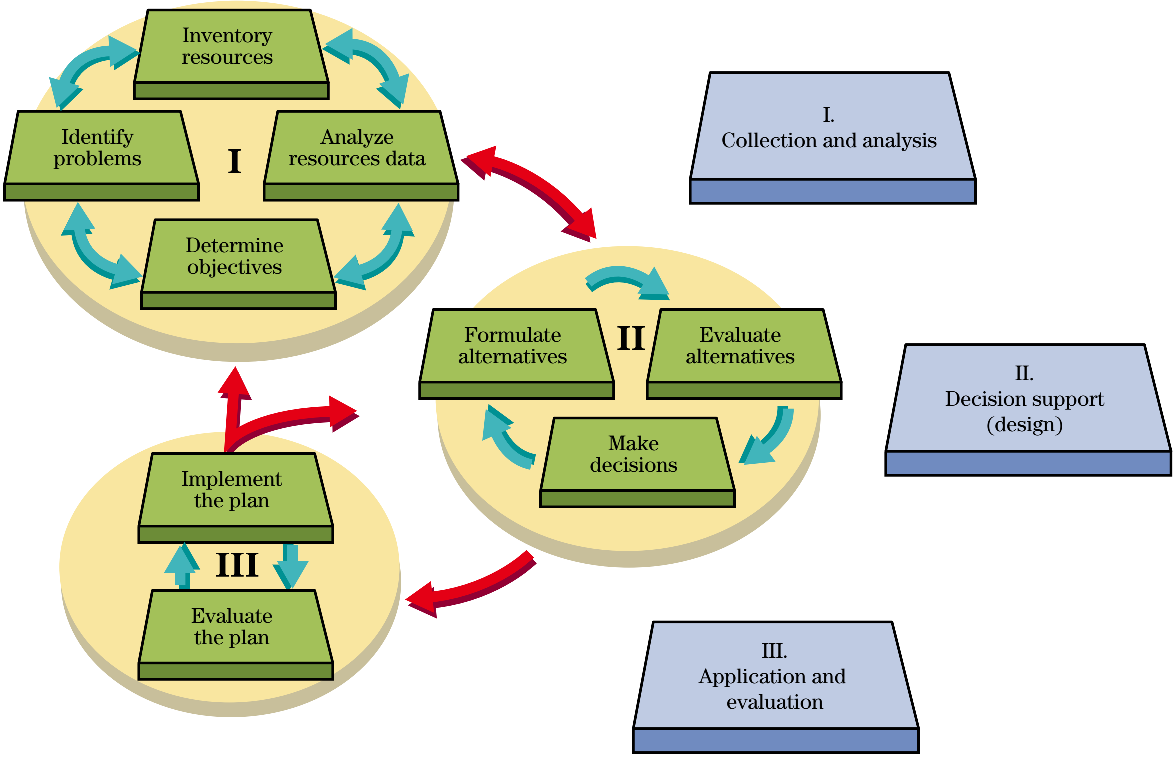
Steps	Planning activity	Level	Potential iterations
1	Identify problems and opportunities	I	
2	Determine objectives		
3	Inventory resources		
4	Analyze resource data		
5	Formulate alternatives	II	
6	Evaluate alternatives		
7	Make decisions		
8	Implement the plan	III	
9	Evaluate the plan		

Figure 4–5 NRCS CPP showing the dynamic interaction between the steps



654.0404 Designing solutions for the stream corridor

While an array of suitable practices is available for most stream corridor conditions, client objectives usually focus treatments to a more limited range. Planning site problems, however, typically exceed the client's focus and, more than likely, are symptomatic of larger area and watershed concerns (habitat fragmentation or an imbalance in sediment transport).

Table 4–2 describes the interplay of stream restoration with three common client problem/objective scenarios. While all objectives are justifiable management options, multiple resource concerns and ecological functions are usually only addressed with example objective C.

(a) Landscape context for restoration

Once site problems and client objectives have been evaluated (NPPH planning steps 1 through 4), potential treatment and restoration activities can be considered. From a context viewpoint, an important first step is to recognize the site-level landscape settings or zones on the CMU/stream corridor that influence the selection of potential practices. Figure 4–6 (adapted from Hoag et al. 2001) illustrates an idealized, conceptual cross section of a stream and one side of the stream's riparian area. Not all of these zones will exist in all streams and rivers. Table 4–3 provides more detail on applicable landscape zones, descriptions of each zone, and an overview of correlated practices.

Because of the strong physical and ecological interaction of streams with their flood plain and adjacent corridors, a CMU should be delineated to encompass the stream corridor, which includes the streambed, banks, and riparian areas. These landscape components strongly interact and are best planned as a whole to optimize desired effects and meet client and ecological objectives.

Tables 4–4, 4–5, and 4–6 provide information on selection of NRCS Conservation Practice Standards and their considerations and effects related to landscape zones in and along the stream. Table 4–4 focuses on accelerated erosion, sediment, and site instability, whereas tables 4–5 and 4–6 focus on habitat and biodiversity and production and land use, respectively. Each zone depicted in these tables has particular characteristics and correlated practices. Practices can be reviewed and studied by referring to section IV of the FOTG. From a biotic perspective, the plant community potential is an important ecological reference in thinking about restoration and triggering site-level planning questions:

- Is the reference plant community (or a successional stage of it) present?
- Are the site's landscape zones in a physical condition to mutually sustain the reference community or stages?
- Are watershed-level landscapes in a physical and biotic condition to sustain site-level stream corridor recovery or restoration?

(b) Selecting conservation practices for stream restoration

With an understanding of the planning process and stream corridor landscape settings, the planner is ready to match site impairments, landscape zones, and client objectives with conservation practices (idealized in fig. 4–7). Tables 4–4, 4–5, and 4–6 provide information for use by the planner in choosing appropriate treatments and vegetation types. An important strategy when using the table is to match existing problems in each impairment category with coinciding conservation practices suited to the particular landscape zone or zones making up the CMU. An assumption is that once impairments are recognized, the client's objective is to remedy problems by using a system of conservation practices (fig. 4–8).

Selection of some practices at the beginning of tables 4–4, 4–5, and 4–6 will influence or curtail the selection and extent of others listed later. For example, a client wants to improve forage resources in the overbank and transitional zone, but has eroding banks and overbank zones lacking protective ground cover. Treatment of the bank and overbank zones (using rock, mulching, and/or specialized vegetation) to control bank or surface erosion will necessarily restrict the use and extent of forage establishment practices. In this situation, the bank and overbank zones may require livestock exclusion temporarily or permanently, with a corresponding revision of the site's prescribed grazing management.

Table 4–2 Relationship of stream restoration components with client problems and objectives

Example problems/client objectives	Channel/riparian/watershed characteristics	Desired outcome/effects
A. Erosion and sediment control (streambank erosion, channel aggradation, channel degradation, concentrated flow and scour erosion, sheet and rill erosion)	• Excessive bank recession rates • Instream bar formation • Incised channels that are deepening, then widening • Lack of vegetative cover on banks, flood-prone zones and riparian areas, allowing concentrated flow, sheet, rill, and scour erosion • Concentrated-flow gullies from adjacent areas and land uses • Overall watershed cover has less native perennial cover, more impervious areas or more direct flow paths, which are unbuffered	• Return to normal reference bank recession rates and point bar dynamics • Incised channels are stabilized and flood-prone areas are reestablished. This occurs at a lower elevation than preincisement conditions • Aggressive herbaceous plants substantially reduce surface erosion and hinder the invasion of weeds, but they can impede successional progression to the desirable plant community • Woody plants bind streambank soils and in adjacent flood-prone areas, increase surface roughness, which can reduce scour erosion • Buffers and associated practices in adjacent uplands can slow runoff, reducing stress to streambanks and channel degradation processes
B. Production and use of stream and streamside vegetation (game fish, livestock forage, forest products)	• Channel banks and bed are modified and maintained to favor specific game fish • Streamside herbaceous plants, woody plants or a combination consistent with the client's operation and marketing capability are grown to satisfy economic requirements	• Production and utilization goals are achieved when fish and vegetation products reach desired biomass, size, or quality • Aquatic and plant community succession is retarded/managed (or completely supplanted by a production community) to maintain the desired operational condition
C. Restoration of ecological functions (creation of a successional stage which can be maintained or allowed to succeed to a desired plant community)	• Herbaceous plants, woody plants or a combination consistent with desired successional stage or progression to the reference reach plant community	• Functions such as site-soil stability, vertical and spatial habitat, and nutrient cycling are achieved when vegetation reaches the desired successional condition • Domestic use for recreation, grazing, timber harvesting, or other exploitation is excluded or sufficiently restricted so that the desired successional stage is reached and maintained

Figure 4–6 Conceptual cross section of a riparian area with landscape zones for planning restorations

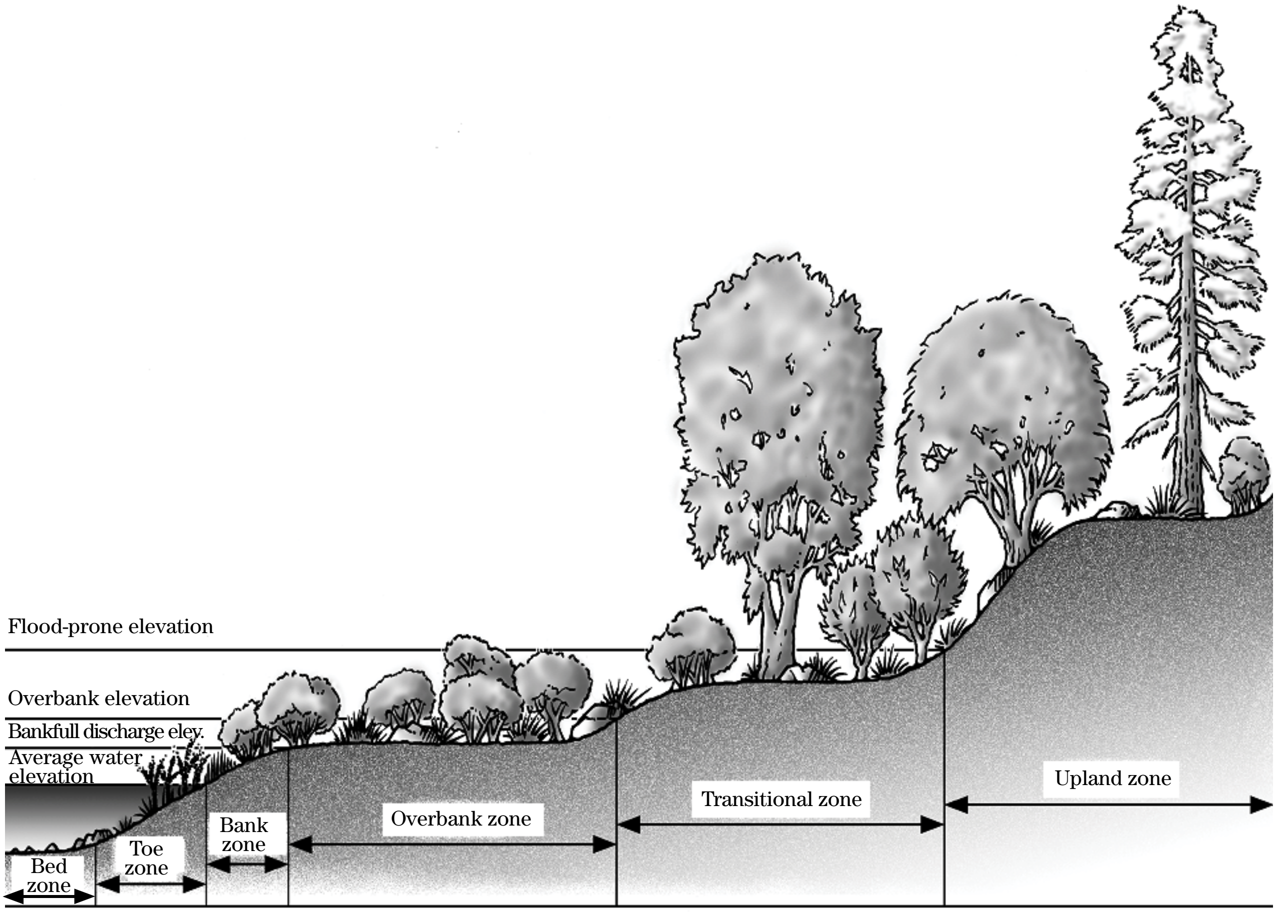


Table 4–3 Description of riparian landscape zones for stream corridor design and management

Definitions and descriptions of landscape zones	Potential RMS conservation practices*
Bed zone—The bottom of the channel that can consist of a variety of bed materials. Vegetation may consist of periphyton (diatoms, algae, phytoflagellates attached to substrate material), phytoplankton (suspended in the water column), and macrophytes (vascular and nonvascular plants), depending on bed material, pool, riffle, run proportions, and flow rate	Channel Stabilization (584)*, Clearing and Snagging (326), Fish Passage (396), Open Channel (582), Stream Crossing (578), Stream Habitat Improvement and Management (395)
Toe zone—The portion of the bank that is between the average water level and the upper edge of the bottom of the channel. This zone has the highest stress because of frequent exposure to wave wash, channel-forming currents, ice and debris movement, and wet-dry and freeze-thaw cycles. Vegetation is generally herbaceous emergent aquatic species, tolerant of long periods of inundation	Channel Stabilization (584), Clearing and Snagging (326), Fish Passage (396), Streambank and Shoreline Protection (580), Stream Crossing (578), Stream Habitat Improvement and Management (395)
Bank zone—The area above the toe zone located between the average water level and the bankfull discharge elevation. (The bankfull discharge elevation, in natural streams, is the elevation at which water fills the channel without overflowing onto the flood plain.) This zone is exposed periodically to wave wash, erosive river currents, ice and debris movement, and traffic by animals or humans. Vegetation may be herbaceous or woody and is typically characterized by flexible stems and rhizomatous root systems. Plants are periodically submerged	Channel Stabilization (584), Channel Bank Vegetation (322), Streambank and Shoreline Protection (580), Stream Crossing (578), Stream Habitat Improvement and Management (395), Use Exclusion (472)
Overbank zone—The area located above the bankfull discharge elevation continuing upslope to an elevation equal to two-thirds of the flood-prone depth. Vegetation may consist of some proportion of herbaceous plants, shrubs and trees, depending on the plant community potential of the site	Critical Area Planting (342), Early Successional Habitat Development/ Management (647), Fence (382), Filter Strip (393), Forest Stand Improvement (666), Irrigation System (441/442/443), Mulching (484), Nutrient Management (590), Pasture and Hay Planting (512), Pest Management (595), Prescribed Grazing (528), Range Planting (550), Recreation Area Improvement (562), Restoration and Management of Declining Habitats (643), Riparian Forest Buffer (391), Riparian Herbaceous Cover (390), Stream Crossing (578), Use Exclusion (472), Watering Facility (614), Wetland Wildlife Habitat Management (644)
Transitional zone—One or more levels of terraces located between the overbank zone and the flood-prone width elevation. On forest potential sites, vegetation is usually larger shrub and tree species with a shrub/herbaceous understory. On herbaceous potential sites, a combination of overbank and upland herbaceous vegetation is usually present in some proportion, as well as other herbaceous species intolerant of upland (dryer) or overbank conditions (wetter)	
Upland zone—The area above the transitional zone. This area is seldom influenced by stream/riparian soil moisture	Various practices, section IV of the local FOTG consisting of 150+ practices

*NRCS National Conservation Practice Standard codes, Specific information for these practice standards is available at the following Web site: *http://www.nrcs.usda.gov/technical/Standards/nhcp.html*

Table 4–4 NRCS Conservation Practice Standards selection for accelerated erosion, sediment, and site instability. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system.

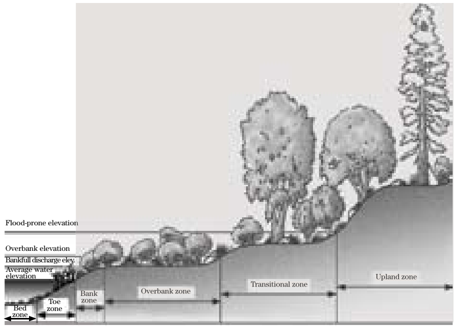
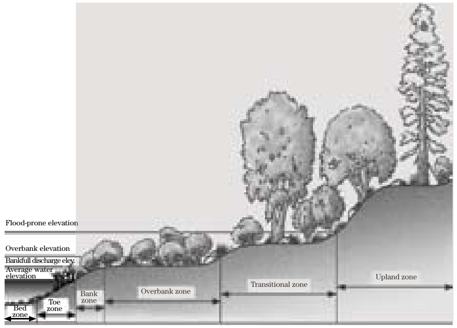
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: accelerated erosion, sediment, and site instability	Landscape zones
Unbalanced channel sediment transport and deposition; unstable channel bed and/or gradient[2/]	Bed, toe	Open Channel (582)	Various techniques including channel meander reconstruction at a site will reconfigure the bed and bank topography and influence the extent of overbank and transitional zones and related soil moisture and the selection of vegetation species	
		Channel Stabilization (584)	Measures to support balance and stability will reduce risk of bank recession and damage to overbank zone vegetation	
		Clearing and Snagging (326)	Where practical, restore native vegetation to all bank, overbank and transitional areas disturbed by use, ingress, or egress of obstruction removal equipment	
Accelerated bank erosion and instability[2/]	Bank, toe	Channel Bank Vegetation (322)	In the overbank zone nearest the stream, use the same or similar riparian area plant species as channel bank vegetation to provide additional support to controlling bank erosion	
		Streambank and Shoreline Protection (580)	See notes for Channel Bank Vegetation (322), which is the vegetation component of this practice	
		Clearing and Snagging (326)	Restore vegetation (native species where practical) to all bank, overbank and transitional areas disturbed by use, ingress and egress of obstruction removal equipment	

Table 4–4 NRCS Conservation Practice Standards selection for accelerated erosion, sediment, and site instability. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

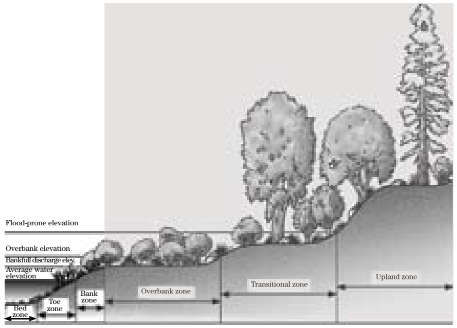
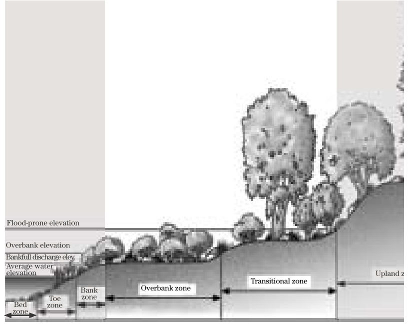
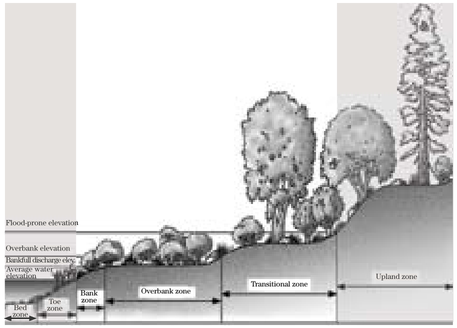
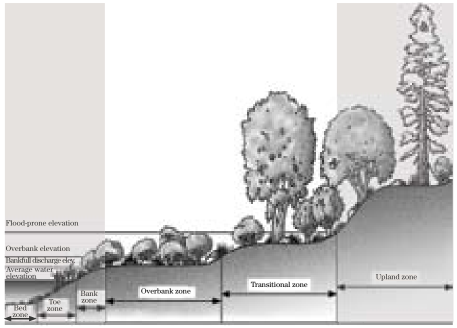
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: accelerated erosion, sediment, and site instability	Landscape zones
Excessive damage by animals, people or vehicles (soil compaction and rutting, loss of protective ground cover) and associated liability and health concerns	Bed, toe, bank,	Use Exclusion (472) Fence (382)	Use Exclusion by use of a fence or other means may be sufficient in restoring the desired vigor and density of the site's vegetation to mitigate damage. Use Exclusion is also used to protect new plantings and accelerate their establishment period	
Accelerated or potential high-rate surface erosion from sheet, rill, ephemeral, or flood scour erosion processes	Overbank and transitional	Critical Area Planting (342)	Introduced plant species and cultivars are usually chosen over native plant species because of improved vigor or establishment density. Flood scour may require additional, shrubby plantings of sufficient height and width (perpendicular to flow) placed strategically to slow out-of-bank flows	
		Mulching (484)	Mulch materials can accelerate establishment of riparian area erosion control plantings by suppressing weed growth, moderating soil temperature, and conserving soil moisture. Seeding can be incorporated into and applied concurrently with some mulching techniques (hydroseeding)	

Table 4–4 NRCS Conservation Practice Standards selection for accelerated erosion, sediment, and site instability. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: accelerated erosion, sediment, and site instability	Landscape zones
Overgrazing	Overbank and transitional	Prescribed Grazing (528)	Prescribed grazing controls the timing, duration and intensity of domestic animals, while maintaining some use of existing forage. Based on the degree of damage to riparian and bank vegetation, use exclusion and livestock deferment may be needed for several years before grazing can resume	
Excessive sediment and/or other pollutants in runoff reaching the channel	Overbank and transitional	Filter Strip (393)	Introduced herbaceous species filter sediment in runoff reaching and passing through the strip. In areas with forest potential, filter strips are used as zone 3 of a riparian forest buffer to filter and slow upland runoff	
		Riparian Forest Buffer (391)	Tree and shrub species further slow upland runoff and aid in the infiltration of pollutant-laden water. Uptake and microbial processes break down nitrates and pesticides. Riparian forest buffers are not intended to withstand unabated upland runoff. Native woody species may not be of sufficient vigor or establish quickly enough for some pollutant loadings	

1/ NRCS National Conservation Practice Standard codes, *http://www.nrcs.usda.gov/technical/Standards/nhcp.html*

2/ The feasibility of site-level versus watershed-level treatment needs to be assessed during the planning process to determine if the erosion problems are due to local conditions or are the result of stream instability in multiple reaches or over a wide area.

Table 4–5 NRCS Conservation Practice Standards selection for unsuited or insufficient habitat and biodiversity. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system.

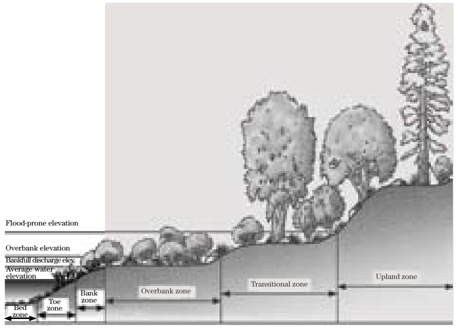
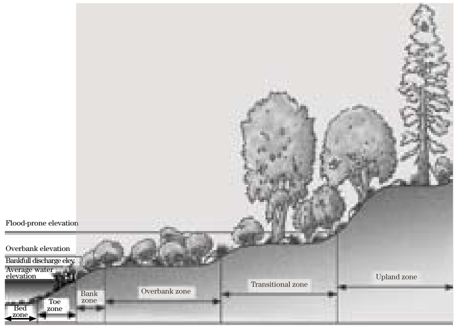
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: unsuited or insufficient habitat and biodiversity	Landscape zones
Unsuited instream physical habitat (lack of pools, large and fine woody debris, channel depth)	Bed, toe, and bank	Stream Habitat Improvement and Management (395)	Measures applied instream for aquatic species habitat can be enhanced with supporting shade, detritus, and debris from adjacent bank and overbank vegetation. The needs of aquatic species using this practice must be coordinated closely with Channel Bank Vegetation (322), Riparian Forest Buffer (391) (if forest potential) and Riparian Herbaceous Cover (390) (if herbaceous only potential)	
Unsuited near-stream habitat (lack of spatial and vertical structure)	Bank and toe	Channel Bank Vegetation (322)	All practices dealing with vegetation must be coordinated to provide needed habitat for the wildlife species of concern in the bank, overbank, and transitional zones	

Table 4–5 NRCS Conservation Practice Standards selection for unsuited or insufficient habitat and biodiversity. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

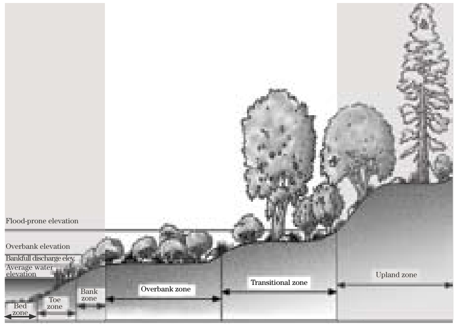
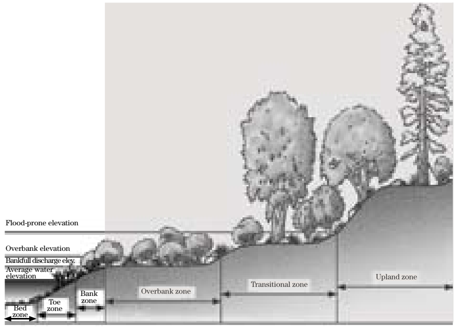
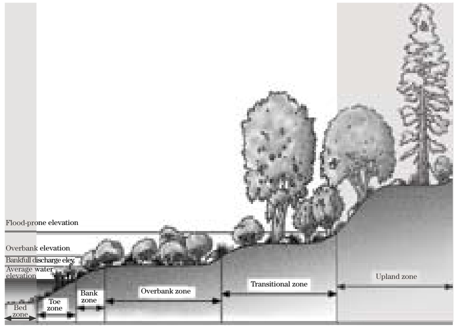
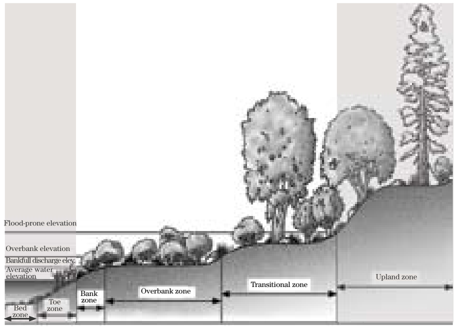
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: unsuited or insufficient habitat and biodiversity	Landscape zones
Unsuited near stream habitat (lack of spatial and vertical structure)	Overbank and transitional	Riparian Forest Buffer (391) Riparian Herbaceous Cover (390)	Depending on the site's plant community potential for forest or herbaceous, Riparian Forest Buffer (391) and Riparian Herbaceous Cover (390) are used singly, but not together	
		Wetland Wildlife Habitat Management (644)	Wetland Wildlife Habitat Management (644) is used on those areas within the overbank and transitional zones that are wetland in nature	
		Prescribed Grazing (528)	For sites grazed by livestock, use Prescribing Grazing (528) to enhance and maintain desired habitat structure. As a general rule for all practices, native plant species are chosen or favored over introduced species	
Obstructions or channel configurations affecting flow capacity or fish passage	Bed, toe, and bank	Clearing and Snagging (326)	Restore vegetation (native species where practical) to all bank, overbank and transitional areas disturbed by use, ingress or egress of obstruction removal equipment	
		Fish Passage (396)	Consider the quality of stream corridor habitat upstream of obstructions before applying Fish Passage (396)	
		Open Channel (582)	Various techniques including channel meander reconstruction at a site will reconfigure the bed and bank topography and influence the overbank extent, soil moisture and vegetation species	

Table 4–5 NRCS Conservation Practice Standards selection for unsuited or insufficient habitat and biodiversity. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: unsuited or insufficient habitat and biodiversity	Landscape zones
Lack of early successional habitat for target wildlife	Bank, toe, overbank, and transitional	Early Successional Habitat Development/ Management (647)	Coordinate plant selection and management of Channel Bank Vegetation (322), Riparian Forest Buffer (391), Riparian Herbaceous Cover (390), and/or Wetland Wildlife Habitat Management (644) to coincide with specifications developed for Early Successional Habitat Development/ Management (647). For sites grazed by livestock, use Prescribed Grazing (528) to enhance and maintain early successional habitat. Field Border (386) can be used at the edge of adjacent upland cropland nearest to the transitional zone to ease movement into and along agricultural land	
Presence of rare or declining native plant communities and impacted wildlife	Bank, overbank, and transitional	Restoration and Management of Declining Habitats (643)	Coordinate specifications and supporting management of all instream and near-stream practices to coincide with specifications developed for Restoration and Management of Declining Habitats (643). Rare and declining sites may need temporary or permanent Use Exclusion (472) to buffer from intensive land use and management. Field Border (386) can be used at the edge of adjacent upland cropland nearest to the transitional zone to ease movement into and along agricultural land	

1/ NRCS National Conservation Practice Standard codes. Specific information for these codes is available at the following Web site: *http://www.nrcs.usda.gov/technical/Standards/nhcp.html.*

Table 4–6 NRCS Conservation Practice Standards selection for unsuited or insufficient production/land use. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system.

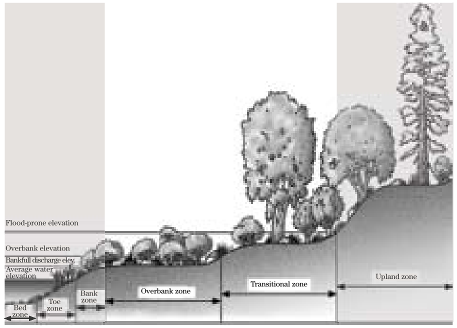
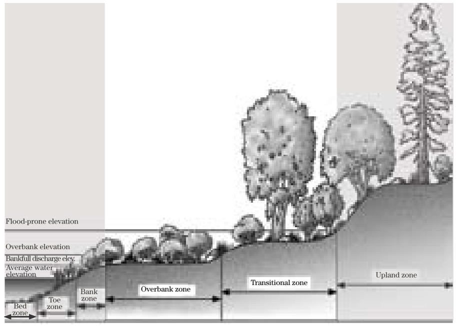
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: unsuited or insufficient production/land use	Landscape zones
Insufficient forage quantity and quality for livestock	Overbank and transitional	Pasture and Hay Planting (512) Range Planting (550), (528) Prescribed Grazing (328) Silvopasture Establishment (381) Forest Stand Improvement (666)	Plant species are chosen and managed for their forage quality and quantity attributes insofar as compatible with site erosion and sediment control, instability improvement, and habitat improvement. For sites with a combined forage and wood production use, Silvopasture (381) and Forest Stand Improvement (666) are used to manipulate the tree or tall shrub overstory to maintain production of forage cultivars in the understory. For native understory species, only Forest Stand Improvement (666) is used to manipulate the tree or tall shrub overstory. To reduce the risk of erosion, sediment, instability and lack of habitat, the area devoted to forage production may need to be reduced particularly in the overbank zone by Use Exclusion (472), Fence (382) or a modification to Prescribed Grazing (328)	
Under or overstocked forest stands for wood products	Overbank and transitional	Riparian Forest Buffer (391) Forest Stand Improvement (666)	Tree and shrub species are chosen and managed for their wood quality and quantity attributes insofar as compatible with site erosion and sediment control, instability improvement, and habitat improvement. To reduce the risk of erosion, sediment, instability and lack of habitat, the area devoted to wood harvesting may need to be reduced particularly in the overbank zone. Certain techniques (directional felling and skidding) could be used for harvesting in the overbank zone on a periodic basis to maintain vigor of overstory and understory species	

Table 4–6 NRCS Conservation Practice Standards selection for unsuited or insufficient production/land use. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

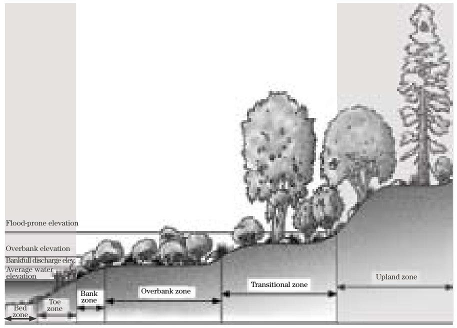
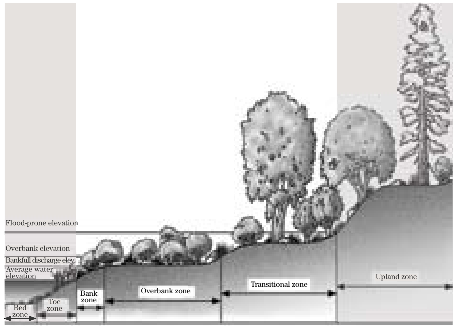
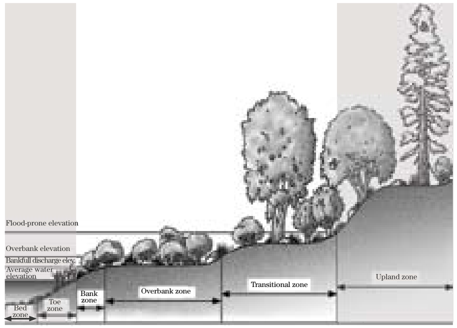
Impairment	Landscape zones	Primary NRCS Conservation Practice Standards	Considerations and effects: unsuited or insufficient production/land use	Landscape zones
Unimproved recreational opportunities	Bank, overbank, and transitional	Recreation Area Improvement (562) Stream Habitat Improvement and Management (395)	Vegetation is established and/or manipulated to enhance specific recreational uses suited to the site and compatible with site erosion and sediment control, instability improvement, and habitat improvement Recreation structures, land grading, and trails may be concurrently applied with vegetation management. Manipulation of bank and overbank conditions for recreation purposes can be detrimental if not tied to and compatible with a geomorphic/hydraulic analysis at bankfull and flood stages	
Insufficient moisture for desired plant communities	Bank, overbank, and transitional	Irrigation System Microirrigation (441) Sprinkler (442) Surface and Subsurface (443)	A suitable irrigation system with associated practices (Pipeline (430), Irrigation Water Conveyance (428)) can be installed to overcome moisture-deficit conditions detrimental to plant growth and establishment. Irrigation is particularly effective on overbank and transitional zones on incised channel reaches, but it can be costly. To minimize costs, select plant materials that, when well established, can reach their site potential size using available amounts and timing of natural precipitation	
Insufficient nutrients for desired plant communities	Bank, overbank, and transitional	Nutrient Management (590)	Meeting nutritional requirements for existing or new plantings can accelerate their growth, establishment, and function. This is particularly the case with nonnative herbaceous species. Addition of nutrients must be carefully balanced with the nutrient loading at the site and any incoming nutrients in surface and subsurface flows. Nutrition becomes less important as plants and onsite nutrient cycling become well established	

Table 4–6 NRCS Conservation Practice Standards selection for unsuited or insufficient production/land use. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

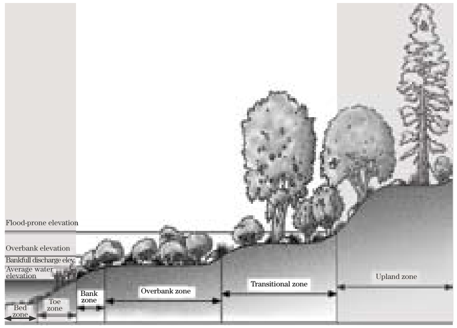
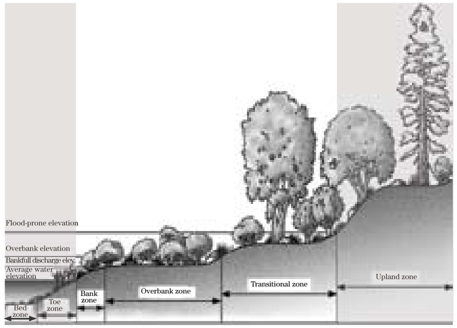
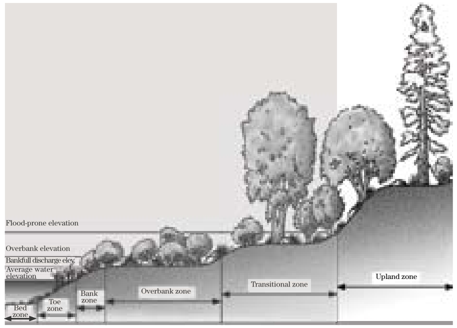
Impairment	**Landscape zones**	**Primary NRCS Conservation Practice Standards**	**Considerations and effects: unsuited or insufficient production/land use**	**Landscape zones**
Presence of pests	Bank, overbank, and transitional	Pest Management (595)	A first and foremost step in pest management is selection of plant materials that help achieve desired site conditions and resist local pests. If pests become problematic (weeds, insects, diseases, animals, and other organisms including invasive and noninvasive species), sufficient control helps assure continued function of existing plantings and establishment of new plantings. A variety of control methods are available including cultural, biological, and chemical which must be matched to the problem, the site, and the vegetation. In all cases, pest management design includes an environmental risk analysis to assure that additional problems are not caused (excess pesticides in surface or ground waters)	
Lack of or need for a conveyance structure or travel way across a channel to facilitate land management	Bank, overbank, and transitional	Stream Crossing (578)	Crossings are located where the streambed is stable or where grade control can be provided to create a stable condition. Crossings are typically not placed in shaded conditions if the stream corridor is grazed and there is a potential for livestock loafing in the stream. Stream crossings allow for the passage of water, fish and other aquatic animals within the channel during all seasons of the year. Restore vegetation (native species where practical) as soon after construction as possible to all bank, overbank and transitional areas disturbed by use, ingress or egress of construction equipment)	

Table 4–6 NRCS Conservation Practice Standards selection for unsuited or insufficient production/land use. Guidance is shown using impairment category and landscape zone, with notes on considerations and effects. Impairments and practices[1/] are listed in general order of consideration for use in formulating a resource management system—Continued

Impairment	**Landscape zones**	**Primary NRCS Conservation Practice Standards**	**Considerations and effects: unsuited or insufficient production/land use**	**Landscape zones**
Point source and nonpoint source pollution, water diversions, flow modifications caused by structures (dams), hydrologic modifications caused by urbanization and other changed land uses	Upland	Nutrient Management (590) Residue and Tillage Management (329, 344, 345, 346), Conservation Crop Rotation (328) Conservation Cover (327) Filter Strip (393) Terrace (600) Water and Sediment Control Basin (638) Waste Treatment and Storage (313, 359. 367, 629, 633, 635) Sediment Basin (350) Subsurface Drain (606) Surface Drainage (606, 607, 608) Constructed Wetland (656) – and others	Protection of watershed areas that contribute water, sediment, and chemicals to the stream may be required to reach the restoration goals of the project. Watershed land use and cover, conservation treatments, and the amount of land converted to urban or suburban uses can have significant effects on runoff to the stream, both in terms of lag times and peak flows	

1/ NRCS National Conservation Practice Standard codes. Specific information for these codes is available at the following Web site: *http://www.nrcs.usda.gov/technical/Standards/nhcp.html*

Figure 4–7 The planner is cautioned to clearly understand the degree and extent of impairments (both onsite and offsite), applicable landscape zones within the CMU, and specific client objectives before considering the selection of conservation practices and vegetation types.

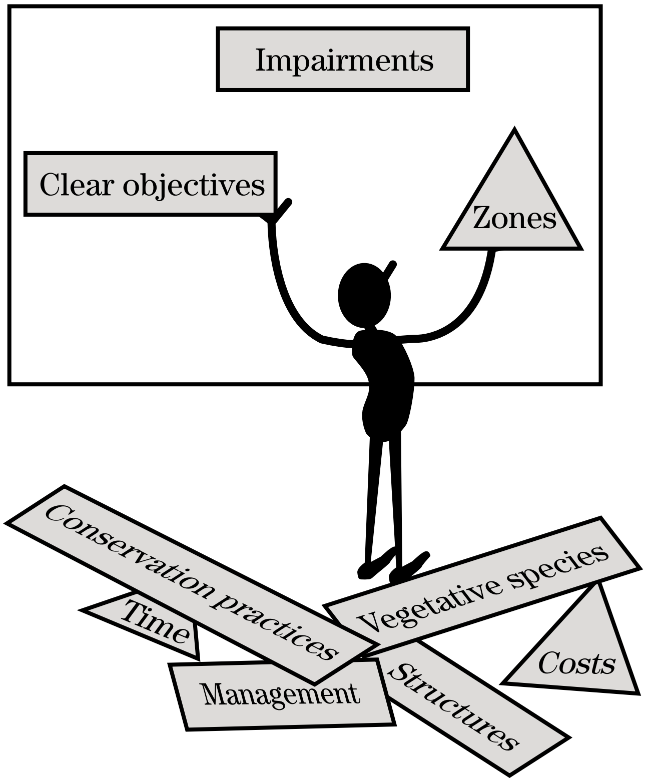


Figure 4–8 Terraces, conservation tillage, and conservation buffers form a system to treat the watershed and protect the stream (Woodbury County in northwestern IA)

(c) Formulating a resource management system for stream restoration

After studying table 4–3 and the applicable conservation practice standards in the FOTG, the planner will have a preliminary idea of the conservation practices that can address site problems and client objectives. Some practices will be either selected or eliminated, based on degree of effect, cost, duplication of outcome (mulching in place of critical area planting for erosion control), or perhaps a change in the client's objectives during the formulation process. This stage of planning (steps 5, 6, and 7) is an iterative phase of the process that must be accomplished with the client. The product of this stage is a plan for the CMU, listing the practices and their locations, types of structures and vegetation, and management requirements. Although more thorough information about certain practices (design options, costs, materials) is sometimes needed by the client to make informed decisions, preparing detailed or preliminary specifications or designs for any practice is not the intent of this phase of planning.

A critical strategy in formulating an RMS for a stream corridor CMU is the interplay between candidate practices in achieving desired conditions. The scenario below illustrates two RMSs developed for a stream corridor-grazing situation. Note how the characteristics of plant materials affect RMS formulation.

Example 1: Streambank erosion control using an RMS that emphasizes management elements for the designed solution

Given benchmark conditions: A CMU at one edge of a farm has a third order stream with fairly wide overbank and transitional zones. Channel banks have accelerated erosion, and the overbank zone has periodic scour erosion; both can be controlled by vegetative means. The client wishes to graze livestock on the entire stream corridor/riparian CMU (both sides of the channel) and use the stream as a water source. Livestock cross the channel at many locations, causing soil compaction and additional bank erosion.

- *RMS Option A*—The Channel Bank Vegetation (322) standard specifies that suitable erosion control plants with low palatability will be used in the bank zone. Pasture and Hay Planting (512) specifies the establishment of forage species with fibrous root systems in the overbank zone. Specifications for Prescribed Grazing (528) identify certain plants in the overbank zone as key forage species that are closely monitored to maintain protection against flood scour erosion. Also, incidental use and trampling damage of bank zone vegetation is monitored, and the livestock are removed immediately when any degradation or loss of vigor is detected. A Stream Crossing (578) in the form of a rock ford is installed to concentrate livestock movement across the channel (livestock choose the ford because of ease of crossing).
- *RMS Option B*—Both Channel Bank Vegetation (322) and Critical Area Planting (342) specify that suitable erosion control plants with low palatability will be used in the bank and overbank zones, respectively. Livestock Use Exclusion (472) is installed in the form of a Fence (382) between the overbank and transitional zones on both sides of the channel. A gated and fenced Stream Crossing (578) is installed to allow ready access to the far side of the CMU and periodic grazing of the bank and overbank zones. Livestock periodically graze the bank and overbank zones for short periods with close monitoring to maintain erosion control (a requirement in the Prescribed Grazing (528) specifications). Because access to water is variable, a Watering Facility (614) is developed within the transitional zone on the far side of the channel. This also improves use of forage on both sides of the stream.

Summary: Both RMSs meet quality criteria and client objectives for livestock grazing. RMS option B affords the greatest assurance that resource concerns and practice purposes will be met, but likely at a higher investment in installation costs and management time. Additional fencing in this option can impact certain types of wildlife and pose a periodic maintenance chore if fences are damaged by floods. RMS option A may require additional monitoring to maintain desired conditions.

Other situations and examples exist for stream/riparian CMUs with cropland, wood production, recreation, or other intensive land uses. Obviously, those sites with little or no demands for crops, wood, forage, or recreation will have the fewest planning constraints and interplay between practices. However, streams and associated riparian areas are typically landscapes with favorable moisture and potential for exploitation. Intensive use of such landscapes will remain the rule, rather than the exception. Planners will need to think through each scenario using the process and techniques presented in this section to formulate sustainable RMSs. Consultation with specialists for complex situations is advised.

Example 2: Streambank erosion control using an RMS that emphasizes a combination of vegetation and structural design elements

Given benchmark conditions: Severe streambank erosion is attacking stream banks in a suburban area, with damage to utilities, loss of land, and degraded habitat. The stream is enlarged, excessive sediment yield, and loss of property and utility services are concerns. In some locations, sewer pipes and gas lines are in imminent danger of collapse. The site constraints are such that relocation of these utilities is not possible. The streambed appears to be stable with no active incision.

- *RMS options*—The objectives are to solve the bank erosion problem, protect the utilities (water and sewer lines) and property, and retain flow-carrying capacities. Measures that are considered include Streambank and Shoreline protection (580) and Channel Bank Vegetation (322). It would be necessary to confirm that the bed is indeed stable. If it is not, some grade control may be necessary. The emphasis will be on protecting the streambank from future undercutting and collapse, so that the toe will be stabilized with rock riprap or gabions. The design will focus on the slope stability that can be achieved with the least impact on land (backyards and easement areas) and result in a stable bank condition. Soil bioengineering will be used to establish woody vegetation that will protect the bank from the erosion of flowing water and also knit together the bank with roots. Where riparian infrastructure is in imminent danger, harder structures such as gabions, sheetpile, and ACBs will be considered. Final design of the solution will depend on hydraulic analyses for the site.

Example 3: Streambank erosion control using an RMS that emphasizes a reliance on vegetative design elements

Given benchmark conditions: Streambank erosion is present along a long stretch of an outside meander bend. This erosion is impacting a farm in a rural area. At one point, a dirt farm road is in jeopardy. No utilities or riparian infrastructure is threatened. The streambed appears to be stable with no active incision. Minimal funds are available for any work.

- *RMS options*—The objectives are to solve the bank erosion problem. The dirt road itself may be relocated. Measures that are considered include Streambank and Shoreline Protection (580) and Channel Bank Vegetation (322). The design may focus on soil bioengineering practices including vertical bundles, live stakes and vegetated stream barbs. All of these techniques, once designed, could be constructed without construction equipment. A site assessment would need to be made to see if Livestock Use Exclusion (472) in the form of a Fence (382) between the overbank and transitional zones on the bank would also reduce some of the stress.

Example 4: Streambank erosion control using an RMS that emphasizes a complete reconstruction of a natural stream channel

Given benchmark conditions: A natural channel was straightened and widened to provide flood control benefits to rural farmland. Historically, the stream had supported healthy populations of fish which are now considered to be threatened. This old channelization of the stream has resulted in a loss of habitat and impacts to the threatened fish species. Riparian land use has now changed such that the original flood control purposes of the project are no longer an issue.

- *RMS options*—The objectives are to restore the stream so that it will support a population of the target fish species. A healthy stream corridor is necessary to achieve this goal and to solve the bank erosion problem. Measures that are considered include Streambank and Shoreline Protection (580), Channel Bank Vegetation (322), Channel Stabilization (584), Open Channel (582), Restoration and Management of Declining Habitats (643), Riparian Forest Buffer (391), and Stream Habitat Improvement and Management (395). The design may focus on a complete recreation of the stream channel. This will involve determining a stable planform, section, and profile of the stream. Techniques which serve to stabilize the grade and protect the banks in targeted areas may be necessary. Instream and edge habitat features, such as soil bioengineering practices including vertical bundles, live stakes, and vegetated stream barbs, may also be used. The analysis, design, and construction effort for such a project may be significant.

(d) Specifications and designs at the conservation practice level

After examining the RMS alternatives and associated practices with the planner, the client makes decisions about the CMU. With a definitive plan of what will occur, the preliminary specifications and designs for stream corridor restoration can be formulated. This is the start of NPPH planning step 8, Implement the Plan. Individual conservation practice standard criteria contained in the local FOTG will guide the planner in:

- location, extent, design specifications, and operation of physical structures
- plant species selection, layout, and spacing
- site preparation and planting techniques
- site management to progress to and maintain desired site conditions

Generic specifications and designs will not be presented here because of the wide array of ecological regions, site conditions, implementation techniques, and plant materials. However, the considerations and effects column in tables 4–4, 4–5, and 4–6 provides important considerations for developing specifications and designs. The planner is advised to carefully study the tables and local FOTG practice standard criteria. During the development of detailed specifications and designs, the planner and client may decide to modify the original RMS. This is a normal iteration of the planning process.

654.0405 Evaluating success of stream restoration designs

The main purpose for evaluating the restoration treatment (planning step 9 in table 4–1) is to determine if desired future conditions are being achieved at the expected level and rate. In the NRCS CPP, desired conditions in relation to existing benchmark conditions are first established and documented in planning step 4 and later used in step 6 to evaluate alternative RMSs. During treatment evaluation, two basic questions are answered:

- Have practices been installed as planned?

  This is answered by examining the plan, implementation schedule, designs in planning steps 7 and 8 (table 4–1), and confirming that practices have been installed. Plans are subject to change and modification, so it is important to verify that practices have actually been applied when and where specified.

- Are desired future conditions being achieved at the specified level and timing?

  The desired conditions were originally specified during planning step 4 and used again in step 6 to evaluate the expected performance of RMS options and, ultimately, help the client choose the best one. To respond to this question, conditions may be measured on an absolute basis (tons of sediment passing a reference point, presence or absence of instream bars, soil loss calculated in scour areas), on an interpretive basis (some kind of index score based on habitat components), or using modeling where before and after values for model variables compared.

The specific measurements and techniques used in planning steps 3 and 4 (table 4–1) are again remeasured during the step 9 evaluation. The results of the evaluation or progress towards success can be expressed in terms of yes or no or as a percentage of improvement. The following examples illustrate two cases of treatment evaluation.

Case 1

Given: Bank erosion has a recession rate of about 0.5 foot per year. Site and upstream conditions have remained constant during the past 10 years. The RMS was developed based on determination that bank erosion is controllable at the site, using primarily Channel Bank Vegetation (322) and Riparian Forest Buffer (391). The recession rate is determined to be of an accelerated nature (above and beyond natural, geologic erosion for the stream type). The desired condition is no evidence of bank recession within 10 years of the last applied RMS practice.

Evaluation: RMS practices have all been applied, with the last practice installed 10 years ago. There is no visual evidence of bank recession. The evaluation indicates yes, the RMS is successful.

Case 2

Given: The client owns a significant part of an upstream watershed. The Agricultural Nonpoint Source Pollution Model (AGNPS) has been used to estimate sediment production at the lowest downstream point of the client's stream system. The stream corridor CMU is continuous along both sides of the stream system and excludes agricultural and other intensive land uses to 150 feet on each side of the stream (perpendicular to streamflow) as measured from the bankfull level. The desired condition is a 70 percent reduction of annual sediment within 10 years of the last applied RMS practice.

Evaluation: RMS practices which include riparian vegetation establishment have all been applied, with the last practice installed 10 years ago. Conditions have been reassessed, and the model rerun. Results indicate there has been only a 30 percent decrease in annual sediment. The evaluation indicates the RMS is not yet successful. If the planner and client are dissatisfied with the evaluation outcome, they can decide to reassess the efficacy of the RMS, reset the target or threshold for success, increase the allowable response time, or use a more exacting model (if available) to improve the sediment yield estimate.

The evaluation procedure presented above is based on the assumption that desired future conditions have been well established during the planning process. If this is not the case, land and water treatment evaluation may require the development of a special strategy in consultation with interdisciplinary specialists to determine the effects of applied RMSs. A challenge with a retroactive approach is re-creating pretreatment conditions and estimates of measurements.

654.0406 Conclusion

The process for designing stream restoration solutions is an integral part of the CPP. Solutions may result in simple designs that may only require changes in management and removal of disturbance factors. However, depending on the complexity of the problem, a solution that integrates both management and structural approaches may be needed. Structural approaches may include design elements that integrate soil materials, plants, large woody material, concrete, rock, steel, or other materials. In either case, the focus should be on solving the stated problems, as well as conserving and restoring natural resources to the extent possible. Local conditions determine what kinds of data are needed for preliminary and detailed designs, and the design process will vary according to the types and number of design elements, complexity of the project, and degree of risk involved, as described in NEH654.02.

The best design will be one that results in minimal maintenance and is also self-sustaining. This may not always be possible, depending on the specific goals and objectives and overall constraints, especially in areas with impaired watersheds, rigid constraints of land ownership, or jurisdictional requirements.

The following chapters provide more detailed information on the use and applicability of various tools for analyzing and designing stream restorations. Some are well entrenched in scientific research and experience, while others reflect the state of the art.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 5 Stream Hydrology

Issued August 2007

Cover photo: Quantifying the flow of the stream involves analysis of rainfall/runoff, storm recurrence intervals, and watershed and flood plain conditions.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 5 Stream Hydrology

Contents

Tables

Figures

Chapter 5 Stream Hydrology

654.0500 Purpose

Stream restoration design should consider a variety of flow conditions. These flows should be considered from both an ecological, as well as a physical perspective. Many sources and techniques for obtaining hydrologic data are available to the designer. This chapter provides a description of the flows and their analyses that should be considered for assessment and design. The computation of frequency distributions, with an emphasis on the log-Pearson distribution as provided in the U.S. Water Resources Council (WRC) Bulletin 17B, is addressed in detail. Examples have been provided to illustrate the methods. Transfer equations, risk, and low-flow methods are also addressed. Finally, this chapter describes advantages and limitations of four general approaches widely used for estimating the channel-forming discharge or dominant discharge.

654.0501 Introduction

Hydrologic analysis has historically been the starting point for channel design. Current and future flows were estimated, then the designer proceeded to further analysis. However, the complexities of stream restoration projects often require that hydrologic analysis be conducted in close coordination with a study of stream geomorphology and stream ecology.

Hydrologic computations are an integral part of any stream design and restoration project. However, design objectives for a stream restoration project cannot adequately be met by assessing channel behavior for only a single discharge. A stream restoration project usually has several design flows selected to meet various objectives. For example:

- Estimates of future flow conditions are often required to properly assess project performance over the long term.
- Estimates of low flows such as 7-day low flow often define critical habitat conditions.
- Estimates of channel-forming discharges are used to estimate stable channel dimensions.
- Flood flow estimates are used to assess stability of structures and flood plain requirements, as well as for scour depth prediction.

Many techniques are available to the designer for determining the various discharges used in assessment and design. The level of accuracy required for the different hydrologic analyses, as well as the need to estimate the different flows, is dependent on the site-specific characteristics of each project. Therefore, it is important to understand not only what each design flow represents, but also the underlying assumptions and the limitations of the techniques used to estimate the flow.

654.0502 Overview of design discharges

A description of some of the various types of design discharges is provided in this section. Although a project may not require the use of all of these flows for design, the hydraulic engineer/designer should still consider how the project will perform during a range of flow conditions.

(a) Low flows

Design of a low-flow channel may be required as part of a channel restoration. Normally, the design of the project for low flows is performed to meet biological goals. For instance, summer low flows are often a critical period for fish, and project goals may include narrowing the low-flow channel to provide increased depths at that time. Design flows may also be necessary to evaluate depths and velocities for fish spawning areas or fish passage during critical times of the year. Coordination with the biologist on the study team and familiarity with regulatory requirements are essential to make sure an appropriate flow (or range of flows) is selected.

(b) Channel-forming discharge

A determination of channel-forming discharge is used for many stability assessment tools and channel design techniques. The channel-forming discharge concept is based on the idea that for any given alluvial stream there exists a single discharge that, given enough time, would produce the width, depth, and slope equivalent to those produced by the natural flow in the stream. This discharge, therefore, dominates channel form and process. The channel-forming discharge concept evolved from the dominant discharge concept used to design irrigation canals in the latter part of the nineteenth and early part of the twentieth centuries. It is recognized, however, that the channel-forming discharge is a theoretical concept and may not be applicable to all stream types, especially flashy and ephemeral streams.

Depending on the application, channel-forming discharge can be estimated by several methods, based on:

- bankfull indices
- effective discharge
- specific recurrence interval
- drainage area

The distinction between channel-forming discharge and the other deterministic discharges is frequently confused, as the terms are used interchangeably. This chapter describes advantages and limitations of the four widely used general approaches.

(c) High discharge

The reaction of a channel to a high discharge can be the impetus for a stream restoration project. An identified high-flow event is often used in the design and specification of a design feature. The choice of a maximum design flow for stability analysis should be based on project objectives and consequences of failure. For example, the 100-year discharge might be used to design bank protection in a densely populated area, while a 10-year discharge might be appropriate in a rural stream. Other examples include:

- It may be a requirement to demonstrate that a proposed project will not raise the water surface profiles produced by a 5-year event (often referred to as nuisance-level flooding) sufficiently to adversely affect riparian infrastructure such as county roads, parks, and playgrounds.
- A significant flood event (typically no smaller than the 10-year frequency discharge) is used to estimate forces and compute scour depths at proposed habitat features constructed with logs. The goal is that these hard project features will withstand a flood of this magnitude without major damage, movement, or flanking.
- A significant flood event may have caused severe bank erosion, initiating a request to fix the erosion problems. It may be a requirement that any proposed fix provide stabilization that will be able to withstand a repetition of the forces produced by this event.
- It may be a requirement of the project design that the impacts of a 25-year flood event be limited to minor deposition of sediment and de-

bris; localized scour, erosion, and stone movement; and erosion of vegetation.

- Often the impact on the water surface profile for the 100-year flood event must be submitted as part of the project's permitting requirements. In many cases, it is a requirement to demonstrate that a proposed project will not result in increases to the 100-year flood plain area.
- It may also be necessary to estimate the flood-level reduction of a project on a 50-year flood event or for a larger event (such as the design discharge for a flood control project.).

(d) Flow duration

A flow-duration curve represents the percentage of time that a flow level is equaled or exceeded in a stream. This analysis is done for sediment transport assessments and ecological assessments, as well as for assessments of the duration of stress on soil bioengineering bank stabilization techniques.

Comparing flow-duration curves of different systems in a single basin or across a larger physiographic region can lend useful insight into a variety of watershed concerns. Issues such a flow contributions from ground water, watershed geology and geomorphology, and degree of flow regulation can also be examined, in part, with such a comparative analysis.

(e) Seasonal flows

It is often important to determine how the proposed restoration project will perform with low or normal flows. In addition, seasonal flow variations can have critical habitat importance. For example, a project goal may include a minimum flow depth during a critical spawning period for anadromous fish species and a lower minimum depth for resident fish species. The same techniques used to develop flow-duration curves for sediment analysis can also be used to assess and design for habitat conditions.

In many states, the U.S. Geological Survey (USGS) has developed regional regression curves for the critical flow periods. This might be the 10-year, 7-day low flow.

(f) Future flows

Estimates of future flow conditions are often required to properly assess future project performance. In some areas, the USGS has developed regional peak flow frequency curves that include a variable that can be used to estimate the impact of future changes in land use, such as an increase in the percent of impervious area for urban development. For example, typically 10 to 20 percent of the average rainfall event becomes runoff for an undeveloped watershed, while 60 to 70 percent of the average rainfall event becomes runoff for a developed (urbanized) watershed. However, regional equations typically do not include this variable, and a hydrologic model must be used to determine the change in the peak flow.

(g) Regulatory

Some Federal and state agencies have established minimum streamflow requirements for fish habitat. For example, the Federal Emergency Management Agency (FEMA) has established flood hazard maps for the 100-year and 500-year flood events and has estimated the flow associated with these events. Consultation with the appropriate authorities is needed if there is a possibility that a project will impact this flood level. Also, the U.S. Environmental Protection Agency (EPA) has established minimum flow requirements in many areas. These should be considered when determining the required design flows. While the determination and maintenance of these established flows may be based more on administrative decisions than current hydrologic data and analysis, they can be a critical component of a stream analysis or project design. A further description of regulatory requirements is provided in NEH654.17.

654.0503 Probability

Streamflow events are typically referred to by their return period. A return period of Rp means that in any given year, the event has a probability of occurrence (P):

$$P = \frac{1}{Rp} \qquad \text{(eq. 5–1)}$$

For example, a 100-year storm has an annual probability of occurrence of P=1/Rp=1/100=0.01 or 1 percent. Therefore, it is synonymous to speak of a 1 percent storm as a 100-year storm.

Risk is defined as the probability that one or more events will exceed a given magnitude within a specified period of years. Risk is calculated by means of the binomial distribution given in simplified form as follows:

$$R = 1 - (1 - P)^n \qquad \text{(eq. 5–2)}$$

where:
R = risk in decimal number
P = exceedance probability of event
n = number of years

The risk formula may be applied to many different scenarios, including the following:

- The likelihood of a 100-year flood occurring at least once in the next 100 years is 63 percent

$$R(100) = 1 - \left(1 - \frac{1}{100}\right)^{100} = 0.63$$

- The likelihood of a 100-year flood occurring at least once in the next 50 years is 39 percent

$$R(100) = 1 - \left(1 - \frac{1}{100}\right)^{50} = 0.39$$

- The likelihood of a 100-year event occurring at least once in 1,000 years is 99.996 percent, a very high probability, but never 100 percent.
- There is a 97 percent risk of a bankfull, 2-year recurrence interval discharge (50% annual chance) being exceeded in the next 5 years.
- Likewise, the 10-year discharge has a 41 percent risk of being exceeded in the next 5 years, or conversely, a 59 percent chance of not being exceeded.

Expected probability is a measure of the central tendency of the spread between confidence limits. Expected probability adjustment attempts to incorporate effects of uncertainty in application of frequency curves. The adjustment lessens as the stream record lengthens. Use of expected probability adjustment is often based on a policy decision.

It is important to note that a precipitation event may not have the same return period as a flow event. On small watersheds, a 100-year rainfall event may produce a 100-year flow or flood event. On large watersheds, however, the 100-year flow event may be produced by a series of smaller rainfall events. This distinction should particularly be kept in mind by the practitioner who is working with projects in large watersheds.

Equation 5–2 can also be rearranged to aid in determining a design storm (see example 1).

Example 1: Risk-based selection of design storm

Problem: A bank protection project involves considerable planting and soil bioengineering. However, the proposed planting would not be able to withstand the design storm until firmly established. The designer is asked to include reinforcement matting that will have a 90 percent chance of success over the next 5 years. What is the design storm?

Solution:

Step 1. Calculate the probability of an event occurring that is larger.

90 percent chance of success means that there is a 10 percent chance that an event will be larger.

Step 2. Rearrange equation 5–2 as follows:

$$R = 1 - \left(1 - P\right)^{n}$$

$$P = 1 - \sqrt[n]{\left(1 - R\right)}$$

And solve as:

$$\begin{aligned} P &= 1 - \sqrt[5]{1 - 0.1} \\ &= 0.0208 \end{aligned}$$

Step 3. Rearrange equation 5–1 as follows:

$$P = \frac{1}{R_p}$$

$$R_p = \frac{1}{P}$$

And solve as:

$R_p = 47.9$ or about a 50-year storm

654.0504 Gage analysis for flow frequency

Flow frequency analysis relates the magnitude of a given flow event with the frequency or probability of that event's exceedance. If a stream gage is available and the conditions applicable, a gage analysis is generally considered preferable, since it represents the actual rainfall-runoff behavior of the watershed in relation to the stream. A variety of Federal, state, and local agencies operate and maintain stream gages. Currently, the USGS operates about 7,000 active stream gaging stations across the country. Such data are also available for about 13,000 discontinued gaging stations. Historical peak flow data can be found at the following USGS Web site at:

http://nwis.waterdata.usgs.gov/usa/nwis/peak

It is important to determine if the present watershed conditions are represented by the stream gage record or if there has been a significant change in land use. If there has been a significant increase in urbanization, the historical record may not represent current conditions. While many hydrologic techniques are available for the prediction of frequency of flow events, this chapter presents concepts and techniques for analyzing peak flows and, to a lesser extent, low flows, following the recommendations of Guidelines for Determining Flood Flow Frequency, Bulletin 17B (WRC 1981).

Flow event data may be analyzed graphically or analytically. In graphical analysis, data are arrayed in order of magnitude, and each individual flow event is assigned a probability or recurrence interval (plotting point). The magnitudes of the flow events are then plotted against the probabilities, and a line or frequency curve is drawn to fit the plotted points. Peak flow data are usually plotted on logarithmic probability scales, which are spaced for the log-normal probability distribution to plot as a straight line. Data are often plotted to verify that the general trend agrees with frequency curves developed analytically.

(a) Analysis requirements and assumptions

In performing a frequency analysis of peak discharges, certain assumptions need to be verified including data independence, data sufficiency, climatic cycles and trends, watershed changes, mixed populations, and the reliability of flow estimates. The stream gage records must provide random, independent flow event data. These assumptions need to be kept in mind, otherwise, the resultant distribution of discharge frequencies may be significantly biased, leading to inappropriate designs and possible loss of property, habitat, and human life.

Data independence

To perform a valid peak discharge frequency analysis, the data points used in the analysis must be independent, that is, not related to each other. Flow events often occur over several days, weeks, or even months, such as for snowmelt. Only the peak discharge for each flow event should be used in the frequency analysis. Secondary peaks are dependent on each other and are not appropriate for use in a frequency analysis. Using secondary peaks would result in lower peak flows for a given frequency, since it would exaggerate the frequency of the magnitude of the event. It is common practice to minimize this problem by extracting annual peak flows from the streamflow record to use in the frequency analysis.

Data sufficiency

Gage records should contain a sufficient number of years of consecutive peak flow data. To minimize bias, this record should span both wet and dry years. In general, a minimum of 10 years is required (WRC 1981). However, longer gage records are generally recommended to estimate larger return periods and/or if there is a potential bias in the data set. This is addressed later in the climate bias example. If a gage record is shorter than optimum, it may be advisable to consider other methods of hydrologic estimations to support the gage analysis.

It is also important to use data that fully capture the peak for peak flow analysis. If a stream is flashy (typical of small watershed), the peak may occur over hours or even minutes, rather than days. If daily averages are used, then the flows may be artificially low and result in an underestimate of storm event values.

Therefore, for small watersheds, it may be necessary to look at hourly or even 15-minute peak data.

Annual duration

Gage analysis for flows with return intervals in excess of 2 years is typically conducted on annual series of data. This is the collection of the peak or maximum flow values that have occurred for each year in the duration of interest. Each year is defined by water year (Oct. 1 to Sept. 30).

Partial duration

When the desired event has a frequency of occurrence of less than 2 years, a partial duration series is recommended. This is a subset of the complete record where the analysis is conducted on values that are above a preselected base value. The base value is typically chosen so that there are no more than three events in a given year. In this manner, the magnitude of events that are equaled or exceeded three times a year can be estimated. Care must be taken to assure that multiple peaks are not associated with the same event, so that independence is preserved.

The return period for events estimated with the use of a partial duration series is typically 0.5 years less than what is estimated by an annual series (Linsley, Kohler, and Paulhus 1975). While this difference is fairly small for large events (100-yr for a partial vs. 100.5-yr for an annual series), it can be significant at more frequent events (1-yr for a partial vs. 1.5-yr for an annual series). Therefore, while an annual series may be sufficient to estimate the magnitude of a channel-forming discharge, it may not provide a precise estimate for the actual frequency of the discharge. It should also be noted that there is more subjectivity at the ends of both the annual and partial duration series frequency curves.

Climatic cycles and trends

Climatic cycles and trends have been identified in meteorological and hydrological records. Cycles in streamflow have been found in the world's major rivers. For example, Pekarova, Miklanek, and Pekar (2003) identified the following cycles of extreme river discharges throughout the world (years): 3.6, 7, 13, 14, 20 to 22, and 28 to 29. Some cycles have been associated with oceanic cycles, such as the El Niño-Southern Oscillation in the Pacific (Dettinger et al. 2000) and the North Atlantic Oscillation (Pekarova, Miklanek, and Pekar 2003). Trends in streamflow volumes and peaks are less apparent. However, trends in streamflow timing are likely, as have been presented in Cayan et al. (2001) for the western United States.

The identification of both cycles and trends is hampered by the relatively short records of streamflow available, as streamflow data increase, more cycles and trends may be identified. However, sufficient evidence does currently exist to warrant concern for the impact of climate cycles on the frequency analysis of peak flow data, even with 20, 30, or more years of record.

When performing a frequency analysis, it can be important to also analyze data at neighboring gages (that have longer or differing period of records) to assess the reasonableness of the streamflow data and frequency analysis at the site of interest. Keeping in mind the design life of the planned project and relating this to any climate cycles and trends identified during such a period, one can identify, in at least a qualitative manner, the appropriateness of the streamflow data. A case study is provided in example 2 that describes an analysis completed to assess climatic bias.

Paleoflood studies use geology, hydrology, and fluid dynamics to examine evidence often left by floods and may lead to a more comprehensive frequency analysis. Such studies are more relevant for projects with long design lives, such as dams. For more information on paleoflood techniques, see Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology (House et al. 2001).

Watershed changes

Land use and water use changes in watersheds can alter the frequency of high flows in streams. These changes, which are primarily caused by humans, include:

- urbanization
- reservoir construction, with the resulting attenuation and evaporation
- stream diversions
- construction of transportation corridors that increase drainage density
- deforestation from logging, infestation, high intensity fire
- reforestation

Example 2: Climatic bias case study

The Willow Creek watershed of the northern San Juan Mountains of Colorado has a wide range of stream-related projects being designed. This includes the remediation of drainage from tailings piles and mines; a braided to sinuous stream restoration; and the rehabilitation of a flume which carries flood flow through the town of Creede, Colorado. Discharge frequency estimates are necessary for all of these projects. The USGS had a gage operable in Creede for 32 years, from 1951 through 1982. Flow peaks measured for this 35.3-square-mile watershed ranged from 66 to 410 cubic feet per second. Thirty-two years of data is usually a reasonable record length for performing a frequency analysis. However, when six historic events were taken into account, the results of the 32-year frequency analysis appeared to be biased on the low side.

Records show that the historic events (with estimated peak flows of 1,200 ft^3/s and greater) occurred in the first half of the century in the Willow Creek watershed. This leads to a series of issues that should be examined:

- Were these historic peak estimates computed properly?
- Were these high flows random occurrences?
- Does this confliction indicate that all of the systematic record was recorded during a period of lesser precipitation and runoff?
- Or is some other mechanism occurring?

To shed more light on this situation an analysis was performed on two nearby, primarily undeveloped, watersheds: Carnero Creek, a 117-square-mile watershed with 78 years of record, and LaGarita Creek, a 61-square-mile watershed with 81 years of record. A sensitivity analysis was performed to assess the impact of a varying period of record. It was assumed that the records at these two locations cover three different periods: the actual period of record, the first half of the record, and the second half of the record. Frequency analyses were performed on each of these records. Results from this analysis are shown in table 5–1.

Table 5–1 Sensitivity analysis on gage record, Willow Creek case study

Gage ID	**08230500**			**Gage ID:**	**08231000**		
Stream	**Carnero Creek**			**Stream:**	**LaGarita Creek**		
Drainage area:	**117 mi^2**			**Drainage area:**	**61 mi^2**		
Years of record:	**1920–23, 26–28, 30, 32–2001**			**Years of record:**	**1920, 22–2001**		
	Log-Pearson results				**Log-Pearson results**		
	Full	**First half**	**Second half**		**Full**	**First half**	**Second half**
Record (yr)	78	39	39	Record (yr)	81	40	41
200-yr (ft^3/s)	1,690	1,780	695	200-yr (ft^3/s)	840	816	552
100-yr (ft^3/s)	1,290	1,470	554	100-yr (ft^3/s)	711	736	468
50-yr (ft^3/s)	958	1,180	435	50-yr (ft^3/s)	591	652	392
25-yr (ft^3/s)	694	921	333	25-yr (ft^3/s)	481	564	322
10-yr (ft^3/s)	424	618	223	10-yr (ft^3/s)	348	441	239
5-yr (ft^3/s)	271	417	155	5-yr (ft^3/s)	257	340	181
2-yr (ft^3/s)	118	187	80	2-yr (ft^3/s)	141	193	108
1.25-yr (ft^3/s)	53	79	43	1.25-yr (ft^3/s)	77	99	66

Example 2: Climatic bias case study—Continued

This analysis indicates sensitivity towards the specific period of record. Possible reasons for this bias include watershed changes such as forestry practices, climate cycles, and climate trends. For this Willow Creek example, additional stream gages within the region could be analyzed and extrapolated, using a regional regression methodology, to develop a more robust discharge frequency. A comparison of the computed discharges on a square-mile basis for selected discharges may show that the full record for the three stations is not that dissimilar.

For all frequencies, varying time periods used in a frequency analysis result in readily apparent differences. If a project's design were based on a frequency analysis for a gage with data gathered only during the second half of the twentieth century (as is the case in Willow Creek), this design may have attributes that are inappropriately sized.

Before a discharge-frequency analysis is used, or to judge how the frequency analysis is to be used, watershed history and records should be evaluated to assure that no significant watershed changes have occurred during the period of record. If such significant change has occurred, the period of record may need to be altered, or the frequency analysis may need to be used with caution, with full understanding of its limitations.

Particular attention should be paid to watershed changes when considering the use of data from discontinued gages. It was common to discontinue the small (<10 mi^2) drainage areas in the early 1980s. Aerial photographs can provide useful information in determining if the land use patterns of today are similar to those during the gage's period of record. Each gage site must be evaluated on an individual basis to determine whether today's watershed is still represented by yesteryear's flow records.

Mixed populations
At many locations, high flows are created by different types of events. For example, in mountain watersheds, high flow may result from snowmelt events, rain on snow events, or rain events. Also, tropical cyclones may produce differences from frontal systems. Gages with records that contain such different types of events require special treatment.

Reliability of flow estimates
Errors exist in streamflow records, as with all measured values. With respect to USGS records, data that are rated as excellent means that 95 percent of the daily discharges are within 5 percent of their true value, a good rating means that the data are within 10 percent of their true value, and a fair rating means that the data are within 15 percent of their true value. Records with greater than 15 percent error are considered poor (USGS 2002b).

These gage inaccuracies are often random, possibly minimizing the resultant error in the frequency analysis. Overestimates may be greatest for larger, infrequent events, especially the historic events. For example, research indicates that mobile bed streams cannot maintain supercritical flow over long distances and time periods. Therefore, a critical flow assumption is more appropriate in these situations. For more information on these methods, see Grant (1997) and Webb and Jarrett (2002). If consistent overestimation has occurred, the error is not random, but is instead, a systematic bias.

Regulated flows
Flows from dams are considered to be regulated flows. The normal statistical techniques in Flood Flow Frequency, Bulletin No. 17B (WRC 1981) cannot be used in these situations. However, in some cases, standard graphic statistical techniques can be used to determine the frequency curve. A review of the reservoir operation plan and project design document will provide information on the downstream releases.

(b) Frequency distributions

A flow frequency analysis is a consistent, statistical method for denoting the probability of occurrence of flows at a specific point in a stream system. Such relationships are required in the planning and design of structures in and near streams. However, peak flow frequency analysis techniques have limitations as described in NEH654.0502. Until hydrologic process modeling becomes more developed, the use of the following statistical methods is necessary.

Statistical parameters
The basic statistical parameters used in frequency analyses (applied to both normal and logarithmic values) are:

Mean:

$$\text{Mean: } \bar{X} = \frac{\sum X}{n} \qquad \text{(eq. 5–3)}$$

Standard deviation:

$$\text{Standard deviation: } S = \left[\frac{\sum\left(X-\bar{X}\right)^2}{n-1}\right]^{0.5} \qquad \text{(eq. 5–4)}$$

Skew coefficient:

$$\text{Skew coefficient: } G = \frac{n\sum\left(X-\bar{X}\right)^3}{\left(n-1\right)\left(n-2\right)S^3} \qquad \text{(eq. 5–5)}$$

where:
X = annual peak flow or logarithm of annual peak flow
n = length of data set

The mean is the arithmetic average of the data. It is the expected value of the data. The standard deviation is essentially an indication of how much the data is spread about the mean. The smaller the standard deviation value, the closer are the data points to the mean. For a normally distributed data set, approximately two-thirds of the data will be within plus or minus one standard deviation of the mean, while almost 95 percent will be within two standard deviations of the mean. Skewness is the third central moment about the mean and a measure of symmetry (or rather the lack of symmetry) of a data set (Fripp, Fripp, and Fripp 2003). If values are further from the mean on one side than the other, the distribution will have a larger skew. The skew has a large effect on the shape, and thus, the value of a distribution. Transformations (such as converting to logarithmic forms) are often made on skewed data. Spreadsheets are commonly used to compute these parameters.

Common distributions

Four distributions are most common in frequency analyses of hydrologic data, specifically the normal distribution, log-normal distribution, Gumbel extreme value distribution, and log-Pearson type III distribution. The log-Pearson distribution has been recommended by the WRC and is the primary method for discharge-frequency analyses in the United States. It is also recommended in NEH630.18.

However, the use of the log-Pearson distribution is not universal. For example, Great Britain and China use the generalized extreme value distribution and the log-normal distribution, respectively, while other countries commonly use other distributions (Singh and Strupczewski 2002). This section presents an overview of the four distributions. However, only the log-Pearson distribution will be addressed in detail.

Normal distribution

The normal or Gaussian distribution is one of the most popular distributions in statistics. It is also the basis for the log-normal distribution, which is often used in hydrologic applications. The distribution, as used in frequency analysis computations, is provided:

$$X_{N,T} = \overline{X} + K_{N,T}S \qquad \text{(eq. 5–6)}$$

where:

$X_{N,T}$ = predicted discharge, at return period T

$\overline{X}$ = average annual peak discharge

$K_{N,T}$ = normal deviate (z) for the standard normal curve, where area = $0.50 - \frac{1}{T}$

S = standard deviation, of annual peak discharge

Log-normal distribution

The annual maximum flow series is usually not well approximated by the normal distribution; it is skewed to the right, since flows are only positive in magnitude, while the normal distribution includes negative values. When a data series is left-bounded and positively skewed, a logarithmic transformation of the data may allow the use of normal distribution concepts through the use of the log-normal distribution. This transformation can correct this problem through the conversion of all flow values to logarithms. This is the method used in the log-normal distribution:

$$X_{LN,T} = \overline{X}_l + K_{LN,T}S_l \qquad \text{(eq. 5–7)}$$

where:

$X_{LN,T}$ = logarithm of predicted discharge, at return period

$\overline{X}_l$ = average of annual peak discharge logarithms

$K_{LN,T}$ = normal deviate (z), of logarithms for the standard normal curve, where area = $0.50 - \frac{1}{T}$

S_l = standard deviation, of logarithms of annual peak discharge

Gumbel extreme value distribution

Peak discharges commonly have a positive skew, because one or more high values in the record result in the distribution not being log-normally distributed. Hence, the Gumbel extreme value distribution was developed.

$$X_{G,T} = \overline{X}_l + K_{G,T}S \qquad \text{(eq. 5–8)}$$

where:

$X_{G,T}$ = predicted discharge, at return period T

$\overline{X}_l$ = average annual peak discharge

$K_{G,T}$ = a function of return period and sample size, provided in table 5–2

S = standard deviation of annual peak discharge

Log-Pearson Type III distribution

The log-Pearson type III distribution applies to nearly all series of natural floods and is the most commonly used frequency distribution for peak flows in the United States. It is similar to the normal distribution, except that the log-Pearson distribution accounts for the skew, instead of the two parameters, standard deviation and mean. When the skew is small, the log-Pearson distribution approximates a normal distribution. The basic distribution is:

$$X_{LP,T} = \overline{X}_l + K_{LP,T}S_l \qquad \text{(eq. 5–9)}$$

where:

$X_{LP,T}$ = logarithm of predicted discharge, at return period T

$\overline{X}$ = average of annual peak discharge logarithms

$K_{LP,T}$ = a function of return period and skew coefficient, provided in table 5–3

S_l = standard deviation of logarithms of annual peak discharge

The mean in a log-Pearson type III distribution is approximately equal to the logarithm of the 2-year peak discharge. The standard deviation is the slope of the line, and the skew is shown by the curvature of the line.

The log-Pearson type III distribution has been recommended by the WRC, and the NRCS has adopted its use (NEH630.18). Details on the use of the log-Pearson distribution for the determination of flood frequency are presented later in this chapter. More information is also available in WRC Bulletin 17B.

Plotting position

The graphical evaluation of the adequacy-of-fit of a frequency distribution is recommended when performing an analysis. Plotting positions are used to estimate the return period of actual annual peak flows in these plots. The Weibull equation is provided:

$$\text{Weibull:} \quad PP = \frac{100m}{n} \qquad \text{(eq. 5–10)}$$

where:

n = sample size

m = data rank

The basic computations for a discharge-frequency analysis are illustrated in example 3.

Application of log-Pearson frequency distribution

Numerous statistical distributions that can provide a fit of annual peak flow data exist. The hydrology committee of the WRC (WRC 1981) recommended the use of the log-Pearson type III distribution because it provided the most consistent fit of peak flow data. NRCS participated on the hydrology committee and has adopted the use of WRC Bulletin 17B for determining flood flow frequency, using measured streamflow data.

Several computer programs and Microsoft® Excel® spreadsheet programs exist that can be used to perform log-Pearson frequency analysis. A spreadsheet example is used in many of the examples in this chapter.

Table 5–2 K-values for the Gumbel extreme value distribution

Sample size	Return period, T (yr)								
	1.11	1.25	2.00	2.33	5	10	25	50	100
15	–1.34	–0.98	–0.15	0.06	0.97	1.70	2.63	3.32	4.01
20	–1.29	–0.95	–0.15	0.05	0.91	1.63	2.52	3.18	3.84
25	–1.26	–0.93	–0.15	0.04	0.89	1.58	2.44	3.09	3.73
30	–1.24	–0.91	–0.16	0.04	0.87	1.54	2.39	3.03	3.65
40	–1.21	–0.90	–0.16	0.03	0.84	1.50	2.33	2.94	3.55
50	–1.20	–0.88	–0.16	0.03	0.82	1.47	2.28	2.89	3.49
60	–1.18	–0.87	–0.16	0.02	0.81	1.45	2.25	2.85	3.45
70	–1.17	–0.87	–0.16	0.02	0.80	1.43	2.23	2.82	3.41
80	–1.16	–0.86	–0.16	0.02	0.79	1.42	2.21	2.80	3.39
100	–1.15	–0.85	–0.16	0.02	0.77	1.40	2.19	2.77	3.35
200	–1.11	–0.82	–0.16	0.01	0.74	1.33	2.08	2.63	3.18
400	–1.07	–0.80	–0.16	0.00	0.70	1.27	1.99	2.52	3.05

Table 5–3 K-values for the log-Pearson type III distribution

Skew coefficient C_S	**Recurrence interval/percent chance of occurrence**								
	1.0526	**1.25**	**2**	**5**	**10**	**25**	**50**	**100**	**200**
	95	**80**	**50**	**20**	**10**	**4**	**2**	**1**	**0.5**
–2.00	–1.996	–0.609	0.307	0.777	0.895	0.959	0.980	0.990	0.995
–1.90	–1.989	–0.627	0.294	0.788	0.920	0.996	1.023	1.307	1.044
–1.80	–1.981	–0.643	0.282	0.799	0.945	1.035	1.069	1.087	1.097
–1.70	–1.972	–0.660	0.268	0.808	0.970	1.075	1.116	1.140	1.155
–1.60	–1.962	–0.675	0.254	0.817	0.994	1.116	1.166	1.197	1.216
–1.50	–1.951	–0.690	0.240	0.825	1.018	1.157	1.217	1.256	1.282
–1.40	–1.938	–0.705	0.225	0.832	1.041	1.198	1.270	1.318	1.351
–1.30	–1.925	–0.719	0.210	0.838	1.064	1.240	1.324	1.383	1.424
–1.20	–1.910	–0.732	0.195	0.844	1.086	1.282	1.379	1.449	1.501
–1.10	–1.894	–0.745	0.180	0.848	1.107	1.324	1.435	1.518	1.581
–1.00	–1.877	–0.758	0.164	0.852	1.128	1.366	1.492	1.588	1.664
–0.90	–1.858	–0.769	0.148	0.854	1.147	1.407	1.549	1.660	1.749
–0.80	–1.839	–0.780	0.132	0.856	1.166	1.448	1.606	1.733	1.837
–0.70	–1.819	–0.790	0.116	0.857	1.183	1.488	1.663	1.806	1.926
–0.60	–1.797	–0.800	0.099	0.857	1.200	1.528	1.720	1.880	2.016
–0.50	–1.774	–0.808	0.083	0.856	1.216	1.567	1.777	1.955	2.108
–0.40	–1.750	–0.816	0.066	0.855	1.231	1.606	1.834	2.029	2.201
–0.30	–1.726	–0.824	0.050	0.853	1.245	1.643	1.890	2.104	2.294
–0.20	–1.700	–0.830	0.033	0.850	1.258	1.680	1.945	2.178	2.388
–0.10	–1.673	–0.836	0.017	0.846	1.270	1.716	2.000	2.252	2.482
0.00	–1.645	–0.842	0.000	0.842	1.282	1.751	2.054	2.326	2.576
0.10	–1.616	–0.846	–0.017	0.836	1.292	1.785	2.107	2.400	2.670
0.20	–1.586	–0.850	–0.033	0.830	1.301	1.818	2.159	2.472	2.763
0.30	–1.555	–0.853	–0.050	0.824	1.309	1.849	2.211	2.544	2.856
0.40	–1.524	–0.855	–0.066	0.816	1.317	1.880	2.261	2.615	2.949
0.50	–1.491	–0.856	–0.083	0.808	1.323	1.910	2.311	2.686	3.041
0.60	–1.458	–0.857	–0.099	0.800	1.328	1.939	2.359	2.755	3.132

Table 5–3 K-values for the log-Pearson type III distribution—Continued

Skew coefficient C_S	Recurrence interval/percent chance of occurrence								
	1.0526 **95**	**1.25** **80**	**2** **50**	**5** **20**	**10** **10**	**25** **4**	**50** **2**	**100** **1**	**200** **0.5**
0.70	–1.423	–0.857	–0.116	0.790	1.333	1.967	2.407	2.824	3.223
0.80	–1.388	–0.856	–0.132	0.780	1.336	1.993	2.453	2.891	3.312
0.90	–1.353	–0.854	–0.148	0.769	1.339	2.018	2.498	2.957	3.401
1.00	–1.317	–0.852	–0.164	0.758	1.340	2.043	2.542	3.022	3.489
1.10	–1.280	–0.848	–0.180	0.745	1.341	2.066	2.585	3.087	3.575
1.20	–1.243	–0.844	–0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.30	–1.206	–0.838	–0.210	0.719	1.339	2.108	2.666	3.211	3.745
1.40	–1.168	–0.832	–0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.50	–1.131	–0.825	–0.240	0.690	1.333	2.146	2.743	3.330	3.910
1.60	–1.093	–0.817	–0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.70	–1.056	–0.808	–0.268	0.660	1.324	2.179	2.815	3.444	4.069
1.80	–1.020	–0.799	–0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.90	–0.984	–0.788	–0.294	0.627	1.310	2.207	2.881	3.553	4.223
2.00	–0.949	–0.777	–0.307	0.609	1.302	2.219	2.912	3.605	4.398
2.10	–0.914	–0.765	–0.319	0.592	1.294	2.230	2.942	3.656	4.372
2.20	–0.882	–0.752	–0.330	0.574	1.284	2.240	2.970	3.705	4.444
2.30	–0.850	–0.739	–0.341	0.555	1.274	2.248	2.997	3.753	4.515
2.40	–0.819	–0.725	–0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.50	–0.790	–0.711	–0.360	0.518	1.250	2.262	3.048	3.845	4.652
2.60	–0.762	–0.696	–0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.70	–0.736	–0.681	–0.376	0.479	1.224	2.272	3.093	3.932	4.783
2.80	–0.711	–0.666	–0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.90	–0.688	–0.651	–0.390	0.440	1.195	2.277	3.134	4.013	4.909
3.00	–0.665	–0.636	–0.396	0.420	1.180	2.278	3.152	4.051	4.970

Example 3: Example computations of a discharge-frequency analysis

Problem: A streambank stabilization project is being designed for the Los Pinos River in the San Luis Valley of the Upper Rio Grande Basin. The project is less than a mile downstream from a USGS stream gage. The 167-square-mile watershed consists of forests, grass, and sage on a rural, primarily public land setting. This problem illustrates the analysis of the gaged flow data with the four common distributions.

Solution: First, the gage information is downloaded from the USGS (*http://waterdata.usgs.gov/nwis*), and the data are sorted and transformed. Then the basic statistics are calculated (table 5–4).

After computing these basic statistics, the distributions can be generated. Specifically, the magnitudes of the 1.25-, 2-, 5-, 10-, 25-, 50-, and 100-year events are computed and plotted with the source data. Example computation and plotting of distributions are shown in figure 5–1. Both the Gumbel and log-Pearson distributions fit the plotted data reasonably well.

Table 5–4 Discharge peaks, with basic statistics

USGS 08248000 Los Pinos River near Ortiz, CO

Year	Peak discharge (ft^3/s)	ln (peak discharge)	Rank	Weibull plotting position (yr)
1915	1,620	7.3902	27	3.1
1916	1,690	7.4325	22	3.8
1917	1,750	7.4674	18	4.7
1918	1,020	6.9276	57	1.5
1919	1,550	7.3460	30	2.8
1920	2,300	7.7407	5	16.8
1925	1,160	7.0562	50	1.7
1926	1,600	7.3778	29	2.9
1927	1,680	7.4265	23	3.7
1928	1,240	7.1229	47	1.8
1929	1,180	7.0733	48	1.8
1930	1,100	7.0031	51	1.6
1931	684	6.5280	72	1.2
1932	2,000	7.6009	10	8.4
1933	1,490	7.3065	35	2.4
1934	569	6.3439	75	1.1
1935	1,420	7.2584	40	2.1
1936	1,640	7.4025	26	3.2
1937	2,770	7.9266	4	21.0
1938	2,270	7.7275	6	14.0
1939	1,360	7.2152	43	2.0
1940	887	6.7878	63	1.3
1941	3,160	8.0583	1	84.0
1942	2,000	7.6009	10	8.4
1943	1,370	7.2226	42	2.0
1944	3,030	8.0163	2	42.0
1945	2,180	7.6871	7	12.0
1946	1,090	6.9939	54	1.6
1947	1,740	7.4616	19	4.4
1948	1,660	7.4146	24	3.5
1949	1,620	7.3902	27	3.1
1950	876	6.7754	65	1.3
1951	563	6.3333	77	1.1
1952	2,790	7.9338	3	28.0
1953	924	6.8287	62	1.4
1954	882	6.7822	64	1.3
1955	700	6.5511	71	1.2
1956	926	6.8309	61	1.4
1957	1,850	7.5229	14	6.0
1958	1,490	7.3065	35	2.4
1959	646	6.4708	73	1.2
1960	1,100	7.0031	51	1.6
1961	1,420	7.2584	40	2.1
1962	1,480	7.2998	37	2.3
1963	532	6.2766	78	1.1
1964	1,000	6.9078	60	1.4

Table 5–4 Discharge peaks, with basic statistics—Continued

Year	Peak discharge (ft^3/s)	ln [peak discharge]	Rank	Weibull Plotting Position (yr)
1965	2,000	7.6009	10	8.4
1966	1,010	6.9177	59	1.4
1967	755	6.6267	70	1.2
1968	1,340	7.2004	44	1.9
1969	1,180	7.0733	48	1.8
1970	1,500	7.3132	34	2.5
1971	488	6.1903	81	1.0
1972	385	5.9532	82	1.0
1973	1,940	7.5704	13	6.5
1974	841	6.7346	68	1.2
1975	2,020	7.6109	8	10.5
1976	1,060	6.9660	55	1.5
1977	379	5.9375	83	1.0
1978	1,050	6.9565	56	1.5
1979	1,810	7.5011	15	5.6
1980	1,660	7.4146	24	3.5
1981	580	6.3630	74	1.1
1982	1,530	7.3330	32	2.6
1983	1,700	7.4384	21	4.0
1984	1,790	7.4900	16	5.3
1985	2,020	7.6109	8	10.5
1986	1,710	7.4442	20	4.2
1987	1,430	7.2654	39	2.2
1988	501	6.2166	80	1.1
1989	860	6.7569	66	1.3
1990	564	6.3351	76	1.1
1991	1,470	7.2930	38	2.2
1992	845	6.7393	67	1.3
1993	1,780	7.4844	17	4.9
1994	1,540	7.3395	31	2.7
1995	1,510	7.3199	33	2.5
1996	840	6.7334	69	1.2
1997	1,340	7.2004	44	1.9
1998	1,100	7.0031	51	1.6
1999	1,020	6.9276	57	1.5
2000	516	6.2461	79	1.1
2001	1,300	7.1701	46	1.8

For Q: average = 1,366
standard deviation = 598
skew coefficient = 0.660

For lnQ: average = 7.1165
standard deviation = 0.4763
skew coefficient = -0.507

For lnQ: average = 7.1165
standard deviation = 0.4763
skew coefficient = -0.507

Figure 5–1 Plotting distributions for return period peak discharges

For the normal distribution, equation 5–6 is used to compute the peaks. But first, a table of areas under the standard normal curve (found in most statistics books) is used to determine the K_N and K_{LN} values.

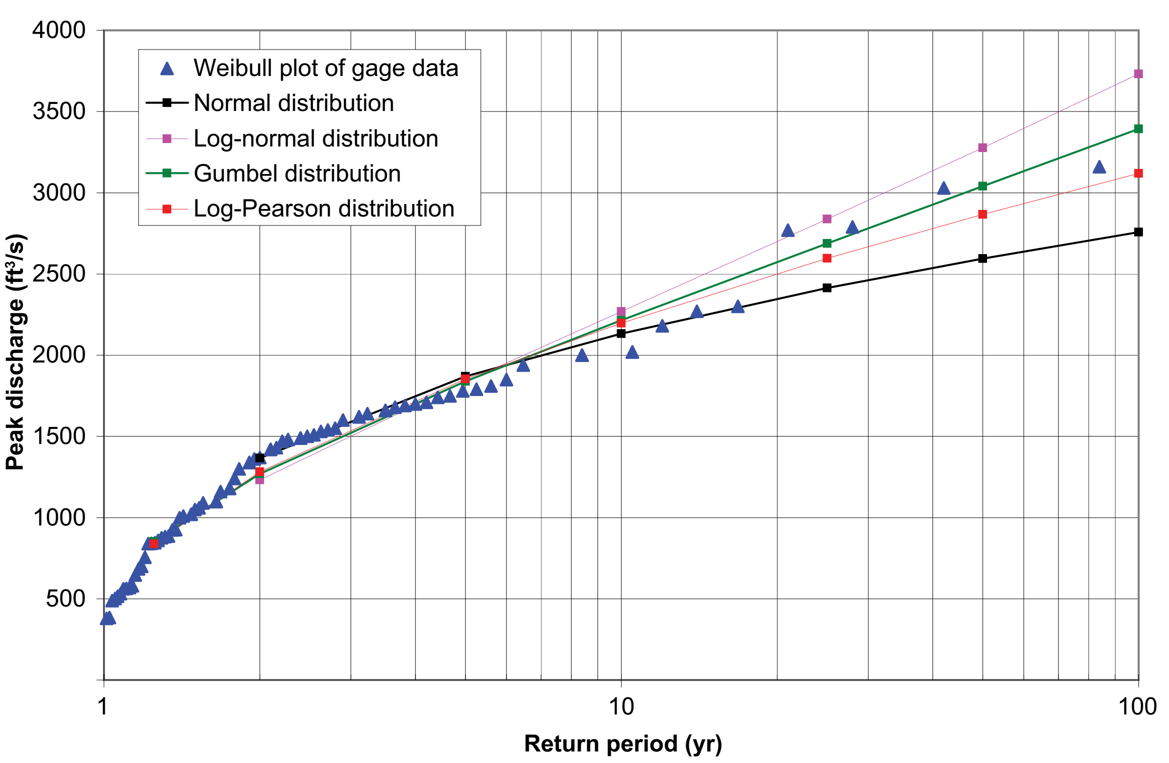
Using the equation $K_{N,T} = K_{LN,T}$ = 0.50¢–1/T, the following table is populated:

Return Period	1.25	2.00	5.00	10.00	25.00	50.00	100.00
K_N & K_{LN}	----	0.00	0.84	1.28	1.75	2.05	2.33

With these K-values and addiing the K-values for the Gumbel and Log-Pearson distributions, the following table is generated, using equations 5–6 through 5–7.

Q: average:	1366	**ln Q:** ıverage:	7.12
standard deviation:	598	standard deviation:	0.48
skew coefficient:	0.66	skew coefficient:	-0.51

Method		Return Period						
		1.25	2	5	10	25	50	100
Normal Distribution	K_N	----	0.00	0.84	1.28	1.75	2.05	2.33
	Q_N (ft³/s)	----	1,366	1,869	2,132	2,413	2,594	2,757
Log-normal distribution	K_{LN}	----	0.00	0.84	1.28	1.75	2.05	2.33
	Q_{LN}	----	7.12	7.52	7.73	7.95	8.09	8.22
	Q_{LN} (ft³/s)	----	1,232	1,840	2,269	2,837	3,277	3,732
Gumbel distribution	K_G	-0.86	-0.16	0.79	1.42	2.21	2.80	3.39
	Q_G (ft³/s)	852	1,270	1,838	2,215	2,688	3,040	3,393
Log-Pearson distribution	K_{LP}	-0.81	0.08	0.86	1.21	1.56	1.77	1.95
	Q_{LP}	6.73	7.16	7.52	7.70	7.86	7.96	8.05
	Q_{LP} (ft³/s)	839	1,282	1,852	2,198	2,596	2,867	3,119



General log-Pearson distribution

This distribution was provided previously as equation 5–9. The average, standard deviation, and skew coefficient were defined by equations 5–5 through 5–7. A complete table of K-values, with skews from –9.0 to +9.0, can be obtained from appendix 3 of WRC Bulletin 17B.

Generalized skew and weighting the skew coefficient

The computed station skew is sensitive to large events, especially with short periods of records. This problem can be minimized by weighting the station skew with a generalized skew that takes into account skews from neighboring gaged watersheds.

Three methods to develop this generalized skew are to:

- develop a skew isoline map
- develop a skew regression (or prediction) equation
- compute the mean and variance of the skew coefficients

These methods should incorporate at least 40 stations with at least 25 years of record within the gage of interest's hydro-physiographic province. Plate 1 of WRC Bulletin 17B could also be used; but, due to the vintage of this compilation, a detailed study may be preferred.

To develop a skew isoline map, the station skews are plotted at the centroid of the watershed and trends are observed. A regression or prediction equation can also be developed to relate skews to watershed and climatologic characteristics. If no relationship can be found with the isoline or regression approach, the arithmetic mean ($\overline{X}$) can be simply computed and used as the generalized skew. Care needs to be taken to ensure that all of the gages are in a similar hydro-physiographic province.

Once the best generalized skew is computed, a weighted skew is computed for the log-Pearson analysis using equation. 5–11.

$$G_W = \frac{S^2_{\bar{G}}(G) + S^2_G(\bar{G})}{S^2_{\bar{G}} + S^2_G} \qquad \text{(eq. 5–11)}$$

where:
G_W = weighted skew coefficient
G = station skew
$\bar{G}$ = generalized skew
$S^2_{\bar{G}}$ = variance (mean square error) of generalized skew
S^2_G = variance of station skew

When generalized skews are read from Plate 1 of WRC Bulletin 17B, a variance of 0.302 should be used in equation 5–11.

The variance of the logarithmic station skew is a function of record length and population skew. This variance can be approximated with equations 5–12, 5–13, and 5–14.

$$S^2_G = 10^{\left[A - B\left(\log_{10}\left(\frac{n}{10}\right)\right)\right]} \qquad \text{(eq. 5–12)}$$

$$\begin{aligned} A &= -0.33 + 0.08|G| && \text{if } |G| \le 0.90 \\ A &= -0.52 + 0.30|G| && \text{if } |G| > 0.90 \qquad \text{(eq. 5–13)} \\ B &= 0.94 - 0.26|G| && \text{if } |G| \le 1.50 \end{aligned}$$

$$B = 0.55 \qquad \text{if } |G| > 1.50 \qquad \text{(eq. 5–14)}$$

where:
n = record length in years
$|G|$ = absolute value of the station skew

If an historic record adjustment has been made. Historically adjusted values should be used.

Broken or incomplete records

Annual peaks for certain years at a gage are often missing. If this happens, the two or more record lengths are analyzed as a continuous record, with a record length equal to the sum of individual records.

Incomplete records refer to a high or low streamflow record that is missing due to a gaging failure. Usually, the gaging agency uses an indirect flow estimate to fill this void. If this has not occurred, effort to fill this gap may be warranted.

Historic flood data

As described in reliability of flow estimates, high flow values and historic events can be overestimated. If historic data are judged not to be biased high, WRC Bulletin 17B provides a special procedure for dealing with these events, instead of using a broken record approach. This method assumes that data from the systematic record is representative of the period between the historic data, and the systematic record and its statistics are adjusted accordingly.

First, a systematic record weight is computed.

$$W_s = \frac{H - Z}{n + L} \qquad \text{(eq. 5–15)}$$

where:
W_s = systematic record weight
H = historical period
Z = number of historic peaks
n = systematic record length
L = number of low values excluded, including low outliers and zero flow years

The historically adjusted average ($\tilde{X}$) is computed using:

$$\tilde{X} = \frac{W_s \sum X_s + \sum X_h}{H - W_s L} \qquad \text{(eq. 5–16)}$$

where:
X_s = logarithmic systematic record peaks
X_h = logarithmic historic record peaks

The historically adjusted standard deviation of logarithms ($\tilde{S}$) is:

$$\tilde{S} = \sqrt{\tilde{S}^2} = \sqrt{\frac{W_s \sum \left(X - \tilde{X}\right)^2 + \sum \left(X_h - \tilde{X}\right)^2}{\left(H - W_s L - 1\right)}} \qquad \text{(eq. 5–17)}$$

The historically adjusted skew coefficient of logarithms ($\tilde{G}$) is:

$$\tilde{G} = \frac{H - W_s L - 1}{\left(H - W_s L - 1\right)\left(H - W_s L - 2\right)} \left[\frac{W_s \sum \left(X - \tilde{X}\right)^3 + \sum \left(X_h - \tilde{X}\right)^3}{\tilde{S}^3} \right] \qquad \text{(eq. 5–18)}$$

Outliers

Outliers are data points that depart significantly from the trend of the remaining data. Including such outliers may be inappropriate in a frequency analysis. The decision to retain or eliminate an outlier is based on both hydrologic and statistical considerations. The statistical method for identifying possible outliers, as presented in WRC Bulletin 17B, uses equations 5–19 and 5–20:

$$X_H = \bar{X}_l + K_o S_l \qquad \text{(eq. 5–19)}$$

$$X_L = \bar{X}_l - K_o S_l \qquad \text{(eq. 5–20)}$$

where:
X_H = high outlier threshold, in logarithm units
X_L = low outlier threshold, in logarithm units (no historic adjustment)
$\bar{X}_l$ = average of annual peak discharge logarithms
K_o = based on sample size n, as listed in table 5–5
S_l = standard deviation of logarithms of annual peak discharge

If the station skew is greater than +0.4, high outliers are considered first and possibly eliminated. If the station skew is less than –0.4, low outliers are considered first, and then possibly eliminated. When the skew is between ± 0.4, a test for both high and low outliers should be first applied before possibly eliminating any outliers from the data set.

If an adjustment for historic flood data has already been made, the low outlier threshold equation is modified in the form:

$$X_{L,H} = \tilde{X} - K_o \tilde{S} \qquad \text{(eq. 5–21)}$$

where:
$X_{L,H}$ = low outlier threshold, in logarithm units (with historic adjustment)
$\tilde{X}$ = historically adjusted mean logarithm
$\tilde{S}$ = historically adjusted standard deviation

Mixed populations

In many watersheds, annual peak flows are caused by different types of events such as snowmelt, tropical cyclones, and summer thunderstorms. Including all types of events in a single frequency analysis may result in large and inappropriate skew coefficients. For such situations, special treatment may be warranted. Specifically, peak flows can be segregated by cause, analyzed separately, and then combined. Importantly, separation by calendar date alone is not appropriate, unless it can be well documented that an event type always varies by time of year.

Zero flow years

Some streams in arid regions may have no flow during the entire water year, thus having one or more zero peak flow values in its record. Such situations require special treatment. See appendix 5 in WRC Bulletin 17B

Table 5–5 Outlier test K_o values, from WRC Bulletin 17B

Sample size	K_o value	Sample size	K_o value	Sample size	K_o value	Sample size	K_o value
10	2.036	45	2.727	80	2.940	115	3.064
11	2.088	46	2.736	81	2.945	116	3.067
12	2.134	47	2.744	82	2.949	117	3.070
13	2.175	48	2.753	83	2.953	118	3.073
14	2.213	49	2.760	84	2.957	119	3.075
15	2.247	50	2.768	85	2.961	120	3.078
16	2.279	51	2.775	86	2.966	121	3.081
17	2.309	52	2.783	87	2.970	122	3.083
18	2.335	53	2.790	88	2.973	123	3.086
19	2.361	54	2.798	89	2.977	124	3.089
20	2.385	55	2.804	90	2.981	125	3.092
21	2.408	56	2.811	91	2.984	126	3.095
22	2.429	57	2.818	92	2.989	127	3.097
23	2.448	58	2.824	93	2.993	128	3.100
24	2.467	59	2.831	94	2.996	129	3.102
25	2.486	60	2.837	95	3.000	130	3.104
26	2.502	61	2.842	96	3.003	131	3.107
27	2.519	62	2.849	97	3.006	132	3.109
28	2.534	63	2.854	98	3.011	133	3.112
29	2.549	64	2.860	99	3.014	134	3.114
30	2.563	65	2.866	100	3.017	135	3.116
31	2.577	66	2.871	101	3.021	136	3.119
32	2.591	67	2.877	102	3.024	137	3.122
33	2.604	68	2.883	103	3.027	138	3.124
34	2.616	69	2.888	104	3.030	139	3.126
35	2.628	70	2.893	105	3.033	140	3.129
36	2.639	71	2.897	106	3.037	141	3.131
37	2.650	72	2.903	107	3.040	142	3.133
38	2.661	73	2.908	108	3.043	143	3.135
39	2.671	74	2.912	109	3.046	144	3.138
40	2.682	75	2.917	110	3.049	145	3.140
41	2.692	76	2.922	111	3.052	146	3.142
42	2.700	77	2.927	112	3.055	147	3.144
43	2.710	78	2.931	113	3.058	148	3.146
44	2.719	79	2.935	114	3.061	149	3.148

for specific details on how to account for zero flow years.

Confidence limits

A frequency curve is not an exact representation of the population curve. How well a stream record predicts flooding depends on record length, accuracy, and applicability of the underlying probability distribution. Statistical analysis allows the advantage of calculating confidence limits, which provide a measure of the uncertainty or spread in an estimate. These limits are a measure of the uncertainty of the discharge at a selected exceedance probability. For example, for the 5 percent and 95 percent confidence limit curves, there are nine chances in ten that the true value lies in the 90 percent confidence interval between the curves. As more data become available at a stream gage, the confidence limits will normally be narrowed. As presented in WRC Bulletin 17B, the following method is provided to develop confidence limits for a log-Pearson type III distribution.

$$X_{CI,U} = \bar{X}_l + S_l\left(K_{CI,U}\right) \quad \text{(eq. 5–22)}$$

$$X_{CI,L} = \bar{X}_l + S_l\left(K_{CI,L}\right) \quad \text{(eq. 5–23)}$$

where:

$X_{CI,U}$ = logarithmic upper confidence limit
$X_{CI,L}$ = logarithmic lower confidence limit
$\bar{X}_l$ = logarithmic peak flow mean
S_l = logarithmic peak flow standard deviation

$$K_{CI,U} = \frac{K_{LP,T} + \sqrt{K_{LP,T}^2 - ab}}{a} \quad \text{(eq. 5–24)}$$

$$K_{CI,L} = \frac{K_{LP,T} - \sqrt{K_{LP,T}^2 - ab}}{a} \quad \text{(eq. 5–25)}$$

$$a = 1 - \frac{z_c^2}{2\left(n-1\right)} \quad \text{(eq. 5–26)}$$

$$b = K_{LP,T}^2 - \frac{z_c^2}{n} \quad \text{(eq. 5–27)}$$

where:

n = record length
$K_{LP,T}$ = as listed in table 5–3, as a function of return period and skew coefficient
z_c = standard normal deviate, that is, the zero-skew $K_{LP,T}$ value at a return period of 1 decimal confidence limit. For the 95 percent confidence limit (0.05), z_c = 1.64485.

Comparisons of the frequency curve

Comparisons of distributions between the watershed being investigated and other regional watersheds can be useful for error checking and to identify possible violations of the underlying assumptions for the analysis. This can be especially illuminating for gages in the same watershed, upstream and downstream of the gage of interest, possibly identifying particular and unexpected hydrologic phenomena.

Discharge estimates from precipitation can be a helpful complement to gage data. However, such discharge estimates require a valid rainfall-runoff model. Such models are best when calibrated, which requires gage information. Such a calibrated model can be useful at other points within the watershed.

Example 4 illustrates analysis for outliers and confidence intervals.

Computation resources for flow frequency analysis

Several computer programs are available for assistance in performing the flood frequency analysis including the U.S. Army Corps of Engineers HEC–FFA (USACE 1992b) or the USGS PEAKFQ (USGS 1998). The USGS provides a computer program, PEAKFQ, at the Web site:

http://water.usgs.gov/software/peakfq.html

Spreadsheet programs have also been used to perform flood frequency analysis calculations as detailed by WRC Bulletin 17B. One of these spreadsheets is used in the examples presented in this chapter. This spreadsheet includes algorithms for generalized skew, 90 percent confidence intervals (95 percent confidence limits), historic data inclusion, and outlier identification. Example output sheets of this spreadsheet are provided in the example 5. It should be noted that these computational aids are for unregulated rivers and streams and that special precautions are necessary when evaluating flood frequencies on rivers with dams and significant diversions.

Transfer methods

Peak discharge frequency values are often needed at watershed locations other than the gaged location. Peak discharges may be extrapolated upstream or downstream from stream gages, for which frequency curves have been determined. In addition, peak dis-

Example 4: Confidence interval and outlier example

Problem: This example illustrates the analysis of USGS 06324500 Powder River at Moorhead, Montana, gage data in Eastern Montana (table 5–6). The following questions are addressed:

- frequency distribution for the gage
- 90 percent confidence interval
- outlier check
- impacts of the use of historic methodology and the impacts of inclusion of any outliers are assessed

Solution: The peak streamflow data were downloaded from the USGS NWIS data system (*http://waterdata.usgs.gov/nwis/*). These data, along with basic statistical computations, are provided in table 5–6.

Inspect the comments accompanying the peak flow data. For this data set, two of the data points are daily averages (instead of peak flows), six data points are estimates, and one estimate is an historic peak. The event on March, 17, 1979, is missing the peak flow (though the gage record does include the associated stage). Effort should be made to populate this point, but for this exercise, the data point is ignored.

It can be useful to plot frequency data to help in the identification of outliers and trends. Figure 5–2 includes a plot of these data.

This plot clearly shows a possible outlier and also qualitatively indicates a possible downward trend during the second half of the data set. A step trend would be more evident in the case of greater reservoir regulation within this watershed.

To assess the impact of using the historic methodology and inclusion or exclusion of the possible outlier, several frequency analyses need to be computed. A frequency analysis is performed on all of the data. Equation 5–9 is used to compute the distribution and confidence limits area, using equations 5–22 and 5–23. The computations and results are provided in table 5–6. The data are plotted in figure 5–3.

Outliers are identified using equations 5–5, 5–19, and 5–20, and the Weibull plotting positions are computed using equation 5–10. The high and low outlier thresholds are 10.96 and 6.48, respectively. Since the skew is between +0.4, high and low outliers are checked at the same time. The identification of outliers and computation of plotting position are shown in table 5–7. An outlier identified by the WRC Bulletin 17B methodology has been highlighted in yellow.

Since the 1923 event has been identified as a possible outlier, a frequency analysis is performed on a data set that excludes this high-flow value. The results of this computation are provided in table 5–8.

WRC Bulletin 17B provides a special methodology for historic peaks. The basis of this method is the assumption that data from the systematic record is representative of the period of the historic data. The systematic record and statistics are adjusted accordingly. This method is applied to the entire record of the Powder River at Moorhead gage, with computations that use equations 5–15 to 5–18 and those results are provided in table 5–9. Results have been plotted in figure 5–3.

Example 4: Confidence interval and outlier example—Continued

Inspection of the plotted results reveals a number of characteristics in the frequency distributions, specifically:

- The frequency analysis that includes the 1923 outlier in its computations (but does not incorporate the historic methodology) has the highest frequency distribution estimate. With the exception of the outlier, it also matches the higher data well. The 90 percent confidence interval brackets the higher data, with the exception of the outlier. This distribution does somewhat overestimate lower frequency events.
- The frequency analysis based on the historic methodology also well represents the higher data and somewhat overestimates lower data. This historic distribution is slightly lower than the nonhistoric distribution.
- The frequency analysis that excludes the outlier from its computations provides a distribution that is much lower than the distributions that include the outlier point. This distribution does not represent the higher flow data well—its 90 percent confidence interval excludes two additional data points, as plotted using the Weibull methodology. It does represent the lower peak data better.

It can be concluded from these observations that inclusion of the high outlier likely best represents the less frequent (higher) events. Exclusion of the data point provides a distribution that better represents more frequent (lower) events. For the Powder River at Moorhead, Montana, gaging station, it may be best to use the distribution that best represents the frequency of a desired event. If one distribution is required for all frequencies, the inclusion of the outlier using the historic methodology is likely best, due to its slightly better representation of all data than the nonhistoric, included outlier computation.

In addition, with the 1923 outlier perhaps being biased high, it may be best to revisit the computation of this historic peak. Additionally, it may be prudent to incorporate the generalized skew procedure to counteract any bias in the skew of the gage data.

Example 5: Log-Pearson spreadsheet frequency analysis example

The frequency analysis for the USGS gage 08251500 Rio Grande near Labatos, CO, is required for a stream stabilization project. The distribution was computed using a log-Pearson spreadsheet. The output sheets are provided in figures 5–4 to 5–6.

Visual observation of the graph of the plotted data indicates the computed record should be accepted for the analysis.

Table 5–6 Peak streamflow data at gage 06324500 Powder River at Moorhead, MT

Date	Peak flow (ft^3/s)	Notes	Date	Peak flow (ft^3/s)	Notes	Date	Peak flow (ft^3/s)	Notes
09/30/1923	100,000	2,3	06/15/1953	8,590		05/27/1980	2,210	
06/03/1929	8,610		08/06/1954	9,740		05/31/1981	2,160	
07/14/1930	4,040		06/18/1955	5,610		07/26/1982	6,350	
05/06/1931	6,040		06/16/1956	7,200		06/13/1983	2,870	
06/08/1932	3,550		06/07/1957	5,600		05/19/1984	4,620	
08/30/1933	14,800		06/12/1958	4,900		07/31/1985	1,410	
06/16/1934	1,920		03/19/1959	5,740		06/09/1986	4,540	
06/01/1935	8,140		03/20/1960	6,200		07/18/1987	11,400	
03/02/1936	9,240		05/30/1961	1,320		05/19/1988	1,990	
07/14/1937	14,500		06/17/1962	23,000		03/12/1989	800	1,2
05/30/1938	5,720		06/15/1963	7,010		08/21/1990	8,150	
06/02/1939	7,200		06/24/1964	15,000		06/04/1991	5,460	
06/04/1940	6,820		04/02/1965	18,300		11/12/1991	6,410	
08/13/1941	8,360		03/13/1966	4,000		06/09/1993	6,740	
06/26/1942	5,070		06/17/1967	17,300		07/09/1994	3,920	
03/26/1943	8,800		06/08/1968	8,580	2	05/11/1995	8,250	
05/20/1944	10,700		07/16/1969	5,280		03/13/1996	3,500	1,2
06/06/1945	6,190		05/24/1970	8,900	2	06/10/1997	4,290	
06/11/1946	5,720		06/01/1971	8,340		07/04/1998	2,760	
03/19/1947	9,300	2	02/29/1972	7,800		05/04/1999	3,960	
06/17/1948	9,320		06/19/1975	12,100		05/20/2000	3,930	
03/06/1949	9,360		06/23/1976	5,370		07/13/2001	1,490	
05/19/1950	2,620		05/17/1977	4,750				
09/09/1951	2,020		05/20/1978	33,000				
03/25/1952	15,300		03/17/1979					

Notes:
1/ Discharge is a maximum daily average
2/ Discharge is an estimate
3/ Discharge is an historic peak

Figure 5–2 Data plot at gage 06324500 Powder River at Moorhead, MT

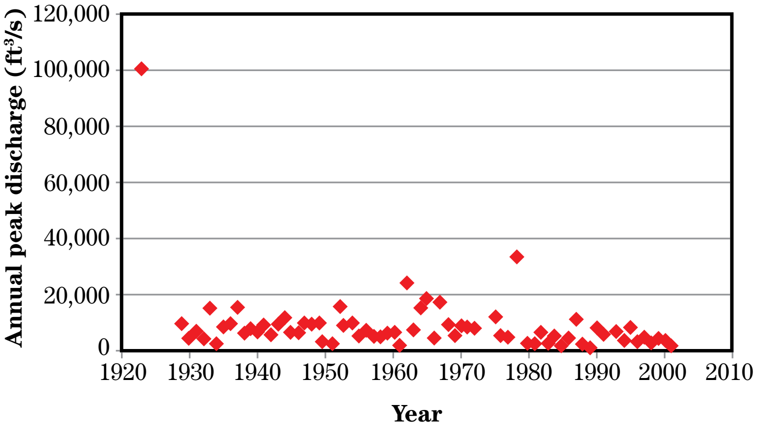


Figure 5–3 Data and frequency plots

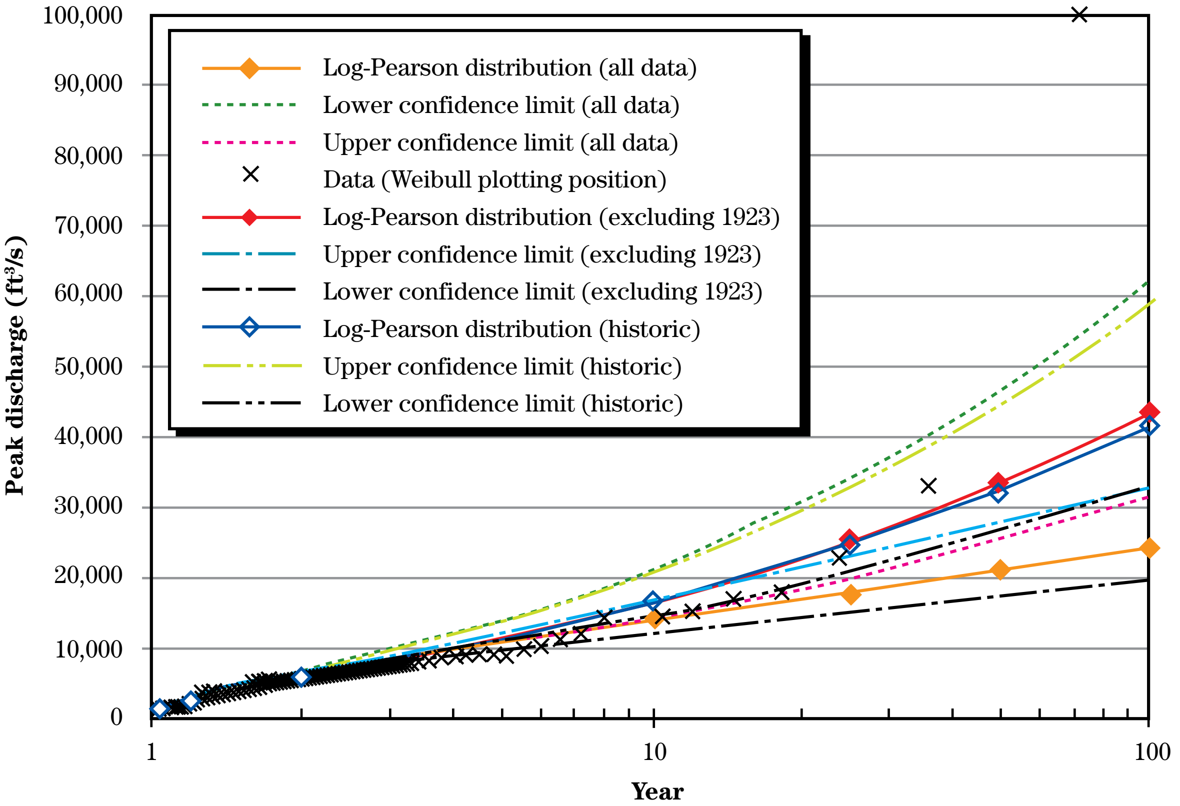


Table 5–7 Logarithmic data and Weibull plotting position values

Year	ln(Q)	Rank	Weibull (yr)
1923	11.513	1	72.0
1929	9.061	20	3.6
1930	8.304	53	1.4
1931	8.706	38	1.9
1932	8.175	58	1.2
1933	9.602	8	9.0
1934	7.560	67	1.1
1935	9.005	27	2.7
1936	9.131	17	4.2
1937	9.582	9	8.0
1938	8.652	40	1.8
1939	8.882	29	2.5
1940	8.828	32	2.3
1941	9.031	23	3.1
1942	8.531	47	1.5
1943	9.083	19	3.8
1944	9.278	12	6.0
1945	8.731	37	1.9
1946	8.652	41	1.8
1947	9.138	16	4.5
1948	9.140	15	4.8
1949	9.144	14	5.1
1950	7.871	62	1.2
1951	7.611	65	1.1
1952	9.636	6	12.0
1953	9.058	21	3.4
1954	9.184	13	5.5
1955	8.632	42	1.7
1956	8.882	30	2.4
1957	8.631	43	1.7
1958	8.497	48	1.5
1959	8.655	39	1.8
1960	8.732	36	2.0
1961	7.185	70	1.0
1962	10.043	3	24.0
1963	8.855	31	2.3
1964	9.616	7	10.3
1965	9.815	4	18.0
1966	8.294	54	1.3
1967	9.758	5	14.4
1968	9.057	22	3.3
1969	8.572	46	1.6
1970	9.094	18	4.0
1971	9.029	24	3.0
1972	8.962	28	2.6
1975	9.401	10	7.2
1976	8.589	45	1.6
1977	8.466	49	1.5
1978	10.404	2	36.0
1980	7.701	63	1.1
1981	7.678	64	1.1
1982	8.756	35	2.1
1983	7.962	60	1.2
1984	8.438	50	1.4
1985	7.251	69	1.0
1986	8.421	51	1.4
1987	9.341	11	6.5
1988	7.596	66	1.1
1989	6.685	71	1.0
1990	9.006	26	2.8
1991	8.605	44	1.6
1992	8.766	34	2.1
1993	8.816	33	2.2
1994	8.274	57	1.3
1995	9.018	25	2.9
1996	8.161	59	1.2
1997	8.364	52	1.4
1998	7.923	61	1.2
1999	8.284	55	1.3
2000	8.276	56	1.3
2001	7.307	68	1.1

Table 5–8 Frequency analysis data at gage 06324500 Powder River at Moorhead, MT

The basic statistics of the peak flow natural logarithms are provided:

Average = 8.7167 n = 71
Standard deviation = 0.7722 z_c = 1.64485 (95% confidence limit)
Skew = 0.2883 a = 0.980674775

Next, the log-Pearson K-Values are extracted from table 5–2, and the frequency values and confidence limits are computed:

Return period	**1.0526**	**1.25**	**2**	**5**	**10**	**25**	**50**	**100**	**200**
K-value	-1.559	-0.853	-0.048	0.825	1.308	1.845	2.205	2.536	2.845
ln (discharge)	7.513	8.058	8.680	9.354	9.727	10.142	10.419	10.675	10.914
Discharge (ft^3/s)	1,832	3,160	5,882	11,539	16,760	25,379	33,500	43,245	54,922
b	2.391	0.689	-0.036	0.642	1.673	3.367	4.824	6.391	8.057
$K_{CI,U}$	-1.293	-0.638	0.148	1.070	1.604	2.209	2.618	2.995	3.350
$K_{CI,L}$	-1.885	-1.101	-0.246	0.612	1.063	1.554	1.879	2.176	2.452
$\ln(Q_{CI,U})$	7.718	8.224	8.831	9.543	9.956	10.423	10.738	11.030	11.304
$\ln(Q_{CI,L})$	7.261	7.867	8.527	9.189	9.538	9.917	10.168	10.397	10.610
QCI,U (ft^3/s)	2,248	3,729	6,844	13,947	21,071	33,614	46,084	61,684	81,115
QCI,L (ft^3/s)	1,423	2,609	5,047	9,790	13,873	20,268	26,043	32,751	40,551

Table 5–9 Historic methodology computations

H = 79 Z = 1 n = 70 L = 0

From equation 5–15: systematic record weight, Ws = 1.114

From equation 5–16: historically adjusted average, $\tilde{X}$ = 8.713

From equation 5–17: historically adjusted standard deviation, $\tilde{S}$ = 0.765

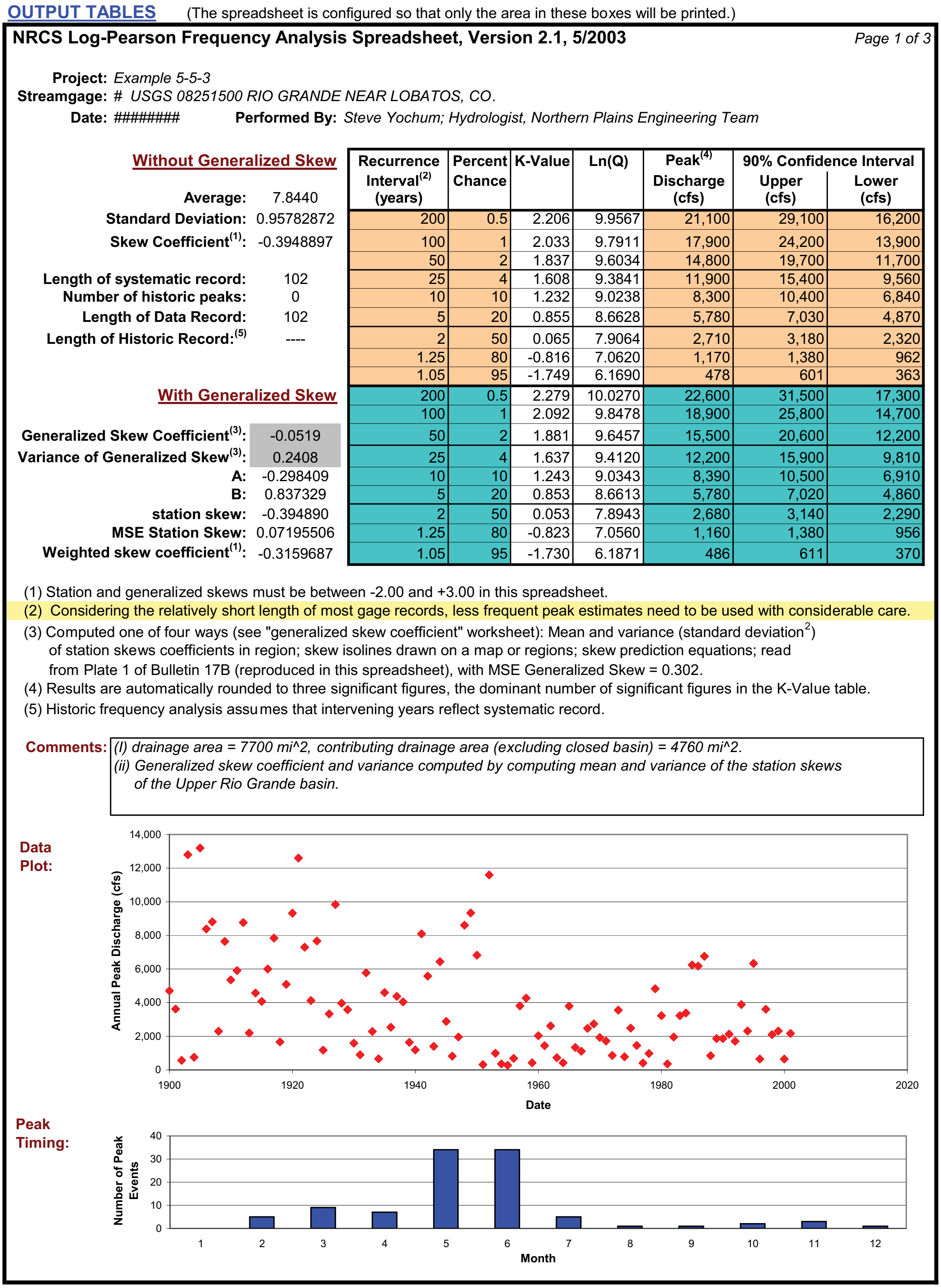
From equation 5–18: historically adjusted skew, $\tilde{G}$ = 0.239

z_c =1.64485 (95% confidence limit) a = 0.980674775

Next, the log-Pearson K-Values are extracted from Table 5–5–2 and the frequency values and confidence limits are computed:

Return period	**1.0526**	**1.25**	**2**	**5**	**10**	**25**	**50**	**100**	**200**
K value	-1.573991189	-0.851162143	-0.039585477	0.827675714	1.304099048	1.830008811	2.179143811	2.499891431	2.799026432
ln (discharge)	7.509	8.062	8.682	9.346	9.710	10.112	10.379	10.624	10.853
Discharge (ft^3/s)	1,824	3,171	5,898	11,448	16,480	24,639	32,180	41,126	51,697
b	2.439	0.686	-0.037	0.646	1.662	3.310	4.710	6.211	7.796
$K_{CI,U}$	-1.306	-0.636	0.158	1.075	1.601	2.193	2.589	2.955	3.298
KCI,L	-1.904	-1.100	-0.239	0.613	1.059	1.539	1.855	2.143	2.411
ln(QCI,U)	7.714	8.227	8.834	9.534	9.937	10.389	10.693	10.973	11.235
ln(QCI,L)	7.257	7.871	8.530	9.182	9.522	9.890	10.131	10.351	10.556
QCI,U (ft^3/s)	2,239	3,739	6,861	13,827	20,682	32,516	44,036	58,261	75,707
QCI,L (ft^3/s)	1,418	2,621	5,064	9,718	13,659	19,730	25,113	31,302	38,409

Figure 5–4 Sheet 1 of log-Pearson spreadsheet output for USGS gage 0825150



OUTPUT TABLES (The spreadsheet is configured so that only the area in these boxes will be printed.)

NRCS Log-Pearson Frequency Analysis Spreadsheet, Version 2.1, 5/2003 *Page 1 of 3*

Project: *Example 5-5-3*
Streamgage: # *USGS 08251500 RIO GRANDE NEAR LOBATOS, CO.*
Date: ######## **Performed By:** *Steve Yochum; Hydrologist, Northern Plains Engineering Team*

Without Generalized Skew

Average: 7.8440
Standard Deviation: 0.95782872
Skew Coefficient[1]: -0.3948897

Length of systematic record: 102
Number of historic peaks: 0
Length of Data Record: 102
Length of Historic Record:[5] ----

With Generalized Skew

Generalized Skew Coefficient[3]: -0.0519
Variance of Generalized Skew[3]: 0.2408
A: -0.298409
B: 0.837329
station skew: -0.394890
MSE Station Skew: 0.07195506
Weighted skew coefficient[1]: -0.3159687

Recurrence Interval[2] (years)	Percent Chance	K-Value	Ln(Q)	Peak[4] Discharge (cfs)	90% Confidence Interval Upper (cfs)	Lower (cfs)
200	0.5	2.206	9.9567	21,100	29,100	16,200
100	1	2.033	9.7911	17,900	24,200	13,900
50	2	1.837	9.6034	14,800	19,700	11,700
25	4	1.608	9.3841	11,900	15,400	9,560
10	10	1.232	9.0238	8,300	10,400	6,840
5	20	0.855	8.6628	5,780	7,030	4,870
2	50	0.065	7.9064	2,710	3,180	2,320
1.25	80	-0.816	7.0620	1,170	1,380	962
1.05	95	-1.749	6.1690	478	601	363
200	0.5	2.279	10.0270	22,600	31,500	17,300
100	1	2.092	9.8478	18,900	25,800	14,700
50	2	1.881	9.6457	15,500	20,600	12,200
25	4	1.637	9.4120	12,200	15,900	9,810
10	10	1.243	9.0343	8,390	10,500	6,910
5	20	0.853	8.6613	5,780	7,020	4,860
2	50	0.053	7.8943	2,680	3,140	2,290
1.25	80	-0.823	7.0560	1,160	1,380	956
1.05	95	-1.730	6.1871	486	611	370

(1) Station and generalized skews must be between -2.00 and +3.00 in this spreadsheet.
(2) Considering the relatively short length of most gage records, less frequent peak estimates need to be used with considerable care.
(3) Computed one of four ways (see "generalized skew coefficient" worksheet): Mean and variance (standard deviation^2) of station skews coefficients in region; skew isolines drawn on a map or regions; skew prediction equations; read from Plate 1 of Bulletin 17B (reproduced in this spreadsheet), with MSE Generalized Skew = 0.302.
(4) Results are automatically rounded to three significant figures, the dominant number of significant figures in the K-Value table.
(5) Historic frequency analysis assumes that intervening years reflect systematic record.

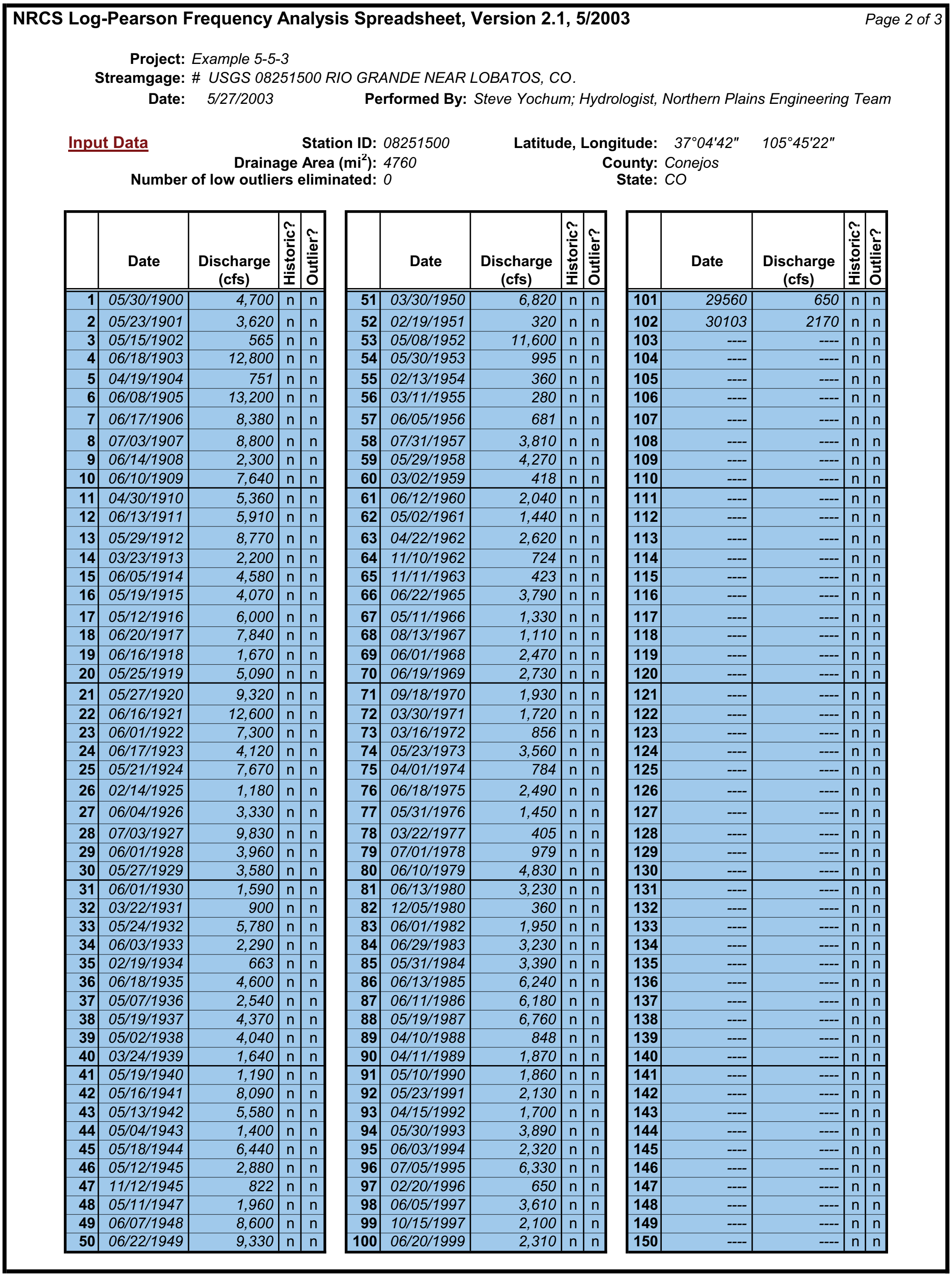
Comments: *(I) drainage area = 7700 mi^2, contributing drainage area (excluding closed basin) = 4760 mi^2.*
(ii) Generalized skew coefficient and variance computed by computing mean and variance of the station skews of the Upper Rio Grande basin.

Data Plot:

Peak Timing:

NRCS 2006

Figure 5–5 Sheet 2 of log-Pearson spreadsheet output for USGS gage 08251500



NRCS Log-Pearson Frequency Analysis Spreadsheet, Version 2.1, 5/2003 *Page 2 of 3*

Project: *Example 5-5-3*
Streamgage: *# USGS 08251500 RIO GRANDE NEAR LOBATOS, CO.*
Date: *5/27/2003* **Performed By:** *Steve Yochum; Hydrologist, Northern Plains Engineering Team*

Input Data
Station ID: *08251500* **Latitude, Longitude:** *37°04'42" 105°45'22"*
Drainage Area (mi^2): *4760* **County:** *Conejos*
Number of low outliers eliminated: *0* **State:** *CO*

	Date	Discharge (cfs)	Historic?	Outlier?		Date	Discharge (cfs)	Historic?	Outlier?		Date	Discharge (cfs)	Historic?	Outlier?
1	*05/30/1900*	*4,700*	n	n	**51**	*03/30/1950*	*6,820*	n	n	**101**	*29560*	*650*	n	n
2	*05/23/1901*	*3,620*	n	n	**52**	*02/19/1951*	*320*	n	n	**102**	*30103*	*2170*	n	n
3	*05/15/1902*	*565*	n	n	**53**	*05/08/1952*	*11,600*	n	n	**103**	----	----	n	n
4	*06/18/1903*	*12,800*	n	n	**54**	*05/30/1953*	*995*	n	n	**104**	----	----	n	n
5	*04/19/1904*	*751*	n	n	**55**	*02/13/1954*	*360*	n	n	**105**	----	----	n	n
6	*06/08/1905*	*13,200*	n	n	**56**	*03/11/1955*	*280*	n	n	**106**	----	----	n	n
7	*06/17/1906*	*8,380*	n	n	**57**	*06/05/1956*	*681*	n	n	**107**	----	----	n	n
8	*07/03/1907*	*8,800*	n	n	**58**	*07/31/1957*	*3,810*	n	n	**108**	----	----	n	n
9	*06/14/1908*	*2,300*	n	n	**59**	*05/29/1958*	*4,270*	n	n	**109**	----	----	n	n
10	*06/10/1909*	*7,640*	n	n	**60**	*03/02/1959*	*418*	n	n	**110**	----	----	n	n
11	*04/30/1910*	*5,360*	n	n	**61**	*06/12/1960*	*2,040*	n	n	**111**	----	----	n	n
12	*06/13/1911*	*5,910*	n	n	**62**	*05/02/1961*	*1,440*	n	n	**112**	----	----	n	n
13	*05/29/1912*	*8,770*	n	n	**63**	*04/22/1962*	*2,620*	n	n	**113**	----	----	n	n
14	*03/23/1913*	*2,200*	n	n	**64**	*11/10/1962*	*724*	n	n	**114**	----	----	n	n
15	*06/05/1914*	*4,580*	n	n	**65**	*11/11/1963*	*423*	n	n	**115**	----	----	n	n
16	*05/19/1915*	*4,070*	n	n	**66**	*06/22/1965*	*3,790*	n	n	**116**	----	----	n	n
17	*05/12/1916*	*6,000*	n	n	**67**	*05/11/1966*	*1,330*	n	n	**117**	----	----	n	n
18	*06/20/1917*	*7,840*	n	n	**68**	*08/13/1967*	*1,110*	n	n	**118**	----	----	n	n
19	*06/16/1918*	*1,670*	n	n	**69**	*06/01/1968*	*2,470*	n	n	**119**	----	----	n	n
20	*05/25/1919*	*5,090*	n	n	**70**	*06/19/1969*	*2,730*	n	n	**120**	----	----	n	n
21	*05/27/1920*	*9,320*	n	n	**71**	*09/18/1970*	*1,930*	n	n	**121**	----	----	n	n
22	*06/16/1921*	*12,600*	n	n	**72**	*03/30/1971*	*1,720*	n	n	**122**	----	----	n	n
23	*06/01/1922*	*7,300*	n	n	**73**	*03/16/1972*	*856*	n	n	**123**	----	----	n	n
24	*06/17/1923*	*4,120*	n	n	**74**	*05/23/1973*	*3,560*	n	n	**124**	----	----	n	n
25	*05/21/1924*	*7,670*	n	n	**75**	*04/01/1974*	*784*	n	n	**125**	----	----	n	n
26	*02/14/1925*	*1,180*	n	n	**76**	*06/18/1975*	*2,490*	n	n	**126**	----	----	n	n
27	*06/04/1926*	*3,330*	n	n	**77**	*05/31/1976*	*1,450*	n	n	**127**	----	----	n	n
28	*07/03/1927*	*9,830*	n	n	**78**	*03/22/1977*	*405*	n	n	**128**	----	----	n	n
29	*06/01/1928*	*3,960*	n	n	**79**	*07/01/1978*	*979*	n	n	**129**	----	----	n	n
30	*05/27/1929*	*3,580*	n	n	**80**	*06/10/1979*	*4,830*	n	n	**130**	----	----	n	n
31	*06/01/1930*	*1,590*	n	n	**81**	*06/13/1980*	*3,230*	n	n	**131**	----	----	n	n
32	*03/22/1931*	*900*	n	n	**82**	*12/05/1980*	*360*	n	n	**132**	----	----	n	n
33	*05/24/1932*	*5,780*	n	n	**83**	*06/01/1982*	*1,950*	n	n	**133**	----	----	n	n
34	*06/03/1933*	*2,290*	n	n	**84**	*06/29/1983*	*3,230*	n	n	**134**	----	----	n	n
35	*02/19/1934*	*663*	n	n	**85**	*05/31/1984*	*3,390*	n	n	**135**	----	----	n	n
36	*06/18/1935*	*4,600*	n	n	**86**	*06/13/1985*	*6,240*	n	n	**136**	----	----	n	n
37	*05/07/1936*	*2,540*	n	n	**87**	*06/11/1986*	*6,180*	n	n	**137**	----	----	n	n
38	*05/19/1937*	*4,370*	n	n	**88**	*05/19/1987*	*6,760*	n	n	**138**	----	----	n	n
39	*05/02/1938*	*4,040*	n	n	**89**	*04/10/1988*	*848*	n	n	**139**	----	----	n	n
40	*03/24/1939*	*1,640*	n	n	**90**	*04/11/1989*	*1,870*	n	n	**140**	----	----	n	n
41	*05/19/1940*	*1,190*	n	n	**91**	*05/10/1990*	*1,860*	n	n	**141**	----	----	n	n
42	*05/16/1941*	*8,090*	n	n	**92**	*05/23/1991*	*2,130*	n	n	**142**	----	----	n	n
43	*05/13/1942*	*5,580*	n	n	**93**	*04/15/1992*	*1,700*	n	n	**143**	----	----	n	n
44	*05/04/1943*	*1,400*	n	n	**94**	*05/30/1993*	*3,890*	n	n	**144**	----	----	n	n
45	*05/18/1944*	*6,440*	n	n	**95**	*06/03/1994*	*2,320*	n	n	**145**	----	----	n	n
46	*05/12/1945*	*2,880*	n	n	**96**	*07/05/1995*	*6,330*	n	n	**146**	----	----	n	n
47	*11/12/1945*	*822*	n	n	**97**	*02/20/1996*	*650*	n	n	**147**	----	----	n	n
48	*05/11/1947*	*1,960*	n	n	**98**	*06/05/1997*	*3,610*	n	n	**148**	----	----	n	n
49	*06/07/1948*	*8,600*	n	n	**99**	*10/15/1997*	*2,100*	n	n	**149**	----	----	n	n
50	*06/22/1949*	*9,330*	n	n	**100**	*06/20/1999*	*2,310*	n	n	**150**	----	----	n	n

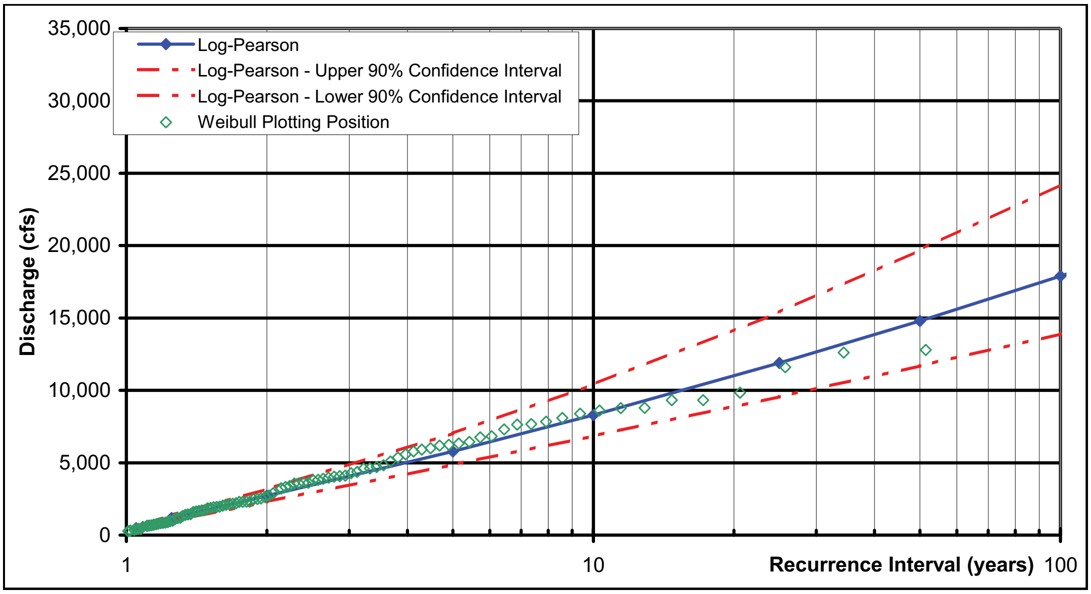
NRCS 2006

Figure 5–6 Sheet 3 of log-Pearson spreadsheet output for USGS gage 08251500

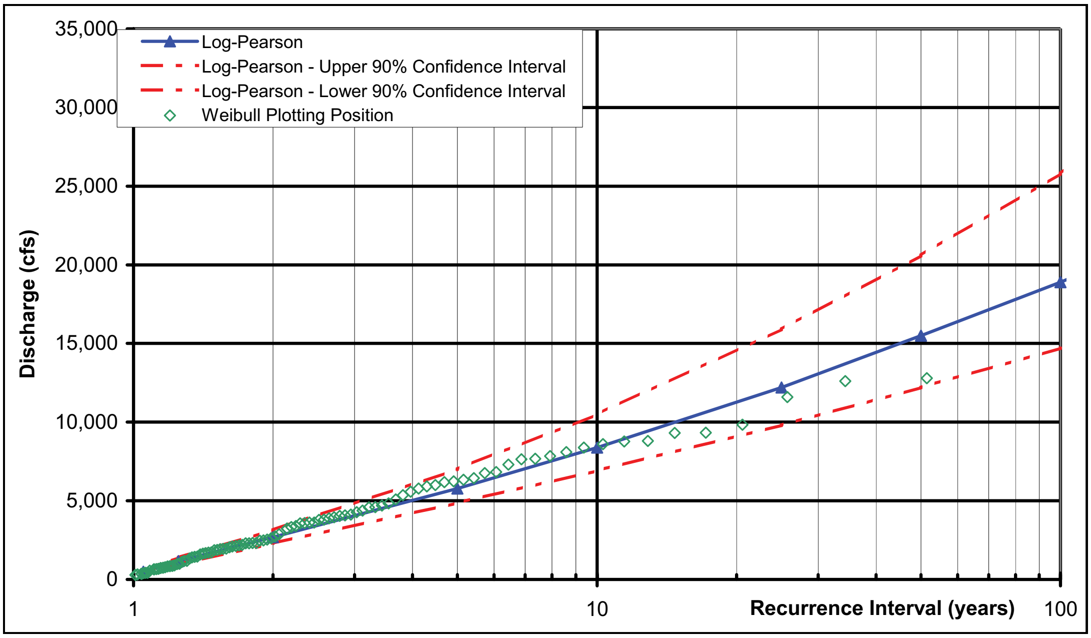
NRCS Log-Pearson Frequency Analysis Spreadsheet, Version 2.1, 5/2003 *Page 3 of 3*

Project: *Example 5-5-3*
Streamgage: # *USGS 08251500 RIO GRANDE NEAR LOBATOS, CO.*
Date: ######## **Performed By:** *Steve Yochum; Hydrologist, Northern Plains Engineering Team*

Discharge-Frequency, with Gage Skew
 # USGS 08251500 RIO GRANDE NEAR LOBATOS, CO



Discharge-Frequency, with Generalized Skew
 # USGS 08251500 RIO GRANDE NEAR LOBATOS, CO



NRCS 2006

charges may also be transferred or correlated from gage data from a nearby stream with similar basin characteristics.

Several equations and techniques exist for data transfer. Equation 5–28 is a simple transfer equation:

$$Q_u = Q_g \left(\frac{A_u}{A_g} \right)^x \qquad \text{(eq. 5–28)}$$

where:
Q_u = flood discharge at the ungaged stream
Q_g = flood discharge at the gaged stream
A_u = area at the ungaged stream
A_g = area at the gaged stream
x = regional exponent for area ratio (typically from 0.5 to 1)

Equation 5–28 can be used to develop comparative estimates. The regional exponent is computed by plotting a graph of flows for the same return period and similar basins, and then determining the slope of the best fit line on log–log paper. Example 6 illustrates the calculation. Again, specific regional data are needed for each state, and each hydrologic region within the state.

Transposition of peak flow rates is adversely affected by large differences in watershed lag times, runoff generated from small area thunderstorms, large differences in drainage area size, and differences in soils and vegetative cover. For transfer relations to be effective, the following conditions should be met:

- The drainage area ratio between the gaged and the ungaged area should be two or less.
- The watershed at the gaged location and ungaged watershed must be in the same climatic and physiographic region.

The more deviation exists from these two conditions, the more it is recommended that calculated values be compared with other sources such as regional regression data and computer models.

Low-flow frequency analysis

A project design may require a low-flow assessment for biological design elements or requirements. For example, it may be necessary to know the flow depths and velocities during a defined critical spawning time in a designed channel. A reference similar to WRC Bulletin 17B is not available for low-flow frequency analysis. However, the same log-Pearson type III frequency distribution, used for peak flow analysis, is often used for low-flow analysis.

In the United States, annual minimum flows usually occur in late summer and early fall. The annual minimum average flow for a specified number of consecutive days (usually 7 days) is the typical data point. Computationally, the annual minimum 7-day flow may be found as the annual minimum value of 7-day means. The USGS provides access to daily mean flow values at stream gages across the United States at:

http://waterdata.usgs.gov/nwis

As is done in peak discharge analysis, the mean and standard deviations of the logarithms of the data values are calculated. Then log-Pearson type III frequency factors are applied to assign frequencies or probabilities to the low-flow magnitudes. The frequencies are nonexceedance probabilities. Equation 5–1 is still applicable, but the practitioner needs to be cautioned regarding the meaning of the statistics. For example, the 50-year, 7-day low flow has a 2 percent annual chance of not being exceeded. For comparison, the 50-year peak flow has a 2 percent annual chance of being exceeded.

Inclusion of a period of substantial drought helps ensure that a data sample is representative for low-flow conditions. It should also be noted that the effects of basin development are relatively greater for low flows than for high flows.

Transfer of low-flow frequency estimates to ungaged sites is difficult because of the geologic influence on low flows. If basin characteristics are very similar, drainage area ratios may be used to transfer low-flow data from gaged to ungaged sites. A few low-flow measurements at the ungaged site are good verification for the transferred data.

Example 6: Transfer method

Problem: The gage site has a drainage area of 10 square miles (fig. 5–7). The designer needs an estimate of the 100-year flow at a drainage area of 20 square miles.

Solution: The regression equation developed from the regional data for 100-year flow values, developed from frequency analysis of stream gages in the area, is as follows:

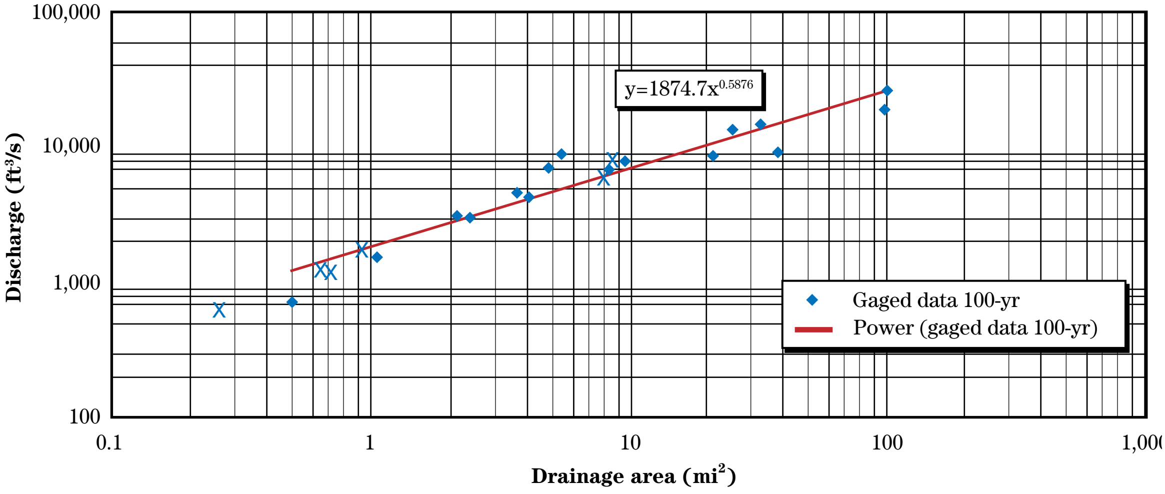
The value or intercept is the coefficient of the equation for a drainage area of 1 square mile (in log units = 0), and the intercept is 1,874.7.

The power of the equation is the slope of the line and is determined in log units as the discharge at 10 square miles, 7,253 cubic feet per second or 3.86 in log units. For a 1-square-mile drainage area, the discharge is 1,874.7 cubic feet per second and in log units is 3.27. The slope would be (3.86–3.27)/1 or 0.59.

Therefore, the 100-year flow at 20 square miles would be:

$$Q_u = 7{,}253\left(\frac{20}{10}\right)^{0.59} = 10{,}917 \text{ cubic feet per second}$$

Figure 5–7 100-yr discharges for the Rock Creek watershed in Montgomery County, MD



654.0505 Regional regression

Cost-effective designs for stream restoration, floodwater retarding structures, and many other conservation practices require peak streamflow frequency estimates. Peak streamflow frequency estimates represent peak discharges for return periods, generally ranging from 2 to 100 years. A regression equation for estimating peak discharges may be developed by statistically relating peak streamflow frequency and drainage basin characteristics for a geographic region of similar flood characteristics.

(a) Basic concepts

Regression forms

Regression is a method for developing a relationship between a dependent (Y) variable and one or more independent (X), predictor variables (NEH630.02, Hydrology). Regression assumptions are:

- No error exists in the independent variable; errors occur only in the dependent variable. Thus, regression is directional.
- Predictor variables are statistically independent.
- The observed values of the dependent variable are uncorrelated events.
- The population of the dependent variable is normally distributed about the regression line.
- A cause-and-effect relationship exists between predictor and dependent variables.

Regression is used to analyze hydrologic data because it provides an easy method for analyzing many factors simultaneously. The simplest form of the linear regression equation, with one predictor variable (X), is written as:

$$Y = a + bX \qquad \text{(eq. 5–29)}$$

where a and b are the intercept and slope regression coefficients. A more complicated form is the linear multiple regression equation, which relates a dependent variable and multiple predictor variables:

$$Y = b_0 + b_1X_1 + b_2X_2 \cdots + b_pX_p \qquad \text{(eq. 5–30)}$$

where:

Y = dependent variable, such as 100-year discharge
$b_0, b_1, b_2, \ldots, b_p$ = partial regression coefficients
$X_1, X_2, \ldots, X_p$ = independent (predictor) variables

Linear regression calculations are tedious by hand and are usually performed with the aid of programmed procedures on a computer. Example calculations may be found in NEH630.18.

Evaluating regression equations

One of the most commonly used measures of goodness of fit is the coefficient of determination, usually expressed as R^2. It is the dimensionless ratio of the explained variation in the dependent variable over the total variation of the dependent variable. A coefficient of determination of 1.0 indicates that the values of the dependent variable can be calculated exactly using the predictor variables in the given data set. The lower the R^2 value, the less direct the relation is and the wider the scatter in the data. Since this value is dimensionless, it can be used to compare goodness-of-fit of different regression equations. It does not provide a quantified expected variation. If a relationship is nonlinear, the regression coefficients will be dependent on the choice of independent variables, as well as on the curve fit relationship.

It should also be noted that a high degree of correlation (R^2 close to 1.0) does not necessarily mean that there is either causation or even a direct dependence between the variables. It only indicates that the given set of data can be predicted with the regression equation. In all circumstances, the reasonableness of the relationship between independent and dependent variables should be examined. Extremely high R^2 values (0.95 and above) can indicate bias in the data collection or an insufficient number of collected data points for the order of the calculated regression equation. For example, if only two data points are collected, a straight line regression equation between the two will have an R^2 value of 1.0.

Another measure of the quality of a regression equation is the standard error of estimate, typically expressed as $S_{Y,X}$. This is the root mean square of the estimates and is a measure of the scatter about the regression line of the independent variable. The standard error of estimate is not reflexive. It shows how well the dependent variable correlates to the independent variable, but not vice versa. The standard error of estimate has similar properties to the standard deviation and can be thought of as the standard deviation of the residuals. A residual is the difference between the value predicted with the regression equation and the observed dependent variable. As the standard error of estimate approaches 0, the quality of the regression equation increases.

Step-type regressions can be used to evaluate the significance of each predictor variable in a regression equation. The significance of adding or deleting predictor variables is evaluated with an F-test. A computed F greater than a table F-value indicates significance (see NEH 630.18 for more details). For example, a step forward regression starts with the most important predictor as the only variable in the equation. The most important of the remaining predictors is added, and the F-value computed. If this predictor is significant, another of the remaining predictors is added, and the process repeated. When a predictor is not found significant, the previous equation, not including that predictor, is used for analysis.

(b) Regional analysis

Regional study helps assure consistency of estimates at different locations and provides means for estimating discharge-frequency values at locations where gaged data are not available. Also, flow discharge estimates at a gaged location can usually be improved by a study of gaged frequency characteristics throughout the region.

Simplified regional study method

Regional analysis allows the estimation of peak discharge magnitude and frequency for ungaged watersheds by using relationships from nearby gaged watersheds. NEH630.02, Hydrology, provides the regional analysis in its simplest form.

- Select nearby gaged watersheds that are climatically and physically similar to the ungaged watershed.
- Construct frequency lines of peak discharges for each gaged watershed.
- Plot peak discharges for selected frequencies of each gaged watershed against its drainage area. Use log-log paper for plotting. A simple regression (curve fitting) between log of drainage area (predictor variable) and log of discharge (dependent variable) aids in drawing a best fit straight line for each selected frequency.
- Construct the frequency line for the ungaged watershed as follows: enter the plot with the ungaged drainage area, find and plot the discharges on log-probability paper, and draw the frequency line through the points.

Use of regression equations

Regression equations are used to transfer flood characteristics from gaged to ungaged sites through use of watershed and climatic characteristics as predictor variables. The USGS has developed regional regression equations for each state and some territories, usually as part of cooperative studies with state departments of transportation (USGS 2002a, Report 02–4168).

General descriptions of techniques that USGS uses in developing regression equations follow. Frequency lines of peak discharges are developed at gaging stations following the recommendations of WRC Bulletin 17B (WRC 1981).

The regression equations generally take the form:

$$Q_T = aX^bY^cZ^d \qquad \text{(eq. 5–31)}$$

where:

Q_T = peak discharge of selected frequency; 100-year discharge (dependent variable)

X,Y,Z = watershed or climatic characteristics (predictor variables)

a,b,c,d = regression coefficients

With the log transform, the equation takes the form of equation 5–30. The most often used watershed and climatic characteristics are drainage area, main channel slope, and mean annual precipitation. Regression regions are generally determined by using major watershed boundaries and an analysis of the areal distribution of the residuals. As noted above, residuals are the differences between regression and observed flow estimates. For USGS regression equations, the region has already been predetermined for the end user. Regression equation use is illustrated in example 7.

Example 7: USGS regional equation (USGS Report 96–4307)

An ungaged watershed is located in Region 5, Texas. The watershed has a drainage area (A) of 13.2 square miles and stream slope (SL) of 71.3 feet per mile, determined with the aid of USGS 7.5 min quadrangle maps. The following regression equation applies for estimating the 100-year discharge:

$$Q_{100} = 295A^{1.01}\left(SL\right)^{0.405} = 22{,}500 \text{ ft}^3\text{/s}$$

Report 96–4307 gives a standard error of estimate of 78 percent. This means that there is roughly a two-thirds chance that the true 100-year discharge falls between 4,950 cubic feet per second and 40,050 cubic feet per second. Report 96–4307 also gives a means to calculate more exact confidence intervals (not shown here). An output report for the same ungaged watershed, generated by the USGS National Flood Frequency Program, follows:

```
National Flood Frequency Program
Version 3.0
Based on Water-Resources Investigations Report 02-4168
Equations from database NFFv3.mdb
Updated by kries 10/16/2002 at 3:51:06 PM new equation from WRIR 02-4140
Equations for Texas developed using English units

Site: MilldamTX, Texas
User: lgoertz
Date: Thursday, July 10, 2003 04:26 PM

Rural Estimate: Rural 1
  Basin Drainage Area: 13.2 mi2
  1 Region
  Region: Region_5_(A<32mi2_(51km2))
   Contributing_Drainage_Area = 13.2 mi2
   Stream_Slope = 71.3 ft/mi

Flood Peak Discharges, in cubic feet per second

             Recurrence    Peak,  Standard   Equivalent
Estimate     Interval, yrs cfs    Error, %   Years
___________ _____________  _____  ________   __________

Rural 1            2        919       75
                   5       2910       63
                  10       5180       66
                  25       9310       69
                  50      15900       72
                 100      22500       78
                 500      50600
```

Accuracy and limitations
The standard errors of estimate or prediction range from 30 to 60 percent for most regression equations. The largest standard errors generally are for equations developed for the western part of the Nation, where the variability of the flood records is greater, gaging stations are less dense, and flood records are generally shorter. Regression equations developed from gaged natural basins should only be used on natural basins to make regression estimates. A natural basin may be defined as a basin with less than 10 percent impervious cover and less than 10 percent of its drainage area controlled or manipulated to affect peak stream flow. Users should exercise caution in extrapolating flood estimates beyond the ranges of predictor variables used in developing the equations.

Regression equations are not as accurate as frequency analysis from gaged data. For design purposes in high risk situations, both regression equations and hydrologic modeling methods should be employed.

(c) Computational resources for regional regression analysis of peak flows

The USGS has developed and published regression equations for a variety of locations within the United States. These equations have been compiled into the National Flood Frequency (NFF) Program. A computer program, National Flood Frequency Program, version 3: A Computer Program for Estimating Magnitude and Frequency of Floods for Ungaged Sites provides access to this information. The following USGS Web site provides regional regressions for flood peaks developed for many regions throughout the United States:

http://water.usgs.gov/software/nff.html

Regional regression relationships for bankfull discharge
Bankfull discharge regional regression relationships can present some different issues to a designer than relationships for peak flows. However, the basics remain the same. Information on developing regional regression relationships for bankfull discharge is provided in NEH654 TS5.

654.0506 Flow duration

Flow duration is the percentage of time that a given flow was equaled or exceeded over a period of time. A flow-duration curve for stream flow represents the hydrograph of the average year (or season) with its flows arranged in order of magnitude. For example, the flow value in the average year to be exceeded 20 percent of the time may be read from the flow-duration curve for that location.

Flow-duration curves have been used in the analysis of sediment transport quantities, critical habitat functions, water quality management alternatives, and water availability. It is often important to determine how the proposed restoration project will perform with low or normal flows. While flow-duration curves are typically calculated for several (usually >10) years of homogeneous record, they can be developed for specific seasons since seasonal flow variations can have critical habitat importance. For example, a project goal may include a minimum flow depth during a critical spawning period for anadromous fish species and a lower minimum depth for resident fish species. The same techniques used to develop flow-duration curves for sediment analysis can also be used to assess and design for habitat conditions. An example is provided in figure 5–8.

The USGS has developed flow-duration curves for many gaged locations in the United States. These curves are normally available on request from the USGS. The construction procedure used by USGS is outlined in Searcy (1959). Procedures for developing flow-duration curves are also described in Hydrologic Frequency Analysis, EM 1110–2–1415 (USACE 1993a). Data are typically sorted by magnitude, and the percent of the time that each value is exceeded is calculated. Since the data points are typically daily averages, each point will not necessarily be independent. This is a relatively simple statistical analysis. Data bin ranges are developed, and the numbers of occurrences are counted for each bin. For example, the number of times the flow was between 500 and 1,000 cubic feet per second would be counted. Then the percent of occurrence is assembled as a cumulative distribution function to define the percent of time that the flow is above a certain discharge or level. Flow-duration analysis is performed by using daily average flow (or other periods such as 3-day, 5-day, or weekly) during the period of interest. Historical and real time daily average flow data can be found at the following USGS Daily Flow Stream Gage Data Web site:

http://nwis.waterdata.usgs.gov/usa/nwis/discharge

The data can be stratified by seasons for this analysis, depending on study goals. The information can be for the entire period of record. However, if the watershed has undergone some significant change (as is typical in many stream restoration projects), it may be necessary to use only the record since the change has occurred. This is necessary to keep the data homogeneous.

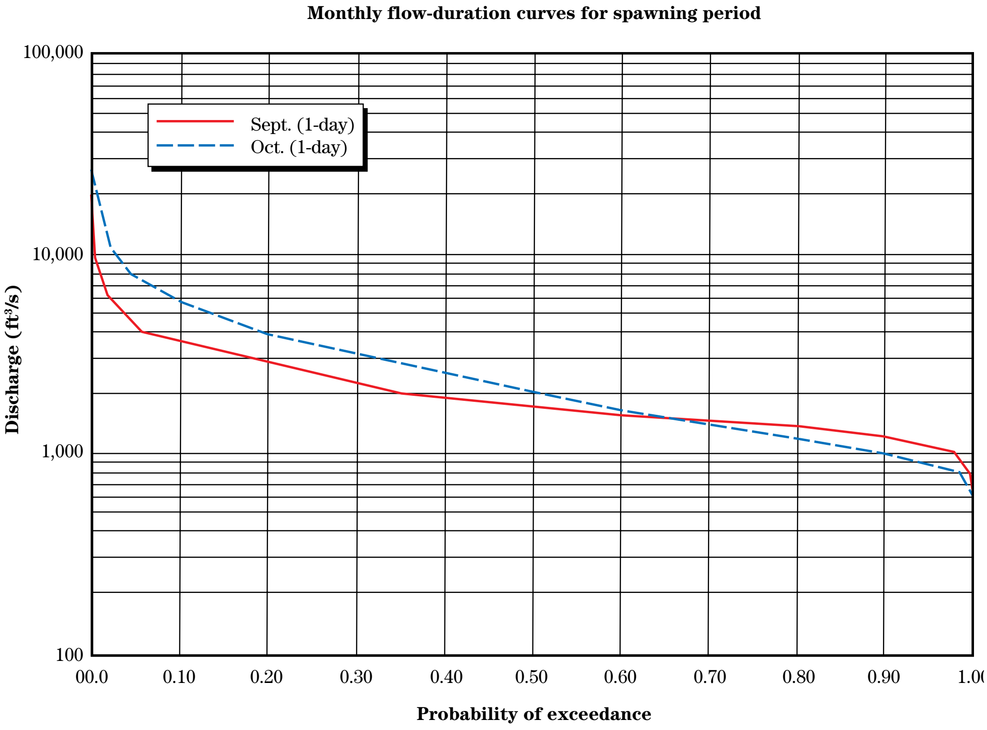
Transfer methods, as described earlier, can be used to transfer flow duration information from gaged sites to ungaged areas. However, these should have similar watershed characteristics, and the ratio of gaged to ungaged drainage area should be between 0.5 and 2.0 for reliable results. The accuracy of such a procedure is directly related to the similarity of the two sites. Typically, there is more error in transferring or estimating the ends of a flow-duration curve. Flow duration is dependent on watershed conditions. If regional flow-duration relations are to be developed, it is recommended that a measure of watershed conditions be included as an independent variable.

Two methods for estimating a flow-duration curve for ungaged sites are described by Biedenharn et al. (2000). They are the:

- drainage area flow-duration curve method
- regionalized-duration curve method

Graphs for the drainage area flow-duration curve method, for a specified recurrence interval discharge versus drainage area, are developed for a number of sites on the same stream or within hydrological similar portions of the same drainage basin. If data are reason-

Figure 5–8 Typical flow-duration curve



ably homogeneous, regression techniques should be used to generate curves of flow for selected percentile versus drainage area. By knowing the drainage area of the selected site(s), a flow-duration curve can be generated from the regression equations.

With the regionalized duration curve method, a nondimensional flow-duration curve is developed for a hydrologically similar gaged site by dividing discharge by bankfull discharge or by a specified recurrence interval discharge. Then a specified recurrence interval discharge is computed for the ungaged site using the aforementioned regression equations. Finally, the flow-duration curve for the ungaged site is derived by multiplying the dimensionless flows (Q/Q_2) from the nondimensional curve by the site Q_2. It should be noted that both methods simply provide an approximation to the true flow-duration curve for the site because perfect hydrologic similarity never occurs.

654.0507 Hydrologic models

There are many mathematical and computer hydrologic modeling systems available for predicting runoff from precipitation and snowmelt events that provide the volume and timing of water moving through the system. Models provide the ability to estimate existing, as well as future rainfall runoff patterns for a variety of conditions. Depending on the hydrologic model used, either single event peak flow or continuous multiple event modeling can be performed.

The accuracy of models is highly dependent on calibration data, which can often be difficult to acquire. However, if the issues that are to be addressed are comparative in nature rather than absolute, the importance of calibration is diminished. However, the results of a model study should fall between the USGS regional regression equation for the site and the upper bounds of one standard error of estimate. If the results of the model calibration are not within these bounds, after adjustment of the model parameters within reasonable limits, the reasons for the final answer and its derivation must be explained in the project documentation.

The level of accuracy required for a specific hydrologic analysis generally depends on the specific characteristics of each individual project. The selection of the appropriate methodology should be done with a firm understanding of the assumptions, accuracy, data requirements, and limitations of the approach. Brief statements on the use of the models are provided.

The rational method (rational formula) is one of the easiest models to implement. It can be used for drainage areas up to 80 hectares (200 acres). Use of the rational formula on larger drainage areas requires sound judgment to ensure reasonable results. The hydrologic assumptions underlying the rational formula include:

- constant and uniform rainfall over the entire basin
- a rainfall duration equal to the time of concentration

The rational method is not appropriate if:

- the basin has more than one main drainage channel

- the basin is divided so that hydrologic properties are significantly different in one section versus another
- the time of concentration is greater than 60 minutes
- storage is an important factor

The NRCS TR–55 method (USDA Soil Conservation Service (SCS) 1986) provides a manual method for computing peak discharges for drainage basins. The TR–55 method is segmental (flow time is computed by adding the travel times for the overland, shallow concentrated, and channel segments). TR–55 considers hydrologic parameters such as slope of the watershed and channel, channel roughness, water losses, rainfall intensity, soil type, land use, and time. TR–55 should be used with caution when the design is highly sensitive to the computed peak flow values. TR–55 also assumes that rainfall is uniform over the entire basin. Additional assumptions include:

- the basin is drained by a single main channel or by multiple channels with times of concentration that are nearly equal
- the weighted curve number should be greater than 40
- runoff from snowmelt or rain on frozen ground cannot be estimated using the procedures in TR–55
- the time of concentration should be between 0.1 and 10 hours
- storage in the drainage area is less than 5 percent of the runoff volume and does not affect the time of concentration
- a single composite curve number can accurately represent the watershed runoff characteristics

A computer program has been developed to automate the manual procedures in TR–55. The computer program developed in the Windows® environment is known as WinTR–55. The WinTR–55 computer program is available at the following Web site:

http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-wintr55.html

The HEC–1/HEC–HMS models are rainfall-runoff models developed by the USACE Hydrologic Engineering Center (USACE 1981). These models can be used with basins of almost any size and complexity. HEC–1 is designed to simulate the surface runoff resulting from precipitation over a watershed by representing that watershed as an interconnected system of components. These components consist of surface runoff, stream channels, and reservoirs. Each component is represented by a set of parameters, which specify its characteristics, and the mathematical relations, which describe its physical processes. The end result of the HEC–1 modeling process is the computation of runoff hydrographs for the subbasins and stream channels. The program is composed of five basic sub models as illustrated in figure 5–9.

HEC–1 assumes that the rainfall is spatially uniform over each subbasin modeled. NRCS rainfall time distributions, loss methods, dimensionless unit hydrographs, and the lag equations often are used; however, careful consideration must be given to the assumptions and limitations underlying these methods. For example, the NRCS has published an upper limit on basin size for the NRCS lag equation of 800 hectares (2,000 acres, 3.1 mi^2) (NEH630.15). The upper limit on basin area for the NRCS Loss Method (runoff curve number) is not well established; however, a limit of 20 square miles has been suggested. These limitations may be overcome by subdivision of the watershed and appropriate routing. Various GIS packages can be used as an interface to HEC–1. These GIS techniques systematize the computation of the physiographic and hydrologic parameters required by HEC–1.

The WinTR–20 model is a rainfall-runoff model developed by the NRCS (USDA NRCS 2004). It can be used with basins of almost any size and complexity. WinTR–20 is designed to simulate the surface runoff resulting from precipitation over a watershed by representing that watershed as an interconnected system of components. These components consist of surface runoff stream channels and reservoirs. The program is composed of five submodels as illustrated in figure 5–9. Normally, it is assumed that the rainfall is uniform over each subbasin. However, that rainfall total can be varied for each subbasin. Actual or design temporal rainfall distributions can be used with standard dimensionless unit hydrographs that are part of the normal inputs. Several GIS computer programs that can be used to develop the areal input values such as curve numbers are available. NRCS has developed a GIS computer program that provides geographical information in the proper format for WinTR–20 (USDA NRCS 2004). The program is available from the following Web site:

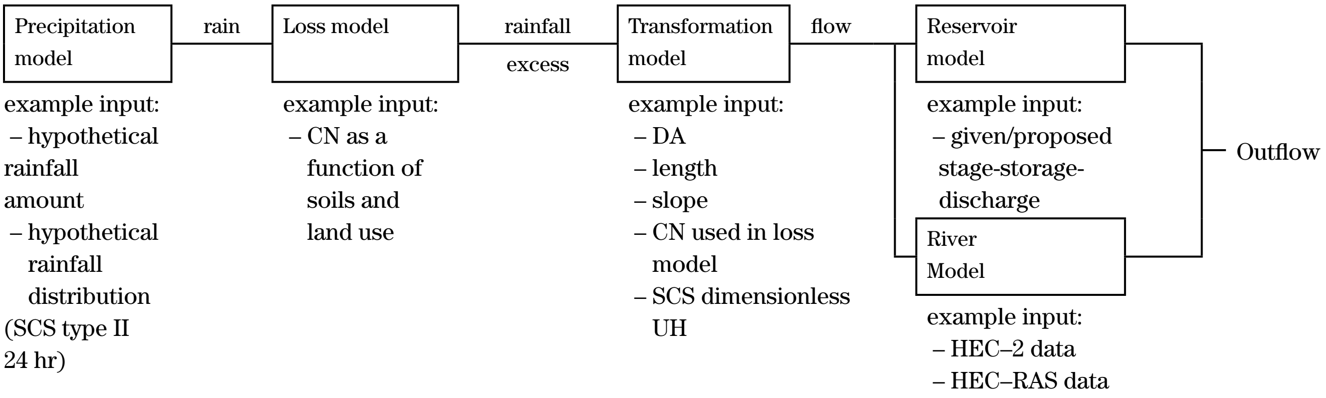
www.wcc.nrcs.usda.gov/hydro/

Use of these models is fairly common in ungaged systems, or in areas where land use and stormwater detention systems significantly alter the hydrograph. With the advent and collection of soil, vegetation, topography and land use types in GIS, model development and database management is a simpler process.

654.0508 Channel-forming discharge

Natural alluvial streams experience a wide range of discharges and adjust their shape and size during flow events that have sufficient energy to mobilize the channel boundary materials. Until the 1960s, it was widely assumed that floods of great magnitude, but low frequency, controlled channel form because of the nonlinear relationship between discharge and sediment transport capacity. Sediment transport increases exponentially with discharge. This view was challenged by Wolman and Miller (1960) who argued that in most streams, over an extended period of time, the total amount of sediment transported by a discharge of a given magnitude depends not only on its transport capacity, but also its frequency of occurrence. Thus, although extremely large events can produce spectacularly high sediment loads, they happen so infrequently and last such a short time that their overall contribution to the total sediment movement during a long period is relatively small. Small events also make a small contribution to the total sediment moved because their high frequency of occurrence is offset by their very low sediment transport capacity. It follows from this logic that flow of both moderate magnitude and moderate frequency is responsible for the greatest

Figure 5–9 Five basic submodels of a rainfall/runoff model



amount of sediment movement (Leopold, Wolman, and Miller 1964). However, recent studies have indicated that this concept may not hold true for all streams (Werrity 1997).

Channel-forming discharge concept

The channel-forming discharge concept is based on the idea that, for a given alluvial channel, there exists a single steady discharge that, given enough time, would produce channel dimensions equivalent to those produced by the natural hydrograph. This discharge is thought to dominate channel form and process. Estimates of channel-forming discharges are used to classify stream types, estimate channel dimensions, assess stability, and express hydraulic geometry relationships.

While many techniques and methodologies are used to estimate a channel-forming discharge in stable alluvial channels, all can be characterized as one of four main types. These are:

- discharge based on bankfull indices
- discharge based on drainage area
- discharge based on specified statistical recurrence intervals
- discharge based on an effective discharge calculation

Discharge based on bankfull indices

Channel-forming discharge based on bankfull indices is determined by visually inspecting the reach in question or surveys of this reach to locate morphological evidence of the bankfull stage. The discharge associated with this stage is then computed or estimated. Identifying relevant features that define the bankfull stage can be problematic (Williams 1978), particularly in dynamic, unstable channels (Simon, Dickerson, and Heins 2004). Many field indicators have been proposed and are briefly described in table 5–10.

Identifying bankfull stage from indicators is subjective. None of the bankfull indicators is applicable in all situations (Williams 1978). Many workers use a combination of the indices in an iterative fashion. However, even experienced observers may arrive at conflicting or misleading results, particularly for conditions outlined in table 5–11.

The field identification of bankfull indicators is particularly problematic in stream reaches that are unstable or threshold. If the project reach is not stable or alluvial, it may be possible to find indicators of bankfull stage in stable alluvial reaches upstream or downstream. However, since stream restoration is most often practiced in unstable watersheds, field determination of bankfull stage may be impractical or impossible (Copeland et al. 2001). An exception could be found in a stable and alluvial incised stream that has formed a new flood plain within the incised channel. In this case, the top of the high bank is now an abandoned flood plain or terrace, and there should be newly formed top-of-bank features within the older incised channel. However, it is important to remember that the new flood plain may not yet be fully formed; that is, the channel may not be stable and may still be aggrading. In addition, a new inset flood plain (sometimes referred to as incipient flood plain) may be restricted in width or height due to channel constraints. Measurements taken in such situations would give misleading values for the bankfull discharge.

When applying the estimate of bankfull stage from one reach to another, it is important to keep in mind that the location of the break between the channel and the flood plain is influenced by many factors, including (but not limited to) the following:

- climatic regime (humid vs. arid)
- geologic erosion conditions of the streambank materials (bedrock vs. unconsolidated material; coarse vs. fine textures; cohesive vs. noncohesive)
- stream slope
- hydrologic regime (perennial vs. intermittent versus ephemeral)
- sediment source, quantity and supply including distribution along the active channel and flood plain.
- stream confinement or width
- stream downcutting or incisement
- size and type of vegetation on the flood plain and within the channel
- controls on channel width and alignment such as riprap and bridge abutments

Table 5–10 Summary of bankfull indices

Bankfull indicator	Reference
Minimum width-to-depth ratio	Wolman (1955) Pickup and Warner (1976)
Highest elevation of channel bars	Wolman and Leopold (1957)
Elevation of middle bench in rivers with several overflow sections	Woodyer (1968)
Minimum width-to-depth ratio plus a discontinuity (vegetative and or physical) in the channel boundary	Wolman (1955)
Elevation of upper limit of sand-sized particles in boundary sediment	Leopold and Skibitzke (1967)
Elevation of low bench	Schumm (1960); Bray (1972)
Elevation of active flood plain	Wolman and Leopold (1957) Nixon (1959)
Lower limit of perennial vegetation	Schumm (1960)
Change in vegetation (herbs, grass, shrubs)	Leopold (1994)
A combination of: • elevation associated with the highest depositional features • break in bank slope • change in bank material • small benches and other inundation features • staining on rocks • exposed root hairs	Rosgen (1994)

Table 5–11 Summary of stream conditions that affect bankfull indices

Reach condition	Process	Effect on bankfull indices
Threshold	Sediment transport capacity of the reach exceeds the sediment supply, but the channel grade is stable	Bankfull indices may be relics of extreme flood events, and may indicate a bankfull flow that is too high
Degrading	The sediment transport capacity of the reach exceeds the sediment supply to the reach, and the channel grade is lowering	The former flood plain is in the process of becoming a terrace. As a result, bankfull indices may indicate a flow that is too high
Aggrading	The sediment transport capacity of the reach is less than the sediment supply	The existing flood plain or in channel deposits may indicate a flow that is too low
Recently experienced a large flow event	Erosion and/or deposition may have occurred on the bed and banks	Bankfull indices may be missing or may reflect the large flow event
Channelized	Sediment transport capacity may not be in balance with sediment supply. The channel may be aggrading or degrading. The reach may be functioning as a threshold channel	Bankfull indices may be relics of previous channel, artifacts of the construction effort, embryonic, or missing altogether

- controls on channel depth and slope such as drop structures, rock weirs, check dams, beaver dams, and cross vanes.

For example, the bankfull discharge measured from a reach with a narrow flood plain may be inappropriate for use on another reach of the same stream, which has a wide flood plain.

Once bankfull stages are estimated for a stream reach (generally over at least one meander wavelength or 10 channel widths); the bankfull discharge can be estimated. This is often done with either a resistance formula calculation such as Manning's equation or with a computer model such as HEC–RAS (Brunner 2002). Practitioners should keep in mind that the use of resistance equations such as Manning's equation or the Darcy-Weisbach equation, while rapid, are subject to the error inherent to the normal depth assumption. In addition, it should be noted that because stage is not a unique function of discharge in alluvial streams, some data scatter should be expected (Copeland et al. 2001). Uncertainty associated with stage-discharge relationships is addressed in more detail in standard manuals and texts (USACE 1996). Additional guidance on the identification of bankfull discharge indicators is provided in NEH654 TS5.

Discharge based on drainage area

Many relationships are available that correlate dominant discharge to drainage area. These offer a quick technique for assessing a dominant discharge. However, the practitioner should keep in mind that these relationships are basically best fit lines that are plotted through a data set. There is a distribution of valid bankfull discharge estimates that will fall both above and below the line. For example, figure 5–10 illustrates such a curve developed by Emmett (1975) for the Salmon River in Idaho. Although the regression line fits the data in a visually satisfactory fashion, it should be noted that for a drainage area of about 70 square miles, the bankfull discharge varied between about 300 and 900 cubic feet per second.

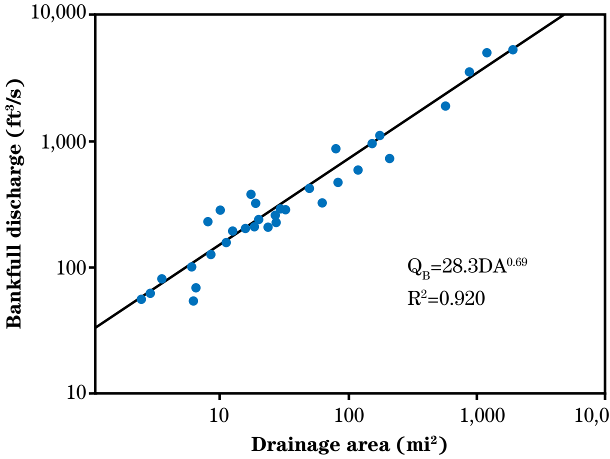
While drainage area is certainly an important factor in estimating streamflow, it is only one of many parameters affecting runoff. Caution should also be used when assessing the relevance of the relationship to watersheds in different physiographic areas or watersheds with different runoff characteristics. Finally, while drainage area is certainly an important factor to estimate streamflow, it is only one of many parameters affecting runoff.

Discharge based on a specific recurrence interval

Many practitioners have related the channel-forming discharge to a specific recurrence interval. The use of a recurrence interval to estimate the channel-forming discharge offers the advantage of being able to calculate a value using gage records, hydrologic modeling, or regional regression relations. Regression equations for estimating discharges with recurrence intervals from 2 to 100 years (Q_2 to Q_{100}) are available for the entire United States via *http://water.usgs.gov/software/nff.html*, as well as from many state and local organizations. This recurrence interval for channel-forming discharge is often assumed to correspond to fall between Q_1 and $Q_{2.5}$, with a mean of $Q_{1.5}$ (Leopold 1994).

However, there are many instances where the channel-forming discharge does not fall within the 1- to 2.5-year range. Williams (1978) showed that out of 35 flood plains he studied in the United States, the bankfull discharge (measured at top of bank) varied between the 1.01- and 32-year recurrence interval, and that only about a third of those streams had a bankfull discharge recurrence interval between 1 and 5 years.

Figure 5–10 Bankfull discharge as a function of drainage area for the Salmon River, ID



In a similar study, Pickup and Warner (1976) showed that bankfull recurrence intervals ranged from 4 to 10 years. The recurrence interval is usually calculated by determining the flow that corresponds to bankfull indices as addressed in the previous section. Therefore, the issues addressed that are associated with the reliable physical identification of bankfull discharge indices impact the calculation of the recurrence interval and may account for some of the discrepancies. Simon, Dickerson, and Heins (2004) used computations based on suspended-sediment transport to compute effective discharge for 10 gages on unstable sand-bed channels in Mississippi. The resulting values of effective discharge ranged from 0.56 to 2.72 of the $Q_{1.5}$, with a mean of 1.04 $Q_{1.5}$.

Nevertheless, the use of a specified recurrence interval is often used as a first approximation of channel-forming discharge. But, because of the noted discrepancies, field verification is generally recommended to ensure that the selected discharge reflects morphologically significant features.

Discharge based on an effective discharge calculation

The effective discharge is defined as the mean of the arithmetic discharge increment that transports the largest fraction of the annual sediment load over a period of years (Andrews 1980). The effective discharge incorporates the principle prescribed by Wolman and Miller (1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. An advantage of using the effective discharge is that it is a calculated value not subject to the problems associated with determining field indicators (Copeland et al. 2001). Effective discharge computation consists of three steps.

Step 1 The flow-duration curve is derived from available stream gage data.

Step 2 Sediment data or an appropriate sediment-transport function is used to construct a bed material sediment rating curve.

Step 3 The flow-duration curve and the bed material sediment rating curve are integrated to produce a sediment load histogram that displays sediment load as a function of discharge for the period of record. The histogram peak is the effective discharge increment.

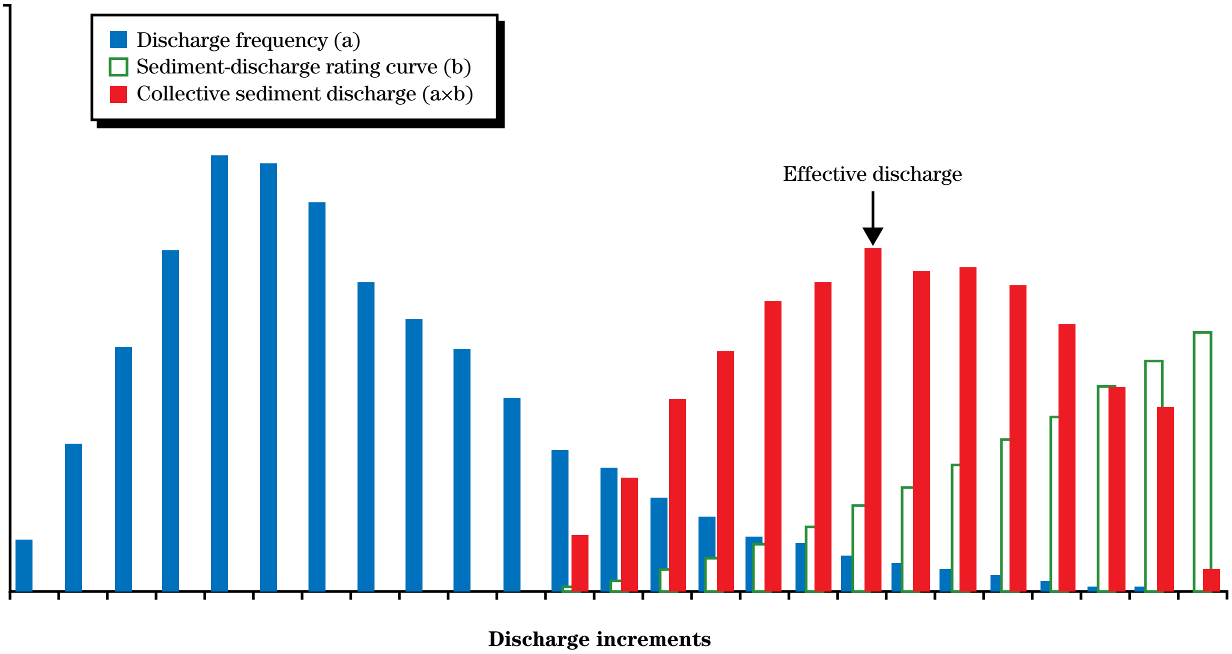
Specific instructions for calculating effective discharge can be found in the literature (Copeland et al. 2001; Biedenharn et al. 2000; and Thomas et al. 2000). Details of the procedure can influence the outcome, so study of these references is recommended. A graphical representation of the relationship between sediment transport, frequency of the transport, and the effective discharge is shown in figure 5–11. The peak of the effective discharge curve in figure 5–11 marks the discharge fraction that transports most of the material, and therefore, does the most work in forming the channel.

Effective discharge analyses may be performed for ungaged reaches by synthesizing a flow-duration curve and applying an appropriate sediment transport function to obtain a bed material sediment rating curve. Flow-duration curve synthesis may be done by plotting curves of discharge versus upstream drainage area for a given exceedance duration, using data from gages within the same watershed as the site of interest. A family of such curves may be created by varying the exceedance duration, and an appropriate flow-duration curve for the site of interest may be interpolated using its drainage area (Hey 1975). If flow-duration data are not available for adjacent gages, then regional information may be used after dividing discharge by either bankfull discharge or the 2-year discharge to produce a dimensionless ratio (Watson, Dubler, and Abt 1997). The dimensionless curve may be applied to the site of interest by multiplying by the base (Q_2 or bankfull Q) that is estimated using one of the aforementioned methods.

Since channel instability is the result of an imbalance in sediment supply and transport capacity, the greatest advantage of using effective discharge in restoration design lies in the fact that it requires quantification of the sediment transport capacity of a channel for a given hydrologic regime. Various channel geometries can be examined for their competence to transport the incoming sediment load, facilitating comparison of permutations of channel dimensions to optimize sediment transport efficiency within logistical constraints. This information is also useful when predicting the impact of alteration of watershed conditions with respect to sediment loads (upstream dam removal) or hydrology (urbanization) on channel stability (Copeland et al. 2001).

An important limitation of using an effective discharge analysis is that it is based on the assumption that the stream will transport the amount of sediment that it is hydraulically capable of moving, and it is this hydraulic capacity that forms the channel. In an urbanized watershed, once the urbanization is complete, the result is that the drainage area is partially covered so that the overland sediment yield reduced. In the Piedmont Region of Maryland, for example, many streams have degraded to bedrock or contain bed material that has been winnowed to a coarse gravel or cobble. These conditions, coupled with an increase in average annual flows, indicate that streams may have an excess sediment transport capacity. In this situation, the channel may be now operating as a threshold channel and the concept of effective discharge may not be relevant. Additional errors occur in effective discharge computations due to the assumption that sediment discharge is a continuous function of water discharge. Internal fluvial system thresholds or limitations on sediment supply may invalidate this assumption, leading to major errors at higher discharges (Nash 1994). An example calculation of effective discharge is provided in example 8.

Figure 5–11 Effective discharge calculation



Example 8: Effective discharge

Problem: Given the following flow-duration curve (fig. 5–12) and sediment transport rating curve (fig. 5–13), calculate the effective discharge:

Solution: The sediment transport rating curve was calculated from data collected during field surveys. The bed material gradation in the upstream supply reach was determined from the average of three volumetric bulk samples taken laterally across the stream. The cross-sectional geometry and slope were surveyed. Hydraulic parameters were calculated assuming normal depth. The Meyer-Peter Muller equation was chosen to make the sediment calculations because the bed was primarily gravel. The calculated bed material sediment transport rating curve is shown in figure 5–13.

The basic approach is to divide the natural range of streamflows during the period of record into a number of arithmetic classes, and then calculate the total bed material quantity transported by each class. This is achieved by multiplying the frequency of occurrence of each flow class by the median sediment load for that flow class. This can be accomplished using a spreadsheet or the USACE SAM program (Thomas, Copeland, and McComas 2003).

Table 5–12 represents output from the SAM program for the given conditions. The discharge increment with the largest increment of sediment transport is between 1,000 and 1,200 cubic feet per second. The effective discharge is then 1,000 cubic feet per second. The program also calculates the average annual sediment load, which is the sum of the sediment loads for each increment. In this case, the annual sediment load is 10,677 tons. A graphical representation of the effective discharge calculation is shown in figure 5–14.

Figure 5–13 Sediment transport rating curve calculated from bed material gradation collected upstream from the project reach and hydraulic parameters from surveyed cross section

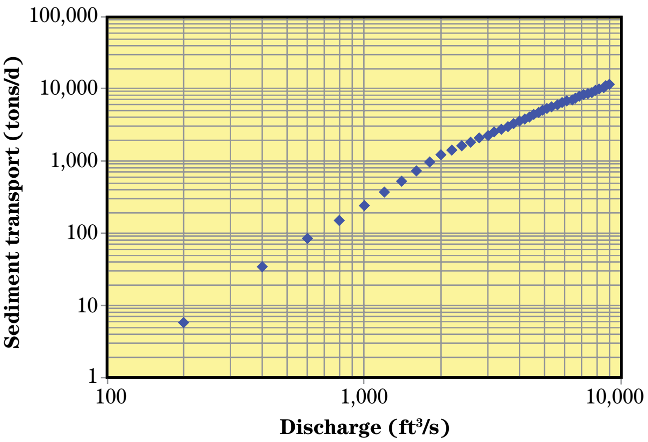


Figure 5–12 Flow-duration curve developed from 39 years of record at a USGS gage downstream from the project reach

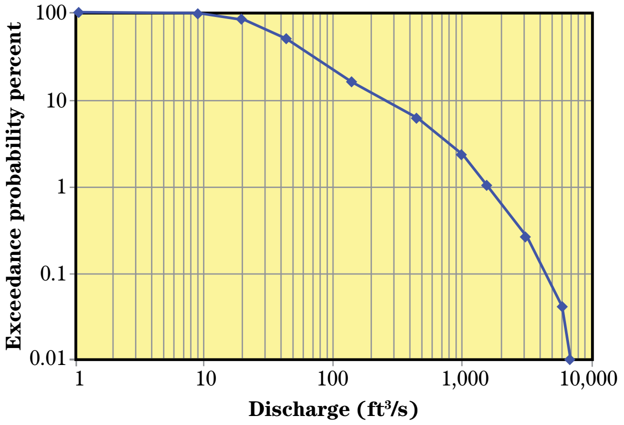


Figure 5–14 Effective discharge calculation

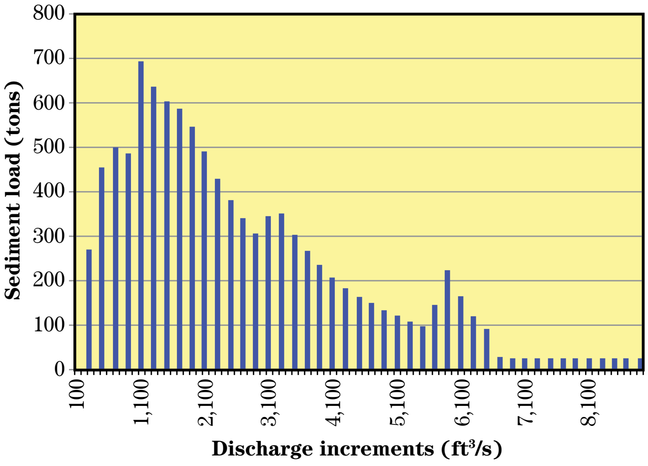


Table 5–12 Effective discharge calculation from SAM program

```
****************************************************************************************************
*                    SAMwin Software Registered to the US Army Corps of Engineers                  *
****************************************************************************************************
*                                     SEDIMENT YIELD CALCULATIONS                                  *
*                                             Version 1.0                                          *
*                      A Product of the Flood Control Channels Research Program                    *
*            Coastal & Hydraulics Laboratory, USAE Engineer Research & Development Center          *
*                                         in cooperation with                                      *
*                           Owen Ayres & Associates, Inc., Ft. Collins, CO                         *
****************************************************************************************************
TABLE 2.1 SEDIMENT DISCHARGE TABLE.
          Q,CFS    =           10.0     20.0      50.0     100.0     200.0
     QS,TONS/DAY   =    0.0      0.0        0.0               0.0       2.3

          Q,CFS    =           500.0    1100.0             2000.0    5000.0    10000.0
     QS,TONS/DAY   =    42.7    283.1             1074.6   4428.0    11178.0
TABLE 2.2 FLOW-DURATION TABLE
    #    CFS      %        #    CFS        %         #     CFS        %

    1       0.00    97.10  5      137.00     15.90     9    3090.00     0.25
    2      20.10    84.10  6      442.00      6.00    10    9000.00     0.00
    3      22.00    50.00  7      988.00      2.30
    4      44.20    50.00  8     1545.00      1.00

TABLE 2.3 INTEGRATION PARAMETERS FOR FLOW-DURATION OPTION
                         MINIMUM FLOW, CFS    =          0.00
                         MAXIMUM FLOW, CFS    =       9000.00
                 INTEGRATION INTERVAL, CFS    =         24.66
               NUMBER OF INTEGRATION STEPS    =           365
TABLE 2.7 DENSITY OF SEDIMENT DEPOSIT.
      IN LB/CUFT         =          93.00
      IN CY/TON          =           0.80
     TABLE 3.1 CALCULATED YIELDS
     SEDIMENT TRANSPORT FUNCTION USED -- MPM(1948),D50
    TIME PERIOD,           DAYS     =   354.415
    WATER YIELD,           ACFT     =   84445.,      Mean Daily Flow,     CFS      =  120.13
    SEDIMENT YIELD,        TONS     =   10677.,       Mean Daily Load,    T/D      =  30.
                           CUYD     =      8504.,     Mean Daily Conc,   mg/l      =  92.880
TABLE 3.2 DISTRIBUTION OF YIELD BY WATER DISCHARGE CLASS INTERVAL.
     NO. OF CLASSES    =       45      ,      CLASS INTERVAL =      200.00
     MINIMUM Q, CFS    =       0.00,   MAXIMUM Q,     CFS    =      9000.00
```

Table 5–12 Effective discharge calculation from SAM program—Continued

Class	Discharge ft^3/s	Sediment tons/d	Increment of water		Increment of sediment		
			acre-ft	%	%	tons	yd^3
	0	0					
1			12	0.01	0	0	0
	200	2					
2			14263	16.89	1.2	128	102
	400	21					
3			11422	13.53	3.0	320	255
	600	66					
4			8311	9.84	3.87	414	329
	800	132					
5			6288	7.45	4.19	448	356
	1000	225					
6			7033	8.33	6.18	660	526
	1200	344					
7			5136	6.08	5.6	598	476
	1400	485					
8			3993	4.73	5.2	555	442
	1600	653					
9			3293	3.9	5.0	534	425
	1800	849					
10			2633	3.12	4.59	490	390
	2000	1075					
11			2154	2.55	4.11	439	349
	2200	1245					
12			1795	2.13	3.6	384	306
	2400	1424					
13			1518	1.8	3.19	340	271
	2600	1612					
14			1301	1.54	2.85	304	242
	2800	1807					
15			1128	1.34	2.57	274	218
	3000	2011					
16			719	0.85	1.7	181	144
	3200	2222					
17			464	0.55	1.13	121	96
	3400	2440					
18			464	0.55	1.17	125	99
	3600	2665					
19			464	0.55	1.21	129	103

Table 5–12 Effective discharge calculation from SAM program—Continued

Class	Discharge ft^3/s	Sediment tons/d	Increment of water		Increment of sediment		
			acre-ft	%	%	tons	yd^3
	3800	2897					
20			464	0.55	1.24	132	105
	4000	3137					
21			464	0.55	1.27	136	108
	4200	3382					
22			464	0.55	1.31	140	111
	4400	3634					
23			464	0.55	1.34	143	114
	4600	3893					
24			464	0.55	1.37	147	117
	4800	4157					
25			464	0.55	1.41	150	119
	5000	4428					
26			464	0.55	1.43	153	122
	5200	4666					
27			464	0.55	1.45	155	123
	5400	4907					
28			464	0.55	1.47	157	125
	5600	5152					
29			464	0.55	1.48	159	126
	5800	5399					
30			464	0.55	1.5	160	128
	6000	5649					
31			464	0.55	1.52	162	129
	6200	5902					
32			464	0.55	1.54	164	131
	6400	6158					
33			464	0.55	1.55	166	132
	6600	6416					
34			464	0.55	1.57	167	133
	6800	6677					
35			464	0.55	1.58	169	135
	7000	6941					
36			464	0.55	1.6	171	136
	7200	7207					
37			464	0.55	1.61	172	137
	7400	7476					
38			464	0.55	1.63	174	138
	7600	7747					
39			464	0.55	1.64	175	140
	7800	8021					
40			464	0.55	1.66	177	141

Table 5–12 Effective discharge calculation from SAM program—Continued

Class	Discharge ft^3/s	Sediment tons/d	Increment of water		Increment of sediment		
			acre-ft	%	%	tons	yd^3
	8000	8297					
41			464	0.55	1.67	178	142
	8200	8575					
42			464	0.55	1.68	180	143
	8400	8855					
43			464	0.55	1.7	181	144
	8600	9138					
44			464	0.55	1.71	183	146
	8800	9423					
45			464	0.55	1.72	184	147
	9000	9710					
Total			84445	100	100	10677	8504

(a) Cautions and limitations

In addition to the previously noted limitations associated with the methods of estimation, other precautions should be applied to the entire nature of channel-forming discharge. The channel-forming discharge concept is based on the idea that there exists a single steady discharge that, given enough time, would produce channel dimensions equivalent to those produced by the natural long-term hydrograph. Although conceptually attractive, this definition is not necessarily physically feasible because riparian vegetation, bank stability, and even the bed configuration would be different in a natural stream than in a stream with a constant discharge (Copeland et al. 2001).

In addition, it is important to note that extreme events often have the capability to move a significant amount of sediment and cause major changes in channel cross section, profile, and planform. In streams that have experienced catastrophic events, the flow-frequency and sediment-transport relations may have changed or be changing with time as the channel adjusts. Results obtained using any technique may represent a condition that does not accurately depict present flow and sediment-transport conditions.

To design a stream restoration project with long-term stability, it is necessary to evaluate the full range of flows that will affect the channel. Therefore, stable channel design includes the evaluation of sediment transport capacity for a range of flows (not just the design discharge) to determine whether the project will aggrade or degrade, as well as meet other objectives for the restoration.

654.0509 Other sources of design flows

Other sources may include estimates of local flows. These can range from hydrologic models conducted as part of another study to historical records of extreme events. Regulatory or legislatively defined flows may be defined. Data may be available for irrigation releases, dam operations or navigation controls. It may be necessary to include an analysis of some or all of these flows. However, it is important to review this information to assess both the technical accuracy, as well as the assumptions made in their estimate. Additional calculations are often required.

654.0510 Conclusion

Rarely does the behavior of a channel under a single discharge adequately reflect the range of design conditions required for a stream restoration project. The design capacity of the channel should consider environmental objectives, as well as flood criteria. Often, habitat features are designed to narrow the channel during summer low flows to increase habitat during a biologically critical period. Project features are designed to withstand a significant flood event, normally a 10-year frequency discharge or larger. A realigned channel is normally designed to convey a flow selected for channel stability, normally larger than the 1-year frequency discharge. If the stream channel is realigned or reconstructed, a suitable design discharge must be selected. In many situations, this is the channel-forming discharge. A wide variety of sources and techniques exist for obtaining hydrologic data available to the designer. If a gage is available and the conditions applicable, a gage analysis is generally considered preferable, since it represents actual data for the stream. However, it is important to assess the applicability of the historic gage data to the current project conditions. For example, rapid increases of imperviousness in an urban watershed may have increased flows and resulted in stream instability. If this is the case, the historic gage data must not be used, because there is no realistic way to adjust the peak flow frequency to predevelopment conditions. Changes in rainfall-runoff characteristics may render historic gage data obsolete. Gage records provide an actual representation of the hydrologic behavior of a watershed. However, when a gage record is of short duration, or poor quality, or the results are judged to be inconsistent with field observations or sound judgment, then the analysis of the gage record should be supplemented with other methods.

Several state and local agencies have developed regional regression relations to estimate peak discharges at ungaged sites. These data can be readily applied, but care must be taken to assure that the regression relations include relevant parameters that can relate the unique characteristics of the study watershed to the data that were used to create the relations. Care must also be taken to make sure that the watershed parameters of the ungaged watershed being analyzed are within the watershed parameters used to develop the regression curves. It is also important to assess the relevance of the confidence limits of the estimates to the project analysis.

Hydrologic models provide the ability to estimate existing, as well as future rainfall runoff patterns for a variety of conditions. The use of models is preferred in cases where the watershed has changed. The accuracy of models is dependent on calibration data, which can be difficult to acquire. However, if the issues to be addressed are comparative in nature rather than absolute, the importance of calibration is diminished. The level of accuracy required for a specific hydrologic analysis generally depends on the specific characteristics of each individual project. The appropriate methodology should be selected with a firm understanding of the assumptions, accuracy, data requirements, and limitations of the approach. The designer should consult with a hydraulic engineer before deciding on which procedure should be used to obtain the needed flow data.

Channel-forming discharge can be estimated using a prescribed methodology. All methodologies for estimating channel-forming discharge present challenges. The practitioner should review the assumptions, data requirements and consider his or her experience when determining which technique to use. It is recommended that all available methods be used and cross checked against each other to reduce the uncertainty in the final estimate of the channel-forming flow.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 6 Stream Hydraulics

Issued August 2007

Cover photo: Stream hydraulics focus on bankfull frequencies, velocities, and duration of flow, both for the current condition, as well as the condition anticipated with the project in place. Effects of vegetation are considered both in terms of protection of the bank materials, as well as on changes in hydraulic roughness.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 6

Stream Hydraulics

Contents

Tables

Figures

Chapter 6 Stream Hydraulics

654.0600 Purpose

Human intervention in the stream environment, especially with projects intended to restore a stream ecosystem to some healthier state, must fully consider the stream system, stream geomorphology, stream ecology, stream hydraulics, and the science and mechanics of streamflow. This chapter provides working professionals with practical information about hydraulic parameters and associated computations. It provides example calculations, as well as information about the role of hydraulic engineers in the design process.

The hydraulic parameters used to evaluate and quantify streamflow are described in this chapter. The applicability of the various hydraulic parameters in planning and design in the stream environment is presented. The complexity of streamflow is addressed, as well as simplifying assumptions, their validity, and consequences. Guidance is provided for determining the level of analysis commensurate with a given project's goals and the associated hydraulic parameters. Finally, a range of analytical tools is described, the application of which depends on the complexity of the project.

Stream hydraulics is a complex subject, however, and this chapter does not provide exhaustive coverage of the topic. Readers are encouraged to supplement this information with the many good references that are available.

654.0601 Introduction

Stream hydraulics is the combination of science and engineering for determining streamflow behavior at specific locations for purposes including solving problems that generally originate with human impacts. A location of interest may be spatially limited, such as at a bridge, or on a larger scale such as a series of channel bends where the streambanks are eroding. Flood depth, as well as other hydraulic effects, may need to be determined over long stretches of the channel.

An understanding of flowing water forms the basis for much of the work done to restore streams. The discipline of hydrology involves the determination of flow rates or amounts, their origin, and their frequency. Hydraulics involves the mechanics of the flow and, given the great power of flowing water, its affect on bed, banks, and structures.

A stream is a natural system that constantly adjusts itself to its environment and participates in a cycle of action and reaction. These adjustments may be gradual, less noticeable, and long term, or they may be sudden and attention grabbing. The impacts causing a stream to react may be natural, such as a rare, intense rainfall, or human-induced, such as the straightening of a channel or filling of a wetland. However, the reaction of a stream to either kind of change may be more than localized. A stream adjusts its profile, slope, sinuosity, channel shape, flow velocity, and boundary roughness over long sections of its profile in response to such impacts. After an impact, a stream may restore a state of equilibrium in as little as a week, or it may take decades.

(a) Hydraulics as physics

Stream characteristics are derived from the basic physics of flowing water. Fluid mechanics is an old science with well-established physical relationships. Typically, simple empirical equations are used that do not account for all the variability that occurs in the flow. An example is Bernoulli's equation for balancing flow depth, velocity, and pressure. In this case, the flow must be considered steady. If it is important to assess how flow depth, velocity, and/or pressure change over time, Bernoulli's equation by itself will not be sufficient.

The assumption that flow velocity is generally downstream in direction is also a common simplification in the analysis of streamflow. Real streams have many eddies where the flow circulates horizontally. Streams also have areas of upwelling, roiling, and vertical circulation. While designers commonly make use of an average velocity at a given cross section, the actual velocities in the plane of a cross section vary markedly from top to bottom, side to side, and in direction, varying with time and three-dimensional space.

Water surface profile analyses generally assume a constant flow elevation across a given cross section. Real streams, however, super-elevate their water surfaces in curved channel sections and may set up significant surface wave patterns that defy prediction. Finally, hydraulic analyses often assume that water flows against a fixed boundary. Real streams actually readjust their bed and banks constantly, move significant amounts of sediment, and transport unpredictable amounts of natural or humanmade debris.

It is, therefore, important to understand the limitations and restrictions of any equations before using them to obtain necessary information.

(b) Hydraulics as empiricism

Although thoroughly founded in physics, many hydraulic relationships require empirical coefficients to account for unmeasured or estimated processes. One of the parameters that has a significant influence on hydraulic calculations is surface roughness, in the form of Manning's *n* value, the Chézy C, or the Darcy-Weisbach friction factor. While the Darcy-Weisbach friction factor is generally considered to be more theoretically based, Manning's *n* is more commonly used for most stream design and restoration analysis. Roughness is a function of many stream physical properties including bed sediment size, vegetation, channel sinuosity, channel irregularity, and suspended sediment load. As a result, many of the estimates have inherent degrees of empiricism in their estimate.

Sediment transport also requires empirical input. Sediment particles vary in size and properties, from tiny silt particles that adhere to large boulders, sometimes redirecting a stream and sometimes transported downstream. Sediment transport is influenced by velocity vectors near the water/sediment boundary, and these bed velocities may not be well predicted by an average cross-sectional velocity. Many of the analytical sediment predictive techniques include many empirical estimates of specific parameters. More information on the analytical, as well as empirical approaches to sediment transport, is provided in other chapters of this handbook. More information on sedimentation analysis is provided in NEH654.09 and NEH654.13.

645.0602 Channel cross-sectional parameters

A variety of channel cross-sectional parameters are used in the hydraulic analysis of streams and rivers. It is important to measure and use these parameters consistently and accurately. A generalized cross section is shown in figure 6–1.

The flow depth is the distance between the channel bottom and the water surface. For rectangular channels, the depth is the same across an entire cross section, but it obviously varies in natural channels. Depth is often measured relative to the channel thalweg (or lowest point). Normal depth is the depth of flow in a uniform channel for which the water surface is normal or parallel to the channel profile and energy slope.

For a cross section aligned so that streamlines of flow are perpendicular, the flow area is the area of the cross section between bed and banks and water surface. For a rectangular channel, flow area is depth multiplied by top width. For a natural channel cross section, the area may be approximated with the sum of trapezoidal areas between cross-sectional points. The top width of a channel cross section at the water surface, typically designated as T, is a factor in the hydraulic depth.

The hydraulic depth is the ratio of the cross-sectional area of flow to the free water surface or top width. The hydraulic depth, d, is generally used either in computing the Froude number or in computing the section factor for critical depth. Since only one critical depth is possible for a given discharge in a channel, the section factor, Z, can be used to easily determine it (Chow 1959).

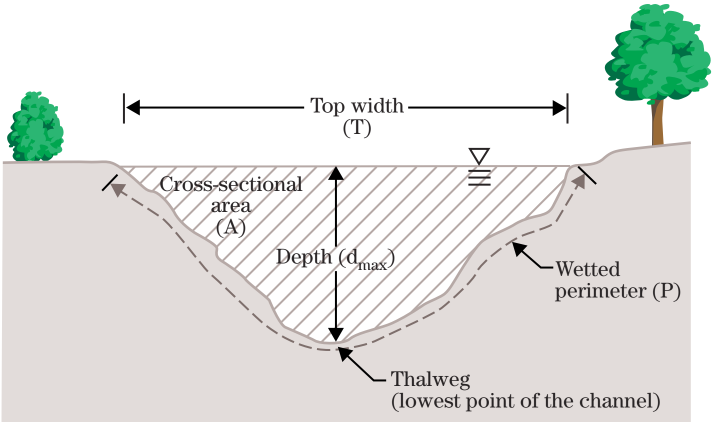
$$Z = \frac{A}{\sqrt{d}} \qquad \text{(eq. 6–1)}$$

$$Q_{\text{critical}} = Z\sqrt{g} \qquad \text{(eq. 6–2)}$$

For a cross section normal to the direction of flow, the wetted perimeter (typically designated P) is the length of cross-sectional boundary between water and bed and banks. The hydraulic radius is the ratio of the cross-sectional area of flow to the wetted perimeter or flow boundary. The hydraulic radius, R= A/P, is used in Manning's equation for calculation of normal depth discharge, as well as for calculation of shear velocity.

Velocity is a physics term for a change in distance during a time interval. Flow velocity refers to the areal extent of the flow (in a cross section) for which a velocity is specified. For example, an average velocity that applies to an entire cross-sectional area may be determined from V = Q/A or if the discharge is unknown, a uniform flow velocity may be determined from Manning's equation.

Figure 6–1 Channel cross-sectional parameters (per ft of channel length)



Another useful formulation is critical velocity, which is average flow velocity at critical depth, and is calculated from equation 6–3:

$$V_{cr} = \sqrt{gd_{cr}} \qquad \text{(eq. 6–3)}$$

where:
V_{cr} = critical velocity
g = gravitational acceleration
d_{cr} = critical depth

Determining the state of flow is a matter of determining whether the velocity is greater than critical velocity V_{cr} (supercritical flow) or less than critical velocity V_{cr} (subcritical flow).

Conveyance is a measure of the flow-carrying capacity of a cross section which is directly proportional to discharge. Conveyance, typically designated K, may be expressed from Manning's equation (without the slope term) as:

$$K = \frac{1.486}{n} AR^{\frac{2}{3}} \qquad \text{(eq. 6–4a)}$$

or

$$K = \frac{Q}{\sqrt{S}} \qquad \text{(eq. 6–4b)}$$

where:
A = flow area (ft^2)
R = hydraulic radius (ft)
Q = flow rate (ft^3/s)
S = slope, dimensionless

In backwater calculations, change in conveyance from cross section to cross section is a useful way to determine the adequacy of section spacing in a stream reach. Within a cross section, conveyance may be used to compare channel and overbank flow carrying capacity.

654.0603 Dimensionless ratios

Dimensionless ratios (also referred to as dimensionless numbers) are used to provide information on flow condition. The units of the variables used in the equation for a dimensionless ratio are such that they cancel. The two most commonly used ratios are Froude and Reynolds numbers. Being dimensionless allows their application to be made across a variety of scales.

(a) Froude number

The Froude number is a dimensionless ratio, relating inertial forces to gravitational forces. The Froude number represents the effect of gravity on the state of flow in a stream (Chow 1959). This useful number was derived by a nineteenth century English scientist, William Froude, who studied the resistance of ships being towed in water. He observed wave patterns along the hull of a moving ship and found that the same number of waves would occur as long as the ratio of the ship's speed to the square root of its length were the same. Applied in hydraulics, the length is replaced by hydraulic depth, as shown in equation 6–5.

$$F = \frac{V}{\sqrt{gd}} \qquad \text{(eq. 6–5)}$$

where:
V = velocity (ft/s)
g = acceleration due to gravity (32.2 ft/s^2)
d = flow depth (ft)

If the Froude number is less than one, gravitational forces dominate and the flow is subcritical, and if greater than one, inertial forces dominate and the flow is supercritical. The Froude number is used to determine the state of flow, since, for subcritical flow the boundary condition is downstream, and for supercritical flow it is upstream. When the Froude number equals one, the flow is at the critical state.

(b) Reynolds number

The Reynolds number is also a dimensionless ratio, relating the effect of viscosity to inertia, used to determine whether fluid flow is laminar or turbulent (Chow 1959). The Reynolds number relates inertial forces to viscous forces and was derived by a nineteenth century English scientist, Osborne Reynolds, for use in wind tunnel experiments.

Inertia is represented in equation 6–6 by the product of velocity and hydraulic radius, divided by the kinematic viscosity of water, with units of length squared per time. For turbulent flow Re>2000, for laminar, Re<500, and values between these limits are identified as transitional.

$$Re = \frac{VR}{\nu} \qquad \text{(eq. 6–6)}$$

where:
V = velocity (ft/s)
R = hydraulic radius (ft)
ν = kinematic viscosity (ft^2/s)

For use in sediment transport analysis, the Reynolds number has been formulated to apply at the water-sediment boundary. In this case, the velocity is local to the boundary and termed shear velocity (V_*). Also, the length term is not the hydraulic radius, but roughness height, or the diameter of particles (D) forming the boundary. This boundary Reynolds number has also been called the bed Reynolds number or shear Reynolds number.

$$Re_{bed} = \frac{V_* D}{\nu} \qquad \text{(eq. 6–7)}$$

where:
V_* = boundary shear velocity (ft/s)
D = particle diameter
ν = kinematic viscosity (ft^2/s)

Because streamflow is almost exclusively turbulent, the Reynolds number is not needed as a flag of turbulence. The Reynolds number has value for sedimentation analyses in that drag coefficients have been empirically related to Reynolds number. Another important use in sedimentation involves incipient motion of sediment particles. Studies have related the bed Reynolds number to critical shear stress (the initiation point of sediment movement). Through the Shields diagram, for example, one can determine critical shear, given a bed Reynolds number. Additional information on this topic is provided in NEH654.13.

654.0604 Continuity

Open channel flow has a liquid surface that is open to the atmosphere. This boundary is not fixed by the physical boundaries of a closed conduit. Water is essentially an incompressible fluid, so it must increase or decrease its velocity and depth to adjust to the channel shape. If no water enters or leaves a stream (a simplification that can be made over short distances) the quantity of the flow will be the same from section to section. Since the flow is incompressible, the product of the velocity and cross-sectional area is a constant. This conservation of mass can be written as the continuity equation as follows:

$$Q = VA \qquad \text{(eq. 6–8)}$$

While the continuity equation can be used with any consistent set of units, it is normally expressed as:

Q = quantity of flow (ft^3/s)
A = cross-sectional area ($ft^{2)}$)
V = average velocity (ft/s)

624.0605 Energy

Energy, an abstract quantity basic to many areas of physics, is a property of a body or physical system that enables it to move against a force. It is an expression of work, which is force applied over a distance. Energy is the amount of work required to move a mass through a distance. Or, it is the amount of work a physical system is capable of doing, in changing from its actual state to some specified reference state.

Many useful concepts of energy exist, the primary one being that, in a closed system, the total energy is constant, the concept of conservation of energy. Water energy is comprised of a number of components, often called head and expressed as a vertical distance. The potential energy of water, or pressure head, is a result of its mass and the Earth's gravitational pull. The kinetic energy of water is related to its movement and is called the velocity head.

The Bernoulli equation (eq. 6–9) is an expression of the conservation of energy.

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_L \qquad \text{(eq. 6–9)}$$

This expression shows the interrelationship of these energy terms, between two cross sections (1 and 2). Each term represents a form of energy, with depth y representing potential energy, the velocity term V representing kinetic energy, and z, a potential energy term relating all to a common datum in a plane perpendicular to the direction of gravity. The head loss or h_L term is called a loss because any energy consumed between the two cross sections must be made up for by a change in height (or head). The head loss is the energy consumed by boundary friction, turbulence, eddies, or sediment transport. The velocity term represents velocity head and the depth term the pressure head.

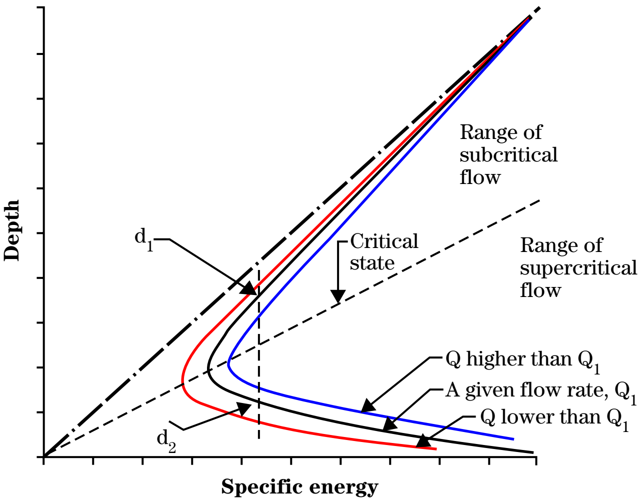
Although energy is a scalar quantity, without direction, the concept of energy as head has an orientation in the direction of gravity. Pressure, however, represents the magnitude of a force in the direction of whatever surface it impinges. So, as a channel slope steepens, the orientation of the pressure head is technically moving further from vertical. It is represented by the depth times the cosine of the slope angle. For most natural channels, the channel slope is sufficiently gradual for this angle to be small enough to be ignored. However, in slopes that are greater than 10 percent, this may become an issue that should be addressed.

Another assumption is that flow is always perpendicular to the cross sections. Finally, alpha (α) in the equation is the energy coefficient, and it varies with the uniformity of velocity vectors in the cross section. For a fairly uniform velocity, alpha may be taken to be one. If velocity varies markedly over the cross section, alpha may go as high as 1.1 in sections of sudden expansion or contraction (Chow 1959).

Specific energy is a particular concept in hydraulics defined as the energy per unit weight of water at a given cross section with respect to the channel bottom.

As shown in figure 6–2, specific energy can be helpful in visualizing flow states of a stream. The points d_1 and d_2 are alternate depths for the same energy level. Only one depth exists at the critical state, which is the lowest possible energy level for a given discharge. In natural streams, this is an unstable state since a very

Figure 6–2 Specific energy vs. depth of flow



small change in energy results in a relatively significant undulating change in depth. An understanding of flow energy is fundamental in hydraulic modeling.

The specific energy at any cross section for a channel of small slope (most natural channels) and $\alpha = 1$ is:

$$E = y + \frac{V^2}{2g} \qquad \text{(eq. 6–10)}$$

654.0606 Momentum

In basic physics, momentum is the mass of a body times its velocity and is a vector quantity, whereas energy is scalar, lacking a direction. In hydraulics, the use of this concept is due mainly to the implication of Newton's second law, that the resultant of all forces acting on a body causes a change in momentum. The momentum equation in hydraulics is similar in form to the energy equation and, when applied to many flow problems, can provide nearly identical results. However, knowledge of fundamental differences in the two concepts is critical to modeling certain hydraulic problems. Conceptually, the momentum approach should be thought of as involving forces on a mass of flowing water, instead of the energy state at a particular location. Friction losses in momentum relate to the force resistance met by that mass with its boundary, whereas in the energy concept, losses are due to internal energy dissipation (Chow 1959).

The momentum equation can have advantages in modeling flow over weirs, drops, hydraulic jumps, and junctions, where the predominate friction losses are due to external forces, rather than internal energy dissipation.

Interpreted for open channel, Newton's second law states that the rate of momentum change in this short section of channel equals the sum of the momentum of flow entering and leaving the section and the sum of the forces acting on the water in the section. Since momentum is mass times velocity, the rate of change of momentum is the mass rate of change times the velocity. The momentum equation may be written considering a small mass or slug of flowing water between two sections 1 and 2 and the principle of conservation of momentum.

$$\rho Q\left(\beta_2 V_2 - \beta_1 V_1\right) = P_1 - P_2 + W \sin\theta - F_{fr} \qquad \text{(eq. 6–11)}$$

The left side of the equation is the momentum entering and leaving, and the right side is the pressure force at each end of the mass, with $W\sin\theta$ being the weight of the mass, θ being the angle of the bottom slope of the channel, and F_{fr} being the resistance force of friction on the bed and banks.

654.0607 Specific force

Specific force is the horizontal force of flowing water per unit weight of water. It is derived from the momentum equation. A specific force curve looks similar to the specific energy curve. The critical depth occurs both at the minimum energy for a given discharge and also at the minimum specific force for a given discharge. This similarity shows how energy concepts and force or momentum concepts can be employed similarly in many hydraulic analyses, often with nearly identical results.

The designer should know what circumstances would cause the two approaches to diverge, however. Specific force concepts are applied over short horizontal reaches of channel, where the difference in external friction forces and force due to the weight of water are negligible. Examples are the flow over a broad-crested weir through a hydraulic jump or at junctions. One way to conceptualize why a momentum-based method, rather than an energy-based method, might be more applicable would be to energy changes in a hydraulic jump. Much energy is lost through turbulence caused by moving mass colliding with other mass that is not accounted for by energy principles alone.

An equation for specific force may be derived from the momentum equation. If the practitioner wishes to apply this equation to short sections of channel such as a weir or hydraulic jump, the frictional resistance forces, F_{fr} can be neglected. With a flat channel of low slope, θ approaches 0, then the last two terms in equation 6–12 can be dropped. As a result, equation 16–11 becomes:

$$\rho Q\left(\beta_2 V_2 - \beta_1 V_1\right) = P_1 - P_2 \qquad \text{(eq. 6–12)}$$

Assume also that the Boussinesq coefficient (β) is 1. From the fact that the pressure increases with depth to the maximum of ρgy at the channel bottom (y being depth, b being channel width, and ρ being fluid density), the overall pressure on the vertical flow area may be expressed as $1/2\rho gby^2$. The velocities may be expressed as Q/A. For a rectangular channel:

$$\rho Q\left(\frac{Q}{A_2} - \frac{Q}{A_1}\right) = \frac{\rho g}{2}\left(A_1 y_1 - A_2 y_2\right) \qquad \text{(eq. 6–13)}$$

that becomes:

$$\frac{2Q^2}{gA_1} + A_1 y_1 = \frac{2Q^2}{gA_2} + A_2 y_2 \qquad \text{(eq. 6–14)}$$

For a channel section of any other shape, the resultant pressure may be taken at the centroid of the flow area, at a depth, z, from the surface. Then the momentum formulation is:

$$\frac{Q^2}{gA_1} + A_1 z_1 = \frac{Q^2}{gA_2} + A_2 z_2 \qquad \text{(eq. 6–15)}$$

Either side of this equation is the definition of specific force, and the specific force is constant over a short stretch of channel such as a hydraulic jump. The first term represents change in momentum over time, and the second term the force of the water mass. As Chow (1959) explains, specific force is sometimes called force plus momentum or momentum flux.

654.0608 Stream power

Stream power is a geomorphology concept that is a measure of the available energy a stream has for moving sediment, rock, or woody material. For a cross section, the total stream power per unit length of channel may be formulated as:

$$\begin{aligned}\Omega &= \gamma Q S_f \\ &= \gamma v w d S_f\end{aligned} \qquad \text{(eq. 6–16)}$$

where:
γ = unit weight of water (lb/ft^3)
Q = discharge (ft^3/s)
S_f = energy slope (ft/ft)
v = velocity (ft/s)
w = channel width (ft)
d = hydraulic depth (ft)

English units are pounds per second per foot of channel length. A second formulation, unit stream power, is the stream power per unit of bed area:

$$\underline{\Omega} = \tau_0 v \qquad \text{(eq. 6–17)}$$

where:
τ = bed shear stress
v = average velocity

A third formulation relates stream power per unit weight of water:

$$\underline{\Omega} = S_f v \qquad \text{(eq. 6–18)}$$

where the terms are as previously defined.

654.0609 Hydraulic computations

(a) Uniform flow

Water flowing in an open channel typically gains kinetic energy as it flows from a higher elevation to a lower elevation. It loses energy with friction and obstructions. Uniform flow occurs when the gravitational forces that are pushing the flow along the channel are in balance with the frictional forces exerted by the wetted perimeter that are retarding the flow. For uniform flow to exist:

- Mean velocity is constant from section to section.
- Depth of flow is constant from section to section.
- Area of flow is constant from section to section.

Therefore, uniform flow can only truly occur in very long, straight, prismatic channels where the terminal velocity of the flow is achieved. In many cases, the flow only approaches uniform flow.

Since uniform flow occurs when the gravitational forces are exactly offset by the resistance forces, a resistance equation can be used to calculate a velocity. The most commonly used resistance equation is Manning's equation (eq. 6–19).

$$Q = \frac{1.486}{n} A R^{\frac{2}{3}} S \qquad \text{(eq. 6–19)}$$

given $Q = VA$

then $$V = \frac{1.486}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \text{(eq. 6–20)}$$

where:
A = flow area (ft^2)
R = hydraulic radius (ft)
S = channel profile slope (ft/ft)
n = roughness coefficient

The 1.486 exponent is replaced by 1.0 if SI units are used. The flow area (A) and the hydraulic radius (R) relate how the flow interacts with the boundary.

A rough estimate of the flow capacity or average velocity at a natural cross section may be determined with Manning's equation. A designer may assume a roughly trapezoidal cross section, estimating bottom width, side slopes, and profile slope from topographic maps. The roughness coefficient is a significant factor, and its determination is described in NEH654.0609(c).

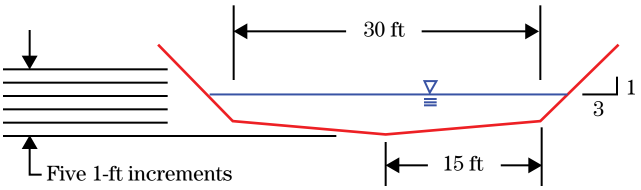
(b) Determining normal depth

Normal depth calculation is one of the most commonly used analyses in stream restoration assessment and design. Several spreadsheets, computer programs, and nomographs are available for use in calculating normal depth. In a natural channel, with a nonuniform cross section, reliability of the normal depth calculation is directly related to the reliability of the input data. Sound engineering judgment is required in the selection of a representative cross section. The cross section should be located in a uniform reach where flow is essentially parallel to the bank line (no reverse flow or eddies). This typically occurs at a crossing or riffle.

Determination of the average energy slope can be difficult. If the channel cross section and roughness are relatively uniform, surface slope can be used. Thalweg slopes and low-flow water surface slopes may not be representative of the energy slope at design flows. Slope estimates should be made over a significant length of the stream (a meander wavelength or 20 channel widths). Hydraulic roughness is estimated based on field observations and measurements.

In addition to normal depth for a given discharge, these same procedures may be used to estimate average velocities in the cross section. These calculations do not account for backwater in a channel reach. The following example calculation refers to the cross section shown in figure 6–3.

Figure 6–3 Problem cross section



Example problem: Normal depth rating curve calculation

Problem 1: Calculate a normal depth rating curve for each foot of depth up to 5 feet. Assume channel slope = 0.0015 and an *n* value = 0.03

Solution:

For

$$Q=\left(\frac{1.49}{n}\right)AR^{\frac{2}{3}}S^{0.5} \quad ,$$

the value

$$\left(\frac{1.49}{n}\right)S^{0.5}=1.924 \; .$$

A and P need to be determined.

$$R=\frac{A}{P}$$

$$A_1=30\times\frac{1}{2}=15\text{ ft}^2$$

$$P_1=2\left(15^2+1^2\right)^{0.5}=30.07\text{ ft}$$

$$R_1=0.499\text{ ft}$$

$$A_2=15+(30\times1)+(1\times3)=48\text{ ft}^2$$

$$P_2=30.07+2\left(3^2+1^2\right)^{0.5}=36.39\text{ ft}$$

$$R_2=1.319\text{ ft}$$

$$A_3=48+(36\times1)+(1\times3)=87\text{ ft}^2$$

$$P_3=36.39+2\left(3^2+1^2\right)^{0.5}=42.71\text{ ft}$$

$$R_3=2.037\text{ ft}$$

$$A_4=87+(42\times1)+(1\times3)=132\text{ ft}^2$$

$$P_4=42.71+2\left(3^2+1^2\right)^{0.5}=49.03\text{ ft}$$

$$R_4=2.692\text{ ft}$$

$$A_5=132+(48\times1)+(1\times3)=183\text{ ft}^2$$

$$P_5 = 49.03 + 2\left(3^2 + 1^2\right)^{0.5} = 55.36 \text{ ft}$$

$$R_5 = 3.306 \text{ ft}$$

Solving for Q, then:

$$Q_1 = 1.924 \times 15 \times (0.499)^{0.667} = 18.1 \text{ ft}^3\text{/s} \quad (\text{at d} = 1 \text{ ft})$$

$$Q_2 = 1.924 \times 48 \times (1.319)^{0.667} = 111.1 \text{ ft}^3\text{/s} \quad (\text{at d} = 2 \text{ ft})$$

$$Q_3 = 1.924 \times 87 \times (2.037)^{0.667} = 269.0 \text{ ft}^3\text{/s} \quad (\text{at d} = 3 \text{ ft})$$

$$Q_4 = 1.924 \times 132 \times (2.692)^{0.667} = 491.6 \text{ ft}^3\text{/s} \quad (\text{at d} = 4 \text{ ft})$$

$$Q_5 = 1.924 \times 183 \times (3.306)^{0.667} = 781.7 \text{ ft}^3\text{/s} \quad (\text{at d} = 5 \text{ ft})$$

Problem 2: Determine the normal depth for a discharge of 350 cubic feet per second and the associated average velocity.

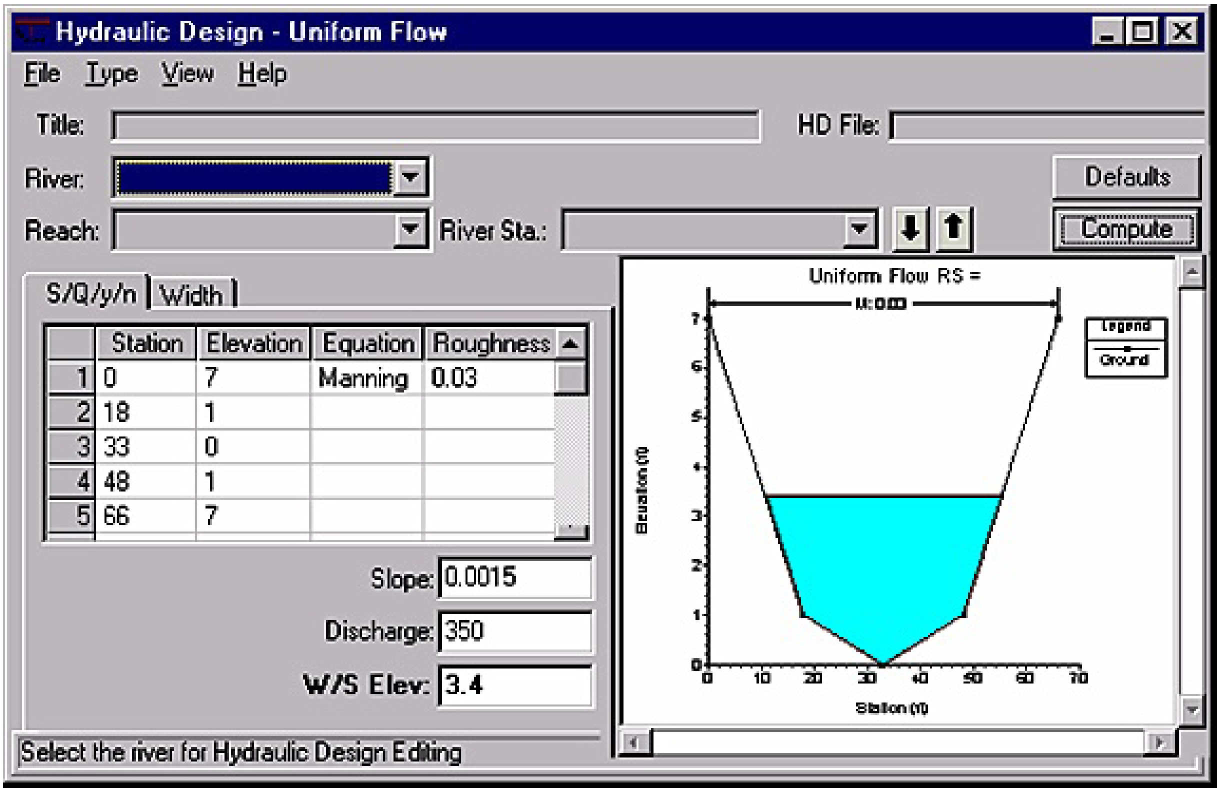
Solution: From the rating curve calculated above, the 350 cubic feet per second discharge in this problem will be between Q_3 and Q_4. A straight-line interpolation gives a depth of 3.4 feet.

For velocity, since $Q = VA$

$$V = \frac{350}{\left(3\left[(3.4 \times 3.4) + 8(3.4) - 4\right]\right)} = 3.36 \text{ ft/s}$$

Discussion:
The more complicated a section becomes, the more tedious is this hand calculation. Numerous computer programs, such as HEC–RAS (USACE 2001b), can perform normal depth calculations for a cross section of many coordinate points. A typical image from HEC–RAS is shown as figure 6–4.

Figure 6–4 HEC–RAS screen shot for uniform flow computation



	Station	Elevation	Equation	Roughness
1	0	7	Manning	0.03
2	18	1		
3	33	0		
4	48	1		
5	66	7		

Slope: 0.0015

Discharge: 350

W/S Elev: 3.4

Select the river for Hydraulic Design Editing

(c) Determining roughness coefficient (*n* value)

The roughness coefficient, an empirical factor in Manning's equation, accounts for frictional resistance of the flow boundary. Estimating this flow resistance is not a simple matter. This parameter is used in computation of water surface profiles and estimation of normal depths and velocities.

Boundary friction factors must be chosen carefully, as hydraulic calculations are significantly influenced by the *n* choice. Factors affecting roughness include ground surface composition, vegetation, channel irregularity, channel alignment, aggradation or scouring, obstructions, size and shape of channel, stage and discharge, seasonal change, and sediment transport.

Significant guidance exists in the literature regarding roughness estimation. Chow (1959) discusses four general approaches for roughness determination. The U.S. Geological Survey (USGS) (Arcement and Schneider 1990) published an extensive step-by-step guide for determination of *n* values. NRCS guidance for channel *n* value determination is available from Faskin (1963). Finally, when observed flow data and stages are known, manual calculations or a computer program such as HEC–RAS may be used to determine *n* values.

With the many factors that impact roughness, and each stream combining different factors to different extents, no standard formula is available for use with measured information. As stated in Chow (1959):

> *...there is no exact method of selecting the n value. At the present stage of knowledge [1959], to select a value of n actually means to estimate the resistance to flow in a given channel, which is really a matter of intangibles. To veteran engineers, this means the exercise of sound engineering judgment and experience; for beginners, it can be no more than a guess, and different individuals will obtain different results.*

While there has been considerable research on estimating roughness coefficients since 1959, flood plain and channel *n* values are still challenging to determine. In practice, to a large extent the selection of Manning's *n* values remains judgement based.

Estimates of channel roughness may be made using photographs or tables provided by Chow (1959), Brater and King (1976), Faskin (1963), and Barnes (1967). NEH–5 supplement B, Hydraulics, can also be used to estimate roughness values. As roughness can change dramatically between surfaces within the same cross section, such as between channel and overbanks, a determination of a composite value for the cross section is necessary (Chow 1959). The choice of a channel compositing method is very important in stream restoration design where large differences exist in bank and bed roughness. While the following example uses the Lotter method, other methods, such as the equal velocity method and the conveyance method, can also be used.

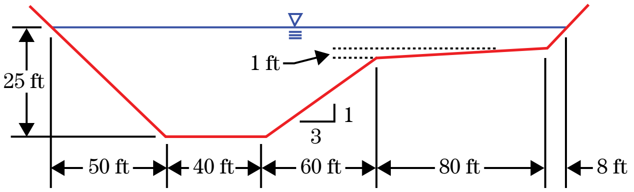
Example problem: Composite Manning's *n* value

Problem: Determine a composite *n* value for the cross section illustrated in figure 6–5 at the given depth of flow.

Assume that this channel is experiencing a 6,094 cubic feet per second flow, with 5,770 cubic feet per second in the main channel and the remainder on the right overbank. The mean velocity in the main channel is 2.3 feet per second and on the overbank, 0.55 foot per second. The channel slope is 0.00016, and a fairly regular profile of clay and silt is observed.

The channel is relatively straight and free of vegetation up to a stage of 10 feet. Above that level, both banks are lined with snags, shrubs, and overhanging trees. The right overbank is heavily timbered with standing trees up to 6 inches in diameter with significant forest litter. In stream work, the convention is that the

Figure 6–5 Cross-sectional dimensions



left bank is on the left when looking downstream. See figures 6–6 and 6–7 where the photos are taken at a lower stage (Barnes 1967).

Solution: To determine the composite Manning's *n* value, the inchannel and overbank *n* values must first be determined.

The solution will first estimate *n* values using reference materials, then this solution will compare this estimate with the value calculated from Manning's equation. Roughness estimates can be found in NEH–5, Hydraulics, supplement B by Cowan (1956). Arcement and Schneider (1990) extended this body of work. Both methods estimate a base *n* value for a straight, uniform, smooth channel in natural materials, then modifying values are added for channel irregularity, channel cross-sectional variation, obstructions, and vegetation. After these adjustments are totaled, an adjustment for meandering is also available.

For the channel below 10 feet, the bed material is silty clay. Arcement and Schneider (1990) show base *n* values for sand and gravel. For firm soil, their *n* value ranges from 0.025 to 0.032. Cowan (1956) shows a base *n* of 0.020 for earth channels. Richardson, Simons, and Lagasse (2001) shows 0.020 for alluvial silt and 0.025 for stiff clay. A reasonable assumption could be 0.024 for the channel below 10 feet of depth. For the remainder of the channel, above 10 feet of depth to top of bank at 20 feet, the effects of vegetation must be added in. The channel is then divided into three pieces: a lower channel, an upper channel, and a right overbank. Other breakdowns of this cross section are possible.

For the lower channel a base *n* value of 0.024 is assumed. Referring to Cowan (1956) in NEH 5, supplement B, a 0.005 can be added for minor irregularity and a 0.005 addition for a shifting cross section. This gives a total *n* value for the lower channel of 0.034.

Figure 6–6 Looking upstream from left bank

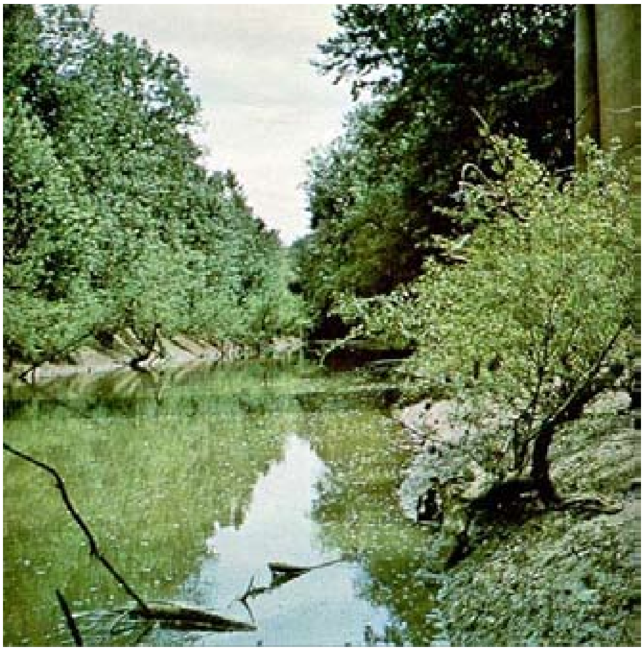
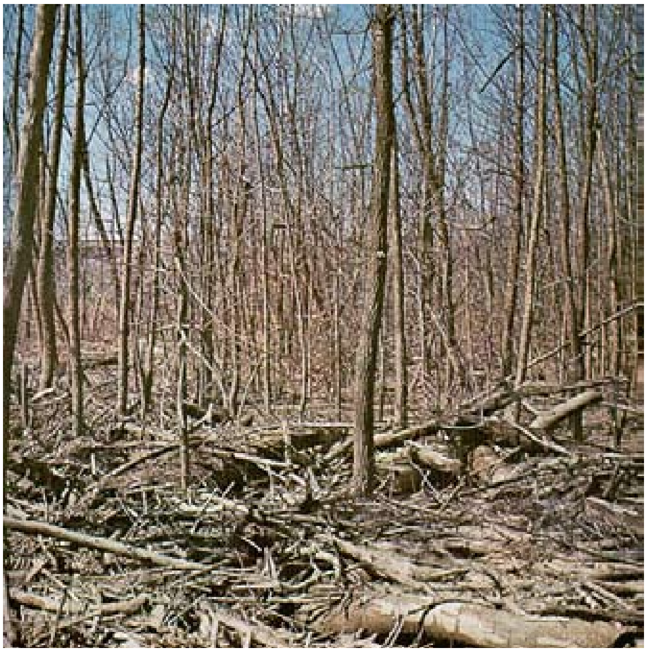


Figure 6–7 Looking downstream on right overbank



For the upper channel, the area above the lower 10 feet of flow depth and excluding the right overbank, the base *n* value is 0.024, a minor irregularity addition of 0.005, a 0.005 addition for a shifting cross section, a minor obstruction addition of 0.010, and a medium vegetation addition of 0.020 can be selected. This gives a total *n* value for the upper channel of 0.064.

For the overbank, a base *n* (from the overbank soil) is needed. Based on site-specific observations, it was found that the soil is slightly more coarse than that of the main channel, $n = 0.027$. Again from NEH 5, supplement B, Cowan (1956) a minor irregularity addition of 0.005, a shifting cross section addition of 0.005, an appreciable obstruction addition of 0.020, and a high vegetation addition of 0.030 can be selected. This gives a total *n* value for the overbank of 0.087.

To obtain composite roughness, use the method of Chow (1959), whereby a proportioning is done with wetted perimeter (P) and hydraulic radius (R):

$$n = \frac{\mathrm{PR}^{\frac{5}{3}}}{\sum_{1}^{N}\left(\frac{\mathrm{P_N R_N}^{\frac{5}{3}}}{\mathrm{n_N}}\right)} \qquad \text{(eq. 6–21)}$$

As follows:

x–s part	P (ft)	A (ft²)	R (ft)	*n*
Lower channel	94	650	6.91	0.034
Upper channel	65	1875	28.8	0.064
Right overbank	89	376	4.22	0.087
Total channel	159	2,525	15.88	—
Total x–s	248	2,901	11.70	—

Using equation 6–21 the composite roughness is:

$$n = \frac{(248)(11.70)^{\frac{5}{3}}}{\frac{(94)(6.91)^{\frac{5}{3}}}{0.034} + \frac{(65)(28.8)^{\frac{5}{3}}}{0.064} + \frac{(89)(4.22)^{\frac{5}{3}}}{0.087}}$$

$$n = 0.042$$

This value can be compared to a value calculated with Manning's equation as follows.

$$n = \frac{1.486}{\mathrm{Q}}\mathrm{AR}^{\frac{2}{3}}\mathrm{S}^{\frac{1}{2}}$$

$$n_{\text{chan}} = \frac{1.486}{5770}(2525)(15.88)^{\frac{2}{3}}(.00016)^{\frac{1}{2}} = 0.052$$

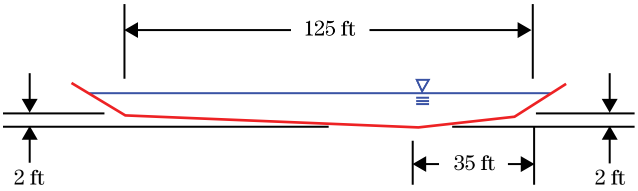
Discussion:
The difference in Manning's *n* initially appears to be cause for concern. However, it does illustrate three important points. First, this process is subjective, and two equally capable practitioners may arrive at different results. Second, Manning's equation is for uniform flow. Differences in measured and calculated *n* values should be attributed to the uncertainty in choosing appropriate values to account for various factors associated with roughness. Manning's equation by itself can provide an estimate, but it cannot precisely determine roughness when the flow is not uniform. Third, an uncertainty analysis is recommended for hydraulic analysis.

As documented in Barnes (1967), the USGS backwater calculations determined the channel *n* value to be 0.046 and the right overbank *n* value to be 0.097. In contrast to this example, Barnes calculated roughness using energy slope, rather than water surface slope and also included expansion and contraction losses.

Example problem: Manning's *n* value for a sand-bed channel

Problem: Determine the *n* value for a wide, sand channel with the following cross section (fig. 6–8). Assume a discharge of 4,100 cubic feet per second, a thalweg depth of 5 feet, 3:1 side slopes and a fairly straight, regular reach. Assume a slope of 0.0013 and a sandy bottom with a D_{50} of 0.3 millimeter.

Figure 6–8 Sand channel cross section



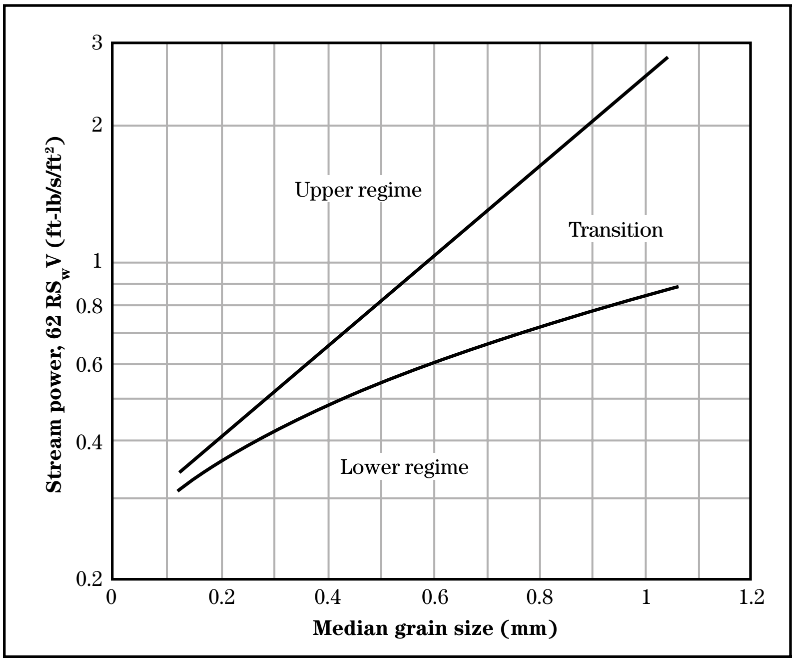
Solution: Roughness in sand channels is highly dependent on the channel bedforms, and bedforms are a function of stream power and the sand gradation. Arcement and Schneider (1990) show suggested *n* values for various D_{50} values with the footnote that they apply only for upper regime flows where grain roughness is predominant. For a D_{50} of 0.3 millimeter, this reference suggests a 0.017 *n* value. However, it is important to assess the regime of the flow. A figure from Simons and Richardson (1966) (also in Richardson, Simons, and Lagasse 2001 and Arcement and Schneider 1990) is shown as figure 6–9. Given stream power and median fall diameter, the flow regime may be estimated, as well as the expected bedform and roughness range.

Stream power may be calculated from where gamma is unit weight of water, Q is discharge, and S_f is the energy slope. Assuming the energy slope is nearly the same as the bed slope, then:

$$\Omega = \left(62.4 \text{ lb/ft}^3\right)\left(4100 \text{ ft}^3\text{/s}\right)\left(0.0013\right)$$
$$= 333 \text{ lb/s}$$
$$\text{(per ft of channel length)}$$

For figure 6–9, stream power per cross-sectional area is needed. The flow area for the given cross section is 554 ft^2, so the stream power is 0.60 pounds per second per square foot (per foot of channel length). Reading figure 6–9, with a D_{50} of 0.3 millimeter, the flow is in the upper regime, but close to the transition. This would support an *n* value of 0.017, particularly if bedforms are present.

Figure 6–9 Plot of flow regimes resulting from stream power vs. median fall diameter of sediment



Upper flow regime	
Plane bed	(0.010≤*n*≤0.013)
Antidunes	
Standing waves	(0.010≤*n* ≤0.013)
Breaking waves	(0.012≤*n*≤0.020)
Chute and pools	(0.018≤*n*≤0.035)
Lower flow regime	
Ripples	(0.018≤*n*≤0.028)
Dunes	(0.020≤*n*≤0.040)

Figure 6–10 (Arcement and Schneider 1990) indicates the general bedforms for increasing stream power.

The anticipated bedform is a plane bed, and figure 6–9 suggests an *n* value between 0.010 and 0.013 for plane beds. The presence of breaking waves over antidunes would raise the roughness estimate to between 0.012 to 0.02. Finally, an estimate may be calculated with the Strickler formula (Chang 1988; Chow 1959) that relates *n* value to grain roughness. So, for a plane bed it should give a good estimate:

$$n = 0.0389\left(D_{50}\right)^{\frac{1}{6}} \quad \text{with } D_{50} \text{ in feet} \qquad \text{(eq. 6–22)}$$

or

$$n = 0.0474\left(D_{50}\right)^{\frac{1}{6}} \quad \text{with } D_{50} \text{ in meters} \qquad \text{(eq. 6–23)}$$

Since the D_{50} is 0.3 millimeter, the calculated *n* value is 0.012, which agrees with figure 6–9 results for plane beds. Arcement and Schneider (1990) show $n = 0.012$ for a D_{50} of 0.2 millimeter, and this calculation is close to the transition range. Considering all of the above, information supports a roughness selection between 0.013 to 0.017. If field observations support the plane bed assumption, a value from the low end of this range should be selected. If antidunes are present, a value from the high end of this range would be reasonable.

Example problem: Manning's *n* value for a gravel-bed channel

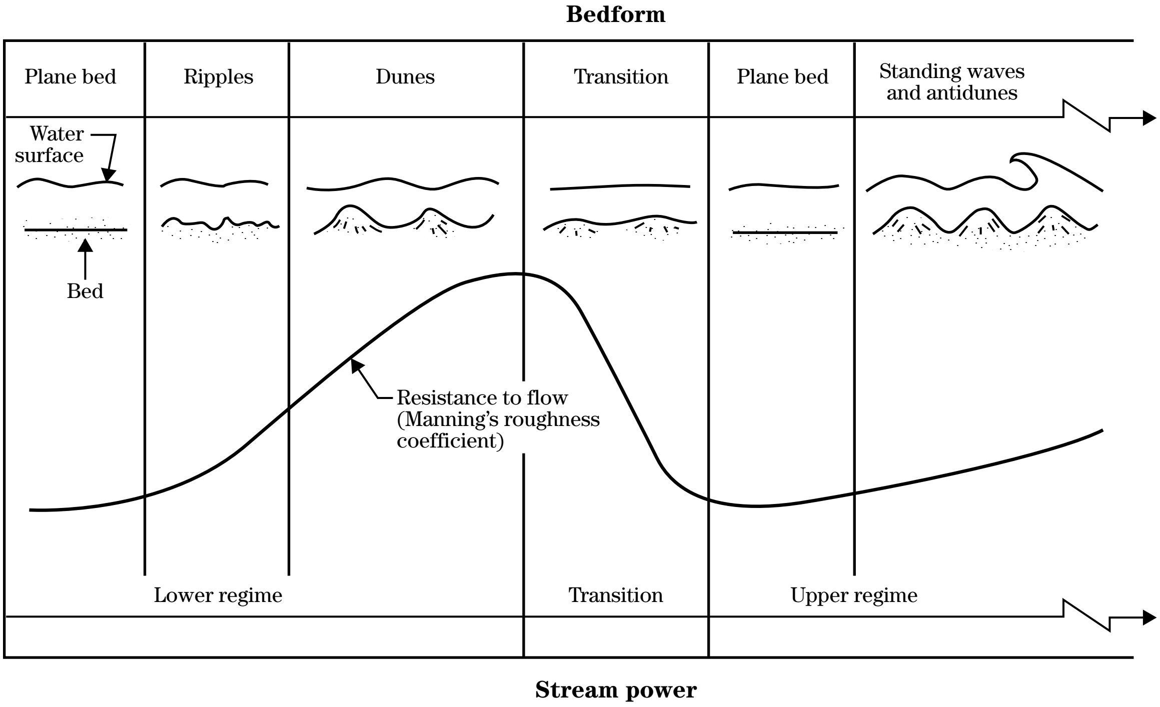
Problem: Determine the *n* value for a wide, gravel-bed channel with a D_{50} of 110 millimeters. Assume a fairly straight, regular reach. Assume minimal vegetation and bedform influence.

Solution: Since the grain roughness is predominant, the Strickler formula can be used.

$$n = 0.0474\left(D_{50}\right)^{\frac{1}{6}} \quad \text{for } D_{50} \text{ in meters}$$

This results in an estimated *n* value of 0.033. It should be noted that this estimate does not take into account many of the factors which influence roughness in natural channels. As a result, a estimate made with Strickler's equation is often only used as an initial, rough estimate or as a lower bound.

Figure 6–10 General bedforms for increasing stream power



(d) Friction factor

As with Manning's *n* value and the Chézy C, the friction factor, f, is a roughness coefficient in a velocity equation, namely, the Darcy-Weisbach equation. Originally developed for pipe flow, the equation adapted for flow in open channels is:

$$V=\left(\frac{8gRS}{f}\right)^{0.5} \text{ with f being dimensionless.} \qquad \text{(eq. 6–24)}$$

$$\text{Alternatively, } f=\left(\frac{8gRS}{V^2}\right) \qquad \text{(eq. 6–25)}$$

In 1963, the ASCE Task Committee on Friction Factors in Open Channels recommended the preferential use of the Darcy-Weisbach friction factor over Manning's *n* (Simons and Sentürk 1992). While Manning's equation remains the most used equation in practice, a comparison between the two is an illustrative exercise. The equation, applicable for steady uniform flow, is a balance of downstream gravitational force and upstream boundary resistance forces. The relationship between Manning's *n* and Chézy C is (Hey 1979, English units):

$$\left(\frac{8}{f}\right)^{0.5}=\frac{d^{\frac{1}{6}}}{ng^{0.5}}=\frac{C}{g^{0.5}} \qquad \text{(eq. 6–26)}$$

where:
d = hydraulic depth

To apply the velocity equation, the friction factor must be determined. As has often been discussed by researchers (Raudkivi 1990; Thorne, Hey, and Newson 2001), the vertical velocity profile can often be assumed to be logarithmic with distance from the bed. For sand and gravel channels, where the relative roughness (flow depth/bed-material size) exceeds 10, this relationship holds.

For use in gravel-bed streams, with width-to-depth ratios greater than about 15, Hey (1979) derived the following (see also Thorne, Hey, and Newson 2001):

$$\frac{1}{\sqrt{f}}=2.03\log\frac{aR}{3.5D_{84}} \quad \text{(SI units)} \qquad \text{(eq. 6–27)}$$

or

$$\left(\frac{8}{f}\right)^{0.5}=5.75\log\frac{aR}{3.5D_{84}} \quad \text{(English units)} \qquad \text{(eq. 6–28)}$$

where:
R = hydraulic radius
D_{84} = bed-material size for which 84 percent is smaller

The dimensionless a is given by (Thorne, Hey, and Newson 2001):

$$a=11.1\left(\frac{R}{d_{max}}\right)^{-0.314} \qquad \text{(eq. 6–29)}$$

where:
d_{max} = maximum flow depth

The coefficient a varies from 11.1 to 13.46 and is a function of channel cross-sectional shape. For channels in which the width-to-depth ratio exceeds 2, the maximum flow depth is valid in the above equation. Otherwise, the value in the denominator should be the distance perpendicular from the bed surface to the point of maximum velocity. This formula for determining f may be used in gravel-bed riffle-pool streams in the riffle section, where flow is often assumed to be uniform. In general, the D_{84} is calculated based on a sample taken at the riffle section.

The Limerinos equation can also be used to determine the friction factor.

$$n=\frac{(0.0926)R^{\frac{1}{6}}}{\left(1.16+2.0\log\left(\frac{r}{D_{84}}\right)\right)} \qquad \text{(eq. 6–30)}$$

where:
R = hydraulic radius, in ft
D_{84} = particle diameter, in ft, that equals or exceeds that of 84 percent of the particles

This equation was developed from samples taken from 11 large United States rivers with bed materials ranging from small gravel to medium size boulders. This equation has been shown to work well on sand-bed streams with plane beds.

(e) Accounting for velocity distributions in water surface profiles

Actual velocities in a cross section are distributed from highest, generally in the center at a depth that is some small proportion beneath the surface, to much lower values in overbanks and at flow boundaries (fig. 6–11). A velocity meter measures velocities related to the vertical flow area close to the instrument.

This elementary phenomenon is responsible for the fact that an average cross-sectional velocity cannot provide a precise measure of the kinetic energy of the flow; the alpha and beta coefficients therefore are needed as modifiers.

When the flow velocity in a cross section is not uniformly distributed, the kinetic energy of the flow, or velocity head, is generally greater than $V^2/2g$, where V is the average velocity. The true velocity head may be approximated by multiplying the velocity head by alpha (α), the energy coefficient. Chow (1959) stated that experiments generally place alpha between 1.03 and 1.36 for fairly straight prismatic channels. The nonuniformity of velocity distribution also influences momentum calculations (as momentum is a function of velocity).

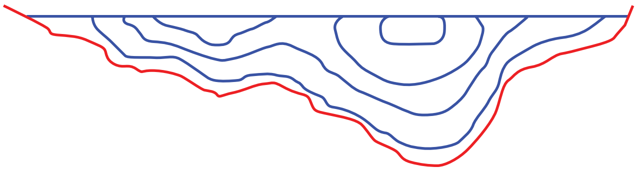
Beta (β) is the momentum coefficient that Chow indicates varies from 1.01 to 1.12 for fairly straight prismatic channels. Beta, also called the Boussinesq coefficient, is also described in Chow (1959). Both coefficients may be calculated by dividing the flow area into subareas of generally uniform velocity distribution.

$$\alpha \approx \frac{\sum v_i^3 A_i}{V^3 A_{total}} \qquad \text{(eq. 6–31)}$$

$$\beta \approx \frac{\sum v_i^2 A_i}{V^2 A_{total}} \qquad \text{(eq. 6–32)}$$

However, for natural channels, the calculation is better made using conveyance. HEC–RAS uses the following formulas:

Figure 6–11 Flow velocities for a typical cross section



$$\alpha \approx \frac{\sum\left(\frac{K_i^3}{A_i^2}\right)}{\frac{K_{total}{}^3}{A_{total}{}^2}} \qquad \text{(eq. 6–33)}$$

$$\beta \approx \frac{\sum\left(\frac{K_i{}^2}{A_i}\right)}{\frac{K_{total}{}^2}{A_{total}}} \qquad \text{(eq. 6–34)}$$

Every cross section is only a two-dimensional slice of a three-dimensional reality. Cross sections change along the stream profile, inevitably setting up transverse velocity vectors, and the flow is induced into a roughly spiral motion. This flow behavior leads to point bars, pools and riffles, meandering patterns, and flood plains. Further information on the velocity and shear in the design of streambank protection in bends is given in NEH654.14, Stabilization Techniques.

(f) Determining the water surface in curved channels

Water surface profiles as computed by HEC–RAS assume a level water surface in each cross section. This is not the case in a curved channel. However, the water surface calculated by HEC–RAS is valid along the centerline of the flow. Generally, HEC–RAS can account for the friction and eddy losses caused by a bend so that the water surface computed upstream would be correct. However, the super-elevated water surface in the bend itself must be calculated separately. The following formula is often used for estimating super-elevation in a water surface.

$$\Delta Z = \frac{bV^2}{gr_c} \qquad \text{(eq. 6–35)}$$

where:

V = average channel velocity (ft/s)

b = channel top width (ft)

g = gravitational acceleration (32.2 ft/s^2)

r_c = radius of curvature of the channel (ft)

ΔZ = super-elevation in ft from bank to bank, so the amount added to or subtracted from the centerline elevation would be half that. A factor of safety of 1.15 is generally applied.

In supercritical flow, curved channels are much more complicated due to wave patterns that propagate back and forth across the channel and downstream. With the disturbances reflecting from one side to the other, higher water surfaces can occur both on the inside and outside banks of a bend. Although a methodology for determining the super-elevation is developed by Chow (1959) for a regular curved channel with a constant width, it also approximates that for a natural channel.

Example problem: Super-elevation

Problem: A trapezoidal channel has a 30-foot bottom width, 1H:3V side slopes, and a radius of 100 feet. For a 500 cubic feet per second discharge, the depth is 4.12 feet, and the cross-sectional area is 174.5 square feet. Find the increase in water surface on the outside of the curve.

Solution: Calculate the velocity, from Q = VA:

$$V = \frac{Q}{A} = \frac{500}{174.5} = 2.87 \text{ ft/s}$$

top width is:

$$30 + (2 \times 3 \times 4.12) = 54.7 \text{ ft}$$

$$\Delta Z = \frac{bV^2}{gr_c} = \frac{(54.7)(2.87)^2}{(32.19)(100)} = 0.14 \text{ feet}$$

so, the increase in the flow depth on the outside of the curve is 0.07 feet, which is half of 0.14 feet.

(g) Transverse flow hydraulics and its geomorphologic effects

Frequently, the intent of channel design is to try to recreate or restore a natural condition, one that is geomorphologically sustainable. The hydraulic engineer needs to be aware of the mechanics of the flow and movable boundaries in channel curves. In a straight channel section, the task of determining boundary stress is easier than in curved reaches, as the direction of flow is more likely to be parallel to the banks. Shear force is dominant, and no significant additional force exists due to the momentum of flow impinging on the bank at some angle. In a curve, accounting for those angles of impinging flow is very important. The problem is three-dimensional, as previously mentioned, accounting for velocity distributions in water surface profiles, and flow in a curve sets up transverse velocity vectors and spiral motion. This phenomenon is completely natural and one of the driving mechanisms of geomorphology.

If a curving section of streambank is to be stabilized, some understanding of the nature of transverse (or secondary) flow is necessary. The task of streambank protection may be roughly divided into two major strategies: installation of measures that enable the bank to resist hydraulic forces at whatever angle they impinge or redirecting the flow so that the bank is no longer subject to damaging forces. Examples of the first would be planting vegetation on the banks or installing woody debris. The second strategy employs such measures as stream barbs, spur dikes, or longitudinal groins. Both of these strategies are covered extensively in NEH654.14 and related technical supplements in this handbook. However, particularly for curved channels, an examination of the hydraulic aspects upon which any streambank protection measure will succeed or fail is given here.

Even in straight channels, some flow spiraling can occur, and a moveable bed sets up transverse slopes that alternate direction along the bed profile. Figure 6–12 (Chang 1988) illustrates the behavior of spiral flow and the resulting transverse bed slopes.

In curved sections, the secondary current is not necessarily only one cell of circulation as shown in figure 6–13 (Chang 1988).

Chang (1988) provides the following equation for a hydraulically rough channel:

$$\tan\delta = 11\frac{d}{r} \qquad \text{(eq. 6–36)}$$

where:

δ = angle of the bottom current with channel centerline
d = depth at the location of interest in the section
r = radius of curvature to the location of d

The channel roughness is not considered to have a significant influence on the angle δ. Chang (1988) documents research that can enable the hydraulic engineer to calculate shear stress in the radial (or transverse) direction, the transverse bed slope a channel might be

Figure 6–12 Spiral flow characteristics for a typical reach

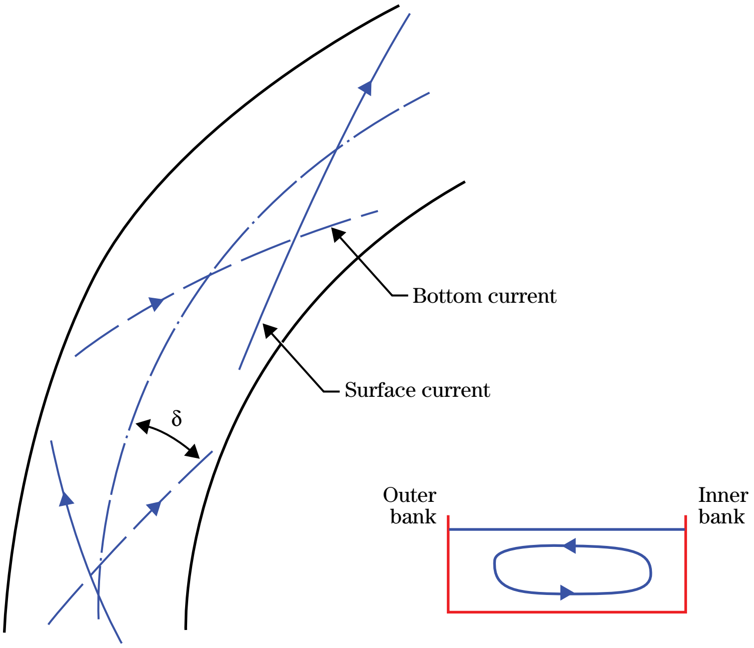
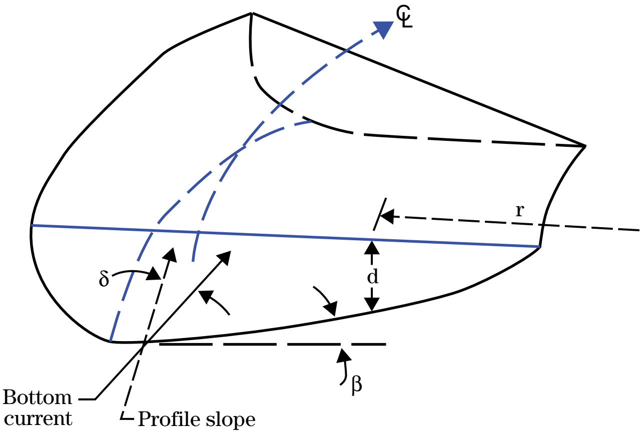


Figure 6–13 Flow characteristics for a typical reach



expected to acquire, and the sediment sorting expected along that transverse slope.

Chang (1988) provides the following two equations to calculate shear stress in the radial direction (both toward the inside of the curve, due to bottom current, and toward the outside due to surface current):

$$\tau_{0r} = -\rho d \frac{U^2}{r}\left[2\left(\frac{\sqrt{g}}{\kappa C}\right)^2 - 2\left(\frac{\sqrt{g}}{\kappa C}\right)^3\right] \qquad \text{(eq. 6–37)}$$

$$\tau_{0r} = \frac{1+m}{m^2+2m}\rho\frac{d}{r}U^2 \qquad \text{(eq. 6–38)}$$

$$m = \kappa\sqrt{\frac{8}{f}} \qquad \text{(eq. 6–39)}$$

where:
ρ = density of water
g = acceleration due to gravity
κ = the dimensionless von Kármán constant ($\kappa \approx 0.40$)
U = avg. cross-sectional velocity
C = Chézy resistance factor, defined below
d = depth at the location of interest
r = radius of curvature to that location
f = friction factor as defined below

The Chézy resistance factor is similar to Manning's *n* value in that it is an empirically derived coefficient serving as an index of boundary roughness. The following Ganguillet and Kutter formula (1869), as provided in Chow (1988), is a method of calculating Chézy C, given Kutter's n:

$$C = \frac{41.65 + \frac{0.00281}{S} + \frac{1.811}{n}}{1 + \left(41.65 + \frac{0.00281}{S}\right)\frac{n}{\sqrt{R}}} \qquad \text{(eq. 6–40)}$$

where:
S = profile bed slope
R = hydraulic radius
n = Kutter's roughness

Chézy's C is related to Manning's *n* by the following equation in English units:

$$C = \frac{\left(1.486\ R^{\frac{1}{6}}\right)}{n} \qquad \text{(eq. 6–41)}$$

R = hydraulic radius (ft)

The Darcy-Weisbach friction factor, f, is described by Chow (1959) and for uniform or near uniform flow may be calculated using:

$$f = \frac{8gRS}{V^2} \qquad \text{(eq. 6–42)}$$

Both Chow (1959) and Chang (1988) describe the relationship of f to boundary Reynolds number. Chang provides three formulas, dependent on hydraulic smoothness, for channels in which form roughness is not a factor as follows.

$$f = \left(0.103 + 2\log R_{bed}\right)^{-.5} \quad \text{for} \quad \log\frac{R_{bed}k_s}{4R} < 0.5 \qquad \text{(eq. 6–43)}$$

(hydraulically smooth)

where:
R = hydraulic radius
R_{bed} = boundary Reynolds number
k_s = equivalent roughness or grain roughness, calculated from the following, one of several similar equations, Chang (1988):

$$k_s = 3D_{90} \qquad \text{(eq. 6–44)}$$

For the transition from hydraulically smooth to rough:

$$f = \left(\sum_{i=0}^{6} A_i\left(\log\frac{R_{bed}k_s}{4R}\right)^i + 2\log\frac{2R}{k_s}\right)^{-.5} \qquad \text{(eq. 6–45)}$$

for

$$0.5 \le \log\frac{R_{bed}k_s}{4R} \le 2.0$$

where the coefficients A_0 through A_6 are 1.3376, -4.3218, 19.454, -26.48, 16.509, -4.9407, and 0.57864, respectively.

For the hydraulically rough regime:

$$f = \left(1.74 + 2\log\frac{2R}{k_s}\right)^{-.5} \quad \text{for} \quad \log\frac{R_{bed}k_s}{4R} > 2.0 \qquad \text{(eq. 6–46)}$$

For gravel-bed rivers, Chang (1988) provides the following equation:

$$f = \left(0.248 + 2.36 \log \frac{d}{D_{50}}\right)^{-.5} \qquad \text{(eq. 6–47)}$$

where:
d = max depth of flow with units same as D_{50}

In figure 6–13, δ is the angle between the velocity vector of the bottom current and the centerline. Also of interest is the resultant angle of shear stress between the two components of shear, and longitudinal and radial. Chang (1988) gives that angle, δ , as:

$$\tan \delta' = \frac{2d}{\kappa^2 r}\left(1 - \frac{\sqrt{g}}{\kappa C}\right) \qquad \text{(eq. 6–48)}$$

where all variables have been previously defined.

Longitudinal shear stress at any point in the cross section is calculated with the following equation:

$$\tau_{0s} = \gamma d S_c \frac{r_c}{r} \qquad \text{(eq. 6–49)}$$

where the c subscript refers to the channel centerline.

The transverse bed slope (β) can be computed using:

$$\beta = \arctan\left(\tan\delta \, \tan\varphi\right) \qquad \text{(eq. 6–50)}$$

where:
δ = the angle shown in the above sketch
φ = the sediment angle of repose

This equation is valid when β is small compared to φ. This relationship is less accurate for channels with significant quantities of suspended sediment. Since φ is generally >30°, then β should be less than 10°. If φ >30°, then β becomes less valid as δ increases toward 20° or in tight curves.

Finally, Chang (1988) provides a formula for determining sediment sorting on the transverse slope:

$$D = \frac{3\rho d S_c r_c}{2r\left(\rho_s - \rho\right)\tan\varphi} \qquad \text{(eq. 6–51)}$$

where:
D = median grain size
d = depth at that location
S_c = longitudinal profile slope along the centerline
r_c = radius of curvature to centerline
r = radius of curvature to location of d
ρ = densities of sediment and water

Example problem: Design radius

Problem: A roughly trapezoidal curved channel is being designed with a moveable boundary in dynamic equilibrium to carry a flow of 700 cubic feet per second. The channel profile slope is 0.0013, channel bottom width is 30 feet, with a transverse bed slope, β, of 10 percent, and 3H:1V side slopes. The bed material is rounded gravel, with a D_{50} of 0.30 inches, and *n* value of 0.035. Considering uniform flow and a maximum depth of 6 feet, calculate the design radius of curvature to the centerline, longitudinal and radial stress vectors at the centerline, and the resultant stress angle in the curve.

Solution:
Part 1—Design radius of curvature to the centerline

The angle of repose φ for 0.3-inch, rounded gravel is about 31 degrees. Assuming a constant transverse bed angle of 10 percent, $\tan \beta = 0.10$, and the resulting angle of the bottom current would be:

$$\tan\beta = \tan\delta \, \tan\varphi \qquad \text{(eq. 6–52)}$$

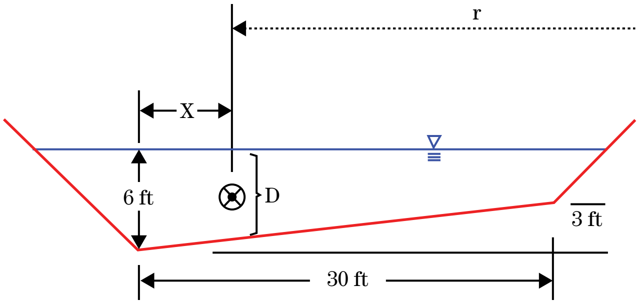
or

$$\delta = \arctan\left(\frac{\tan\beta}{\tan\varphi}\right) \qquad \text{(eq. 6–53)}$$

so, $\delta = 9.4$ degrees

Consider the channel centerline to be horizontally located at the centroid of the flow cross section, as shown in figure 6–14.

Figure 6–14 Channel centerline at centroid of flow ⊗



To find X, the flow area left of the centroid must be equated to that on the right:

$$\frac{18\times 6}{2}+3X+\frac{30\times 3}{2}-\frac{(30-X)(3-0.1X)}{2}$$
$$=3(30-X)+\frac{9\times 3}{2}+\frac{(30-X)(3-0.1X)}{2}$$

Simplifying:

$$54+3X+45=90-3X+13.5+(30-X)(3-0.1X)$$

$$12X-0.1X^2=94.5$$

by trial and error, X = 8.5 feet.

The depth at the centerline is

$$6-(8.5)(0.10)=5.15\text{ ft}$$

given:

$\tan\delta = 11\dfrac{d}{r}$, solving for radius of curvature, r = 342 ft

Part 2—Longitudinal and radial stress vectors

The longitudinal shear stress at the centerline is calculated with equation 6–49.

$$\tau_{0s}=\gamma dS_c\frac{r_c}{r}=62.4\times 5.15\times 0.0013=0.418\text{ lb/ft}^2$$

The total flow area is 202.5 square feet, wetted perimeter = 58.6 feet, so R = 3.46 feet. From Q = VA, the average velocity is 700/202.5 = 3.46 feet per second. The friction factor is:

$$f=\frac{8gRS}{V^2}=\frac{8\times 32.19\times 3.46\times 0.0013}{(3.46)^2}=0.097$$

The radial shear is calculated with equations 6–38 and 6–39.

$$\tau_{0r}=\frac{1+m}{m^2+2m}\rho\frac{d}{r}U^2$$

$$m=\kappa\sqrt{\frac{8}{f}}=0.4\sqrt{\frac{8}{0.097}}=3.36$$

$$\tau_{0r}=0.242\times 1.948\ \frac{\text{slugs}}{\text{ft}^3}\times\frac{\text{lb-s}^2/\text{ft}}{\text{slug}}\times\frac{5.15\text{ ft}}{342\text{ ft}}\times(3.46\text{ ft/s})^2$$
$$=0.085\text{ lb/ft}^2$$

Part 3—Resultant stress angle in the curve

The direction of the resultant stress vector between the longitudinal and radial components is calculated using equations 6–48 and 6–40.

$$\tan\delta' = \frac{2d}{\kappa^2 r}\left(1-\frac{\sqrt{g}}{\kappa C}\right)$$

where:

$$C=\frac{41.65+\dfrac{0.00281}{S}+\dfrac{1.811}{n}}{1+\left(41.65+\dfrac{0.00281}{S}\right)\dfrac{n}{\sqrt{R}}}$$

$$C=\frac{41.65+\dfrac{0.00281}{0.0013}+\dfrac{1.811}{0.035}}{1+\left(41.65+\dfrac{0.00281}{0.0013}\right)\dfrac{0.035}{\sqrt{3.46}}}=52.4$$

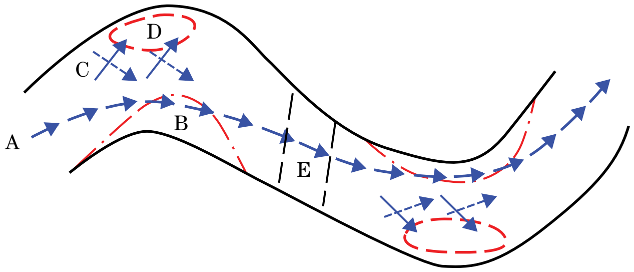
$$\tan\delta' = \frac{2\times 5.15}{(0.4)^2\times 342}\left(1-\frac{\sqrt{32.19}}{0.4\times 52.4}\right)=0.137$$

$$\delta' = 8^\circ$$

Hey (1979) addresses point bar development with a sketch similar to figure 6–15, showing how secondary currents, along with bed-load supply, impact the location of aggradation and degradation in a meander.

During bankfull flows, the strongest velocity vectors follow the course of the arrows starting at A in figure 6–15, cutting across the toe of point bars with the highest bed-load supply. At B, downstream of the bar apex, the shear stress and transport capacity drop, and aggradation occurs. Opposite the point bar at C, low bed load accompanies the incoming flow, and as surface

Figure 6–15 Point bar development



currents angle into the bank and undercurrents move away from the bank, a zone of downwelling results at point D. The low bed load gives the stream a scouring tendency. Toward the inflection point of the meander, flow with a low bed-load supply enters a contracted reach at E that is steeper and shallower, and regains its scouring capacity. Riffles form and, as the highest velocity vectors cut from one point bar toe to the toe of the next downstream bar, riffles are often skewed to the banks.

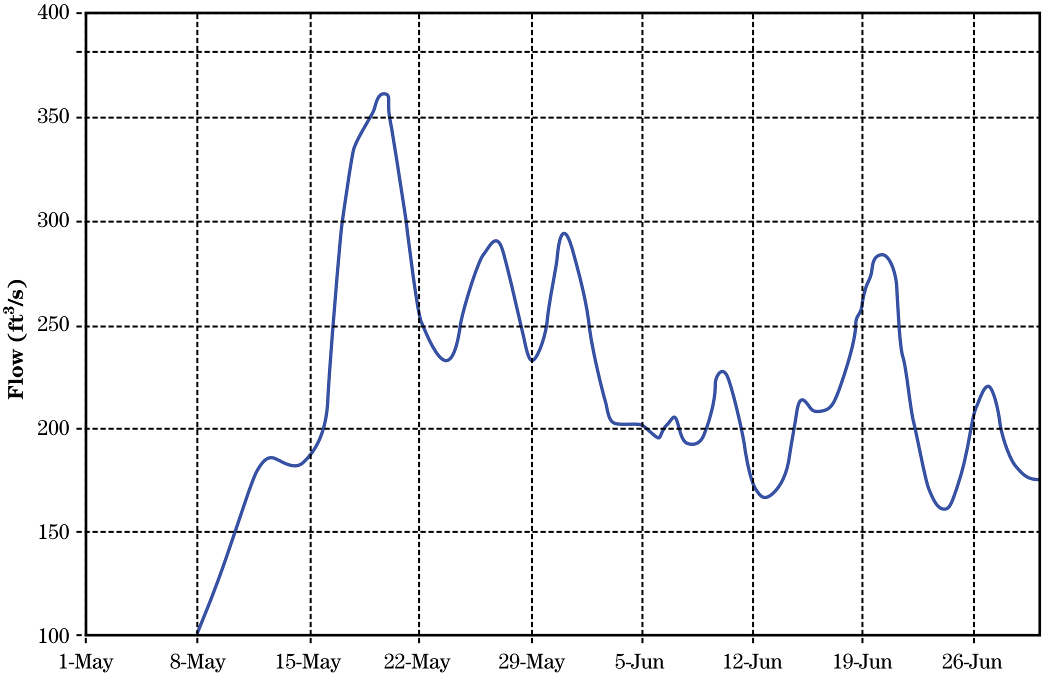
(h) Change in channel capacity

Natural channels will often incise in response to human impacts, such as watershed development, channel straightening, removal of vegetation, or overgrazing. The incision is a lowering of the channel bed, that in effect increases the channel size and capacity. Often, the overbank dries out due to a falling water table. This lowered water table can cause wetlands to shrink and adjacent productive lands to depend on irrigation. For projects in which overbank soil moisture is a concern, the duration of flow is often more important than the peak discharge. Inchannel flow can have a significant effect on overbank soil moisture if it is near bankfull for a sufficient duration.

Example problem: Change in overbank duration

Problem: A channel has, in the span of 10 years, incised by several feet and increased the bankfull flow area from 84 square feet to 107 square feet. The channel slope has increased from 0.0020 to 0.0025. The wetted perimeter increased from 29.4 feet to 42 feet. The vegetation has suffered to the extent that composite *n* value has decreased from 0.045 to 0.038. Approximate the change in duration of overbank flooding, given the season-long hydrograph in figure 6–16.

Figure 6–16 Seasonal hydrograph



Solution: Using a uniform flow assumption and Manning's equation, the original channel capacity was:

$$\begin{aligned} Q &= \frac{1.486}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \\ &= \frac{1.486}{0.045}(84)\left(\frac{84}{29.4}\right)^{\frac{2}{3}}(0.002)^{\frac{1}{2}} \\ &= 250 \text{ ft}^3/\text{s} \end{aligned}$$

With the changed hydraulic parameters:

$$\begin{aligned} Q &= \frac{1.486}{0.038}(107)\left(\frac{107}{42}\right)^{\frac{2}{3}}(0.0025)^{\frac{1}{2}} \\ &= 390 \text{ ft}^3/\text{s} \end{aligned}$$

Looking at the hydrograph, then, the new channel condition fully contains the hydrograph, since the peak is less than 390 cubic feet per second: no days of overbank flooding occur. The previous channel capacity was 250 cubic feet per second, and overbank flow would have occurred four separate times for a total of about 16 days.

654.0610 Water surface profile calculations

The calculation of water surface profiles and associated hydraulic parameters is a common task of hydraulic engineers. In natural, gradually varied channels, velocity and depth change from cross section to cross section. However, the energy and mass are conserved. The energy and continuity equations can be used to step from a water surface elevation at one cross section to a water surface at another cross section that is a given distance upstream (subcritical) or downstream (supercritical). Programs, such as HEC–RAS, use the one dimensional energy equation, with energy losses due to friction evaluated with Manning's equation, to compute water surface profiles. Equation 6–9 becomes:

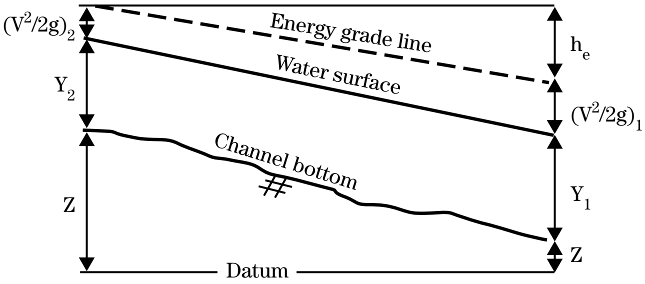
$$\left(\frac{V^2}{2g}\right)_2 + Y_2 + Z_2 = \left(\frac{V^2}{2g}\right)_1 + Y_1 + Z_1 + h_e \qquad \text{(eq. 6–54)}$$

This one dimensional energy equation can be restated as:

$$WS_2 = WS_1 + \frac{1}{2g}\left(\alpha_1 V_1^2 - \alpha_2 V_2^2\right) + h_e \qquad \text{(eq. 6–55)}$$

The water surface profile determination is accomplished with an iterative computational procedure called the standard step method. This is graphically illustrated in figure 6–17.

Figure 6–17 Standard step method



The energy loss includes friction losses (usually evaluated with Manning's equation) and losses associated with changes in cross-sectional areas and velocities. This is represented in equation 6–56:

$$h_e = L\overline{S_f} + C\left|\frac{\alpha V_2^2}{2g} - \frac{\alpha V_1^2}{2g}\right| \qquad \text{(eq. 6–56)}$$

Friction loss is evaluated as the product of the friction slope and the discharge weighted reach length. This is shown in equation 6–57:

$$L = \frac{L_{lob}\overline{Q_{lob}} + L_{ch}\overline{Q_{ch}} + L_{rob}\overline{Q_{rob}}}{\overline{Q_{lob}} + \overline{Q_{ch}} + \overline{Q_{rob}}} \qquad \text{(eq. 6–57)}$$

Example problem: Backwater from a log drop

Problem: Determine the maximum crest level of a log weir set all the way across the channel that would cause no backwater, and the crest level required to cause 1 foot of backwater just upstream of the weir (fig. 6–18). Assume a discharge of 491.5 cubic feet per second, depth of 4 feet, and uniform flow conditions without the weir.

Solution: To create no backwater, the log weir would have to pass the same discharge at the same water surface. The evaluation should be between the log crest (section 2) and a point (section 1) not very far upstream (fig. 6–19).

This can be evaluated using the energy approach with Bernoulli's equation. An assumption can be made that there is very little friction loss between the two points. The difference in the channel bottom elevation is also negligible over this short distance. So,

$$z_1 + y_1 + \alpha_1\frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2\frac{V_2^2}{2g} + h_L$$

where:

h_L = head loss (assumed negligible) becomes:

$$y_1 + \frac{V_1^2}{2g} = y_2 + \frac{V_2^2}{2g} + D$$

where:

D = height of the log weir

If the flow is high enough, the log weir will be drowned out by the normal depth tail water and would not cause backwater. At lower discharges, the flow over the log will pass through critical depth (as shown in fig. 6–19).

At critical depth, the velocity head is equal to half the hydraulic depth:

$$\frac{V_{cr}^2}{2g} = \frac{d}{2} = \frac{A}{2T}$$

Figure 6–18 Problem determinations for determination of log weir

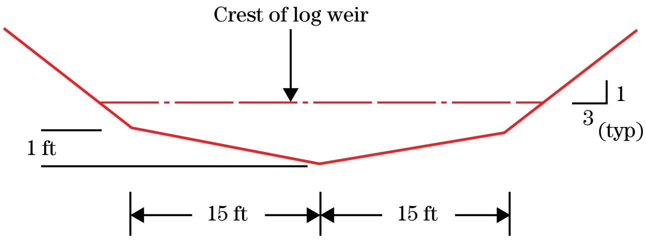
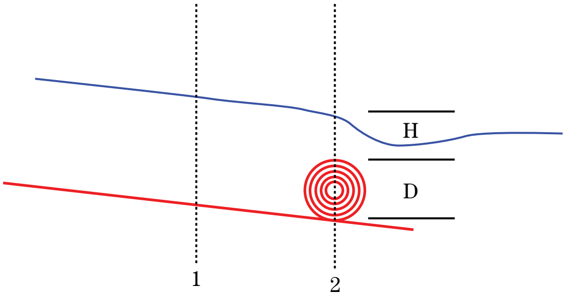


Figure 6–19 Profile for crest of log weir problem



Substituting back into Bernoulli's equation, since V_2 is V_{cr},

$$y_1 + \frac{V_1^2}{2g} = y_{cr} + \frac{A}{2T} + D$$

To determine whether the log causes backwater, compare the y_1 calculated to the flow depth without the log (4 ft). That is:

$$y_{cr} + \frac{A}{2T} + D - \frac{V_1^2}{2g} \quad \text{less than 4}$$

where:
V_1 = velocity upstream of the weir

Using the critical depth formula (where d is hydraulic depth and T is top width) along with the continuity equation, Q = VA, the following can be derived:

$$\frac{V_{cr}^2}{2g} = \frac{d}{2} = \frac{A_{cr}}{2T}$$

$$A_{cr} = \frac{Q}{V_{cr}} \quad \text{and} \quad V_{cr}^2 = \frac{A_{cr}2g}{2T} = \frac{A_{cr}g}{T}$$

$$A_{cr}^2 = \frac{Q^2}{V_{cr}^2} \quad \text{so} \quad A_{cr}^2 = \frac{Q^2T}{A_{cr}g} \quad \text{and} \quad A_{cr} = \sqrt[3]{\frac{Q^2T}{g}}$$

To find the maximum log crest before backwater is created, a log crest must be chosen and checked with a trial and error approach. For this example, suppose D = 1. Choose a depth and calculate the flow area by the dimensions of the cross section. Then compare with the A_{cr}. When the two flow areas are the same, this is the critical depth for that Q (given as 491.5 ft^3/s).

Trial #	y_{cr}	T	A	A_{cr}
1	1.0	36.0	33.0	64.65
2	2.0	42.0	72.0	68.06
3	1.9	41.4	67.8	67.70

However, the velocity head must still be calculated to assure that there is no backwater. Note that the velocity head is negligible as long as the velocity is not too large. For example, a velocity of 5 feet per second results in a velocity head of 0.39 feet.

$$y_{cr} + \frac{A}{2T} + D - \frac{V_1^2}{2g} \quad \text{less than 4}$$

If this velocity head term is neglected, then given y_{cr} = 1.9, T = 41.4, A = 67.8, the above formula solves as:

$$1.9 + \frac{67.8}{2 \times 41.4} + 1 = 3.72 \text{ ft}$$

Since this solution is less than the clear channel depth of 4, it may be possible to raise the weir.

(a) Steady versus unsteady flow

Many hydraulic parameters of interest in typical designs and assessment can be calculated by assuming a normal depth. Normal depth calculations are often based on a solution to Manning's equation. This approach is relatively simple, but only applicable in uniform flow conditions where the gravitational forces are exactly offset by the resistance forces. Manning's equation is an infinite slope model that assumes mean depth, velocity, and area are the same from cross section to cross section. It can only occur in long, straight, prismatic channels where the terminal velocity of the flow is achieved. This assumption cannot account for backwater conditions nor variable channel shape, roughness, and slope. Natural channels approach, but rarely achieve uniform, normal depth. Designs and assessments that depend on calculations based on normal depth must consider the affects of possible errors.

Even though flows in a stream are readily observable at any time, they are unsteady at every spatial and temporal scale. Typically, unsteady modeling results in variations in flow rate, velocity, and depth in space and time throughout the modeled reach. In most unsteady flow models, the discharges can vary within a model, and the boundary conditions are in terms of flow and stage with time. Unsteady flow calculations are often used to analyze a dam breach, inchannel storage, variable boundary conditions, rapidly rising hydrographs on flat slopes, irrigation withdrawals, tributary flow interaction, and locations where duration of flooding is an issue.

Unsteady flow models can be contrasted to steady flow models with no time component in the calculations. Steady flow models are typically much simpler to calibrate and execute than unsteady flow models. For most steady flow models, the depth and velocity may change from section to section, but only one flow is allowed per section per model run. Since the flow is constant with respect to time, only one discharge is calculated for each section in a given steady flow model run. In addition, boundary conditions are held constant. These assumptions are often suitable for many analyses where the reach is short or the primary interest is an assessment of the peak hydraulic parameters for a given discharge.

In alluvial channels, the interaction of sediment with the flow can also have a profound affect since the amount and type of sediment load affects the energy balance of the flow. Equations of sediment motion (sediment continuity and sediment transport) are covered in NEH654.13.

(b) Backwater computational models

Computer programs are used to calculate water surface profiles, lateral velocity distributions, flow regimes, and scour potential. For projects that are likely to involve revisions to Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps, selection of the hydraulic model should be coordinated carefully with FEMA. Following are some standard hydraulic models.

HEC–RAS

HEC–RAS (USACE 2001b) is the recommended computer program for performing hydraulic calculations for steady and unsteady, gradually varied (over distance), one-dimensional, open channel flow. HEC–RAS includes a culvert module that is consistent with HDS–5 and HY–8. The bridge hydraulics algorithms now include the WSPRO models. HEC–RAS applies conservation of momentum, as well as energy and mass, in its hydraulic analysis. HEC–RAS includes all the features inherent to HEC–2 and WSPRO, plus several friction slope methods, mixed flow regime support, automatic *n* value calibration, ice cover, quasi 2–D velocity distribution, and super-elevation around bends.

HEC–2

HEC–2 (USACE 1990b) performs hydraulic calculations for steady, gradually varied (over distance), one-dimensional, open channel flow. One of HEC–2's technical limitations is that the normal bridge routines and standard-step backwater computations use energy conservation only. Conservation of momentum is used only in the special bridge routines when bridge piers are involved.

WSPRO

The WSPRO computer program was developed by the USGS and is comparable to HEC–2, except for the fact that WSPRO had special subroutines for analysis of water surface profiles at bridge locations. All of these WSPRO subroutines have been incorporated into HEC–RAS. The current version of WSPRO is no longer being supported by USGS.

HY–22

HY–22 is a small tool kit of relatively simple computer programs for performing the hydraulic analyses described in the Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22, U.S. Department of Transportation Federal Highway Administration (FHWA) (1996). HY–22 includes pavement drainage, open channel hydraulics, critical depth computation, computation of storage volume, and simple reservoir routing.

654.0611 Weir flow

Flow over a broad-crested weir is an application that can be analyzed with momentum principles. The momentum principle has certain advantages in application to problems involving high internal energy changes (Chow 1959). The pressure force due to the weight of water and the obstruction of the weir is important. The gravitational force vector in the direction of flow may be neglected for a mild channel slope and small distance between the uncontracted upstream section and the cross section at the weir. The friction forces on the wetted boundary in the short distance between the two sections may be neglected, as well.

Weir flow is calculated using:

$$Q = CLH^{\frac{3}{2}} \qquad \text{(eq. 6–58)}$$

where:
L = weir length (ft)
C = weir discharge coefficient (usually from 3.05 to 2.67)
H = approach head (ft)

The actual value of C depends on factors such as the roundedness of the upstream corner of the weir and the width and slope of the weir crest. Brater and King (1976) give C = 3.087 as a maximum value for broad-crested weirs with a vertical upstream face under any conditions, given that the upstream corner is so rounded as to prevent flow contraction and the slope of the crest is at least as great as the head loss on the weir due to friction. Under these conditions, flow over the weir occurs at critical depth. Inclining one or both faces of the broad-crested weir can also increase the C value, and Brater and King document experiments that obtain values of C as high as 3.8.

The flow velocity vectors for this equation are considered to be perpendicular to the crest; that is, the flow momentum is straight into the weir. If the weir is a lateral one or the main channel flow is parallel to the crest and the weir draws flow off to the side, the weir capacity would be less.

The major use of sharp-crested weirs is for flow measurement. Many different crest cross-sectional shapes exist, such as a V-notch, but the weir width is always thin and is perpendicular to the flow. The same discharge equation used for broad-crested weirs may be applied to horizontal, sharp-crested weirs, but the discharge coefficient, C, is highly dependent on the nappe conditions. The nappe is the sheet of water flowing or jetting over the weir. A fully aerated nappe has an air pocket at atmospheric pressure just downstream of the weir and below the sheet of flowing water. A weir with a fully aerated nappe has a higher discharge coefficient than one in which the nappe is partially (air pressure less than atmospheric) or fully submerged (no air pocket).

654.0612 Hydraulic jumps

Determining the strength and location of hydraulic jumps is important for designing energy dissipation structures and assessing the effectiveness of stream barbs or step-pool structures. The following equation is used to estimate energy dissipation at a hydraulic jump:

$$\Delta E = E_1 - E_2 = \frac{(y_2 - y_1)^2}{4y_1y_2} \qquad \text{(eq. 6–59)}$$

Energy is expressed in units of length (a head loss). The height of a jump for a channel of small slope can be estimated from:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8F_1^2} - 1\right) \qquad \text{(eq. 6–60)}$$

where:

y_1 = upstream depth

y_2 = downstream flow depth

F_1 = Froude number of the upstream flow. This equation is derived from the specific force formulation for a rectangular channel.

where:

$$\frac{2Q^2}{gA_1} + A_1y_1 = \frac{2Q^2}{gA_2} + A_2y_2 \qquad \text{(eq. 6–61)}$$

And the Froude number is:

$$F_1 = \frac{V_1}{\sqrt{gy_1}}$$

Substituting VA for Q and bd for A, where b is the channel bottom width, as well as making use of the definition of Froude number, this equation can be simplified to:

$$\frac{y_2^2}{y_1^2} - \left(2F_1^2 + 1\right) + \frac{2F_1^2y_1}{y_2} = 0 \qquad \text{(eq. 6–62)}$$

Knowing the depth of the approaching flow and its Froude number, the flow depth downstream of the jump can be calculated. Froude numbers can also be used to specify different types of jumps as shown in table 6–1 (Chow 1959).

The length of a well-defined hydraulic jump is the distance from the upstream face of the jump to the point on the surface just downstream of the roller. Chow indicates that it cannot be easily determined theoretically and is best estimated empirically. The U.S. Department of Interior Bureau of Reclamation performed numerous experiments and provides figure 6–20 for determining jump length based on upstream Froude number and upstream flow depth (Peterka 1984). L is jump length, y_1 is upstream depth, and the Froude number is that of the flow coming into the jump.

The location along the channel profile of the upstream beginning of the hydraulic jump can be generally determined from

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8F_1^2} - 1\right) \qquad \text{(eq. 6–63)}$$

However, the jump length has a bearing on this estimate. For example, the location of a hydraulic jump formed by a broad-crested weir in the channel can be used to illustrate this situation (fig. 6–21). Downstream tailwater affects the location of the jump, moving it farther upstream and closer to the weir, as the tailwater is raised. A lower tailwater elevation produces a jump farther downstream. Increasing the height of the weir moves the jump upstream, whereas decreasing it moves the jump downstream.

Table 6–1 Froude numbers for types of hydraulic jumps

Froude	Jump type
<1	No jump, subcritical flow
1.0	No jump, critical flow
1.0–1.7	Undular jump: unsteady water surface
1.7–2.5	Weak jump: small rollers develop on surface
2.5–4.5	Oscillating jump: vertical flow jet produces surface waves that may travel long distances
4.5–9.0	Steady jump: best energy dissipation performance
>9	Strong jump: very high energy dissipation, but with surface waves sent downstream

Figure 6–20 Determination of jump length based on upstream Froude number

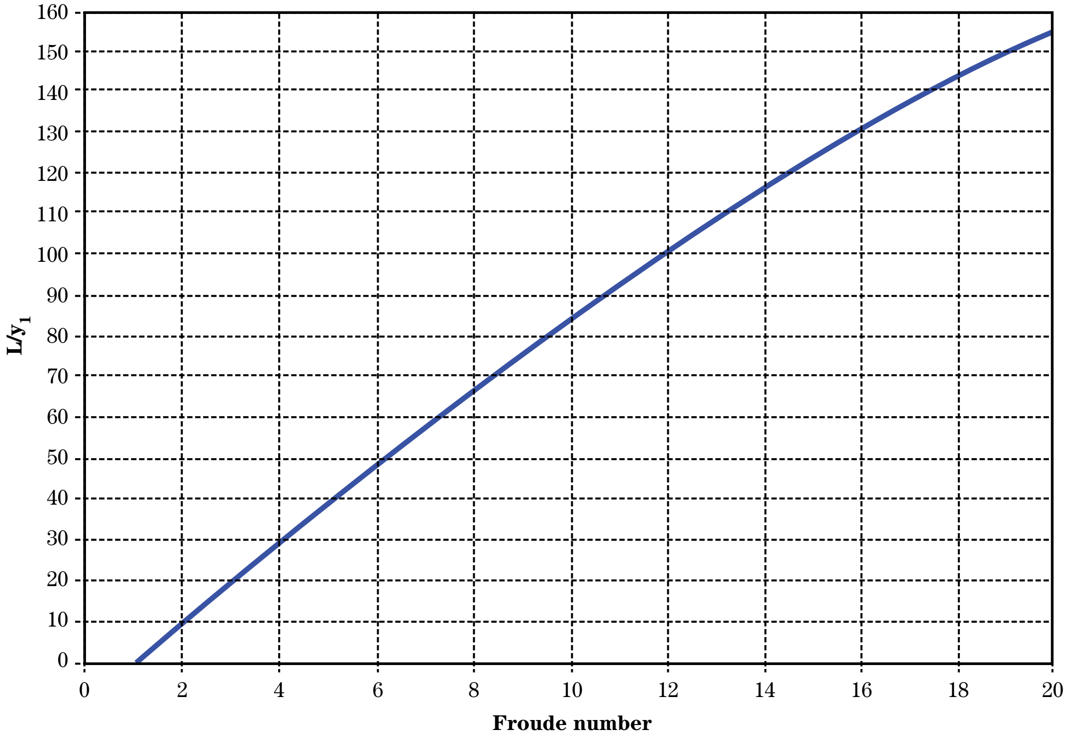
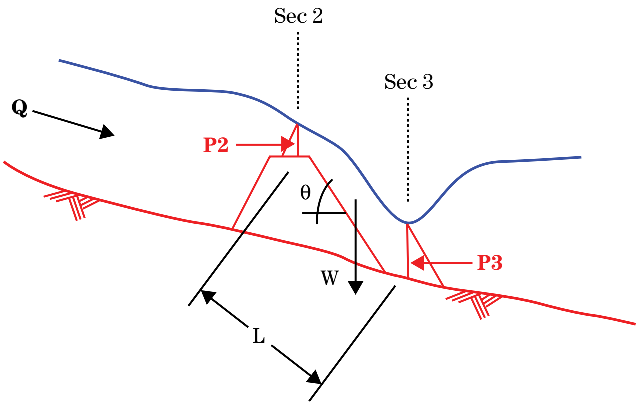


Figure 6–21 Parameters involved with modeling a hydraulic jump



However, the weir will not cause an hydraulic jump if it is drowned out by downstream tailwater. The downstream depth must be less than critical depth over the weir plus the weir height, or, using the definition of critical depth:

$$y_3 < \frac{(2y_1 + h)}{3} \qquad \text{(eq. 6–64)}$$

where:

y_1 = depth upstream of the weir

h = weir height

y_3 = tailwater depth downstream

654.0613 Channel routing

Channel routing is an important component of hydrologic modeling and assessments. Designers need to be able to estimate not only flow volumes, but also hydraulic parameters for many projects. Efforts to mathematically model and predict channel routing started with Jean Claude Saint-Venant in 1871. However, it is only with the advent of high speed computers that many of the techniques are readily available to most designers. The practitioner should keep in mind that even the most advanced computer models simplify natural system processes. It is, therefore, important for the modeler to understand the computational procedures used in the model being applied.

(a) Movement of a floodwave

Channel routing is the calculation of the hydraulic parameters of a floodwave as it moves through a channel. The overall movement is typically described with the concepts of celerity and attenuation. Floodwave celerity is the speed at which the floodwave moves down the channel and is primarily a function of the channel slope. The attenuation of a floodwave is the subsidence or flattening of the wave as it moves down the channel. Floodwave attenuation is directly related to the amount of inchannel or riparian storage available.

(b) Hydraulic and hydrologic routing

The movement of a floodwave is governed by the laws of fluid mechanics. The two equations for clear water flow are the conservation of mass, or the continuity equation, and the momentum equation. These two equations are referred to as the Saint-Venant equations. Traditional hydraulic routing involves a numerical solution to these equations as partial differential equations. Therefore, hydraulic routing is viewed as being more physically based than hydrologic routing.

Traditional hydrologic routing typically uses an algebraic solution to the continuity equation and a relationship between changes in storage in the reach and discharge at the outlet. Hydrologic routing is often based on analogies of stream channels and basins as a set of storage reservoirs with appropriate properties. In fact, hydrologic routing equations are often referred to as storage routing equations. As a result, hydrologic modeling is inherently empirically based. Typical hydrologic routing equations include the Muskingum routing and the Reservoir (Puls) routing procedures.

(c) Saint-Venant equations

Most channel routing performed by computer modeling is based on some simplification of the Saint-Venant equations. These equations provide a very simple model of very complex processes. These equations are:

Continuity

$$A\frac{\partial V}{\partial x}+VB\frac{\partial y}{\partial x}+B\frac{\partial y}{\partial t}=q \qquad \text{(eq. 6–65)}$$

Momentum

$$S_f=S_o-\frac{\partial y}{\partial x}-\frac{V}{g}\frac{\partial V}{\partial x}-\frac{1}{g}\frac{\partial y}{\partial t} \qquad \text{(eq. 6–66)}$$

where:

A = cross-sectional flow area
V = average velocity of water
x = distance along channel
B = water surface width
y = depth of water
t = time
q = lateral inflow per unit length of channel
S_f = friction slope
S_o = channel bed slope
g = gravitational acceleration

The solutions to the momentum and continuity equations concurrently define the propagation of a floodwave with respect to distance along the channel and time. Assumptions for these equations include:

- The momentum and continuity equations are shown for one-dimensional flow in the downstream direction. The natural variation in velocity with respect to depth is ignored. In addition, these equations do not directly address lateral or vertical stream flows that would require a more complex equation.
- Flow is gradually varied so that hydrostatic pressure prevails, and vertical accelerations can be ignored.
- The effects of boundary friction and turbulence can be treated with resistance laws, as they are in steady flow.
- Fluid is incompressible and has a constant density.

(d) Simplifications to the momentum equation

Depending on the relative importance of the various terms of the Momentum equation, it can be simplified for different applications as follow:

Steady uniform flow (kinematic wave approximation)	$S_f=S_o$
Steady nonuniform flow (diffusive wave approximation)	$S_f=S_o-\frac{\partial y}{\partial x}$
Steady nonuniform flow (Quasi-steady state dynamic wave approximation)	$S_f=S_o-\frac{\partial y}{\partial x}-\frac{V}{g}\frac{\partial V}{\partial x}$
Steady nonuniforn flow (full dynamic wave approximation)	$S_f=S_o-\frac{\partial y}{\partial x}-\frac{V}{g}\frac{\partial V}{\partial x}-\frac{1}{g}\frac{\partial y}{\partial t}$

Since simplification means that some aspect is being ignored, it is important for a modeler to understand the basis of the model being applied to answer a hydraulic or hydrologic question. Further discussion on application and limitations of some of routing approaches that are used in many computer programs follows.

- *Kinematic wave approximation*—The kinematic wave approximation assumes that the gravitational and frictional forces are in balance. The kinematic wave approximation works best when applied to steep (0.0019, 10 ft/mi or greater), well-defined channels, where the floodwave is gradually varied. Changes in depth and velocity with respect to time and distance are small in magnitude when compared to the bed slope of the channel. The approach is often applied in urban areas because the routing reaches are generally short and well defined (circular pipes, concrete lined channels). However, the equations do not allow for hydrograph diffusion, but only simple translation of the hydrograph in time.

The application of the kinematic wave equation is limited to flow conditions that do not demonstrate appreciable hydrograph attenuation. This may be an issue in wide channels, since attenuation increases with valley storage. The kinematic wave equations cannot handle backwater effects, since with a kinematic model flow disturbances can only propagate in the downstream direction.

- *Modified Puls reservoir routing*—This approach accounts for the difference of inflow as storage over some defined time period. This method is appropriate if lateral storage is the primary physical mechanism that affects the flood routing. This method disregards the equation of motion by focusing on continuity. It is closely related to level pool reservoir routing.
- *Muskingum river routing*—The Muskingum river routing method is based on two equations. The first is the continuity equation, and the second is a relationship of storage, inflow, and outflow of the reach. This method is based on a weighted function of the difference of inflow as storage over some defined time period. Typically, the coefficients of the Muskingum method are not directly related to physical channel properties and can only be determined from stream gage data.
- *Diffusive wave approximation*—The diffusion wave model is a significant improvement over the kinematic wave model because of the inclusion of the pressure differential term in the momentum equation. This term allows the diffusion model to describe the attenuation (diffusion effect) of the floodwave. It also allows the specification of a boundary condition at the downstream extremity of the routing reach to account for backwater effects. It also allows the specification of a boundary condition at the downstream extremity of the routing reach to account for backwater effects. Since it does not use the inertial terms (last two terms) from the full momentum equation, it is limited to slowly to moderately rising floodwaves in flat channels (Fread 1982). However, most natural floodwaves can be described with the diffusion form of the equations.
- *Muskingum-Cunge*—The theoretical development of the Muskingum-Cunge routing equation is based on the simplification of the convective diffusion equation. In the Muskingum-Cunge formulation, the amount of diffusion is controlled by forcing the numerical diffusion to match the physical diffusion represented by the convective diffusion equation. This approach accounts for hydrograph diffusion based on physical channel properties and the inflowing hydrograph. The method includes the continuity equation and a relationship of storage, inflow, and outflow of the reach. The solution is independent of the user-specified computation interval. The coefficients of the Muskingum-Cunge method are based on data such as cross section and estimated Manning's n and are more physically based than the Muskingum method. Therefore, the Muskingum-Cunge method can be applied to ungaged streams. However, it cannot account for backwater effects, and the method begins to diverge from the full unsteady flow solution when very rapidly rising hydrographs are routed through flat channel sections.
- *Quasi-steady dynamic wave approximation*—The third simplification of the full dynamic wave equations is the quasi-steady dynamic wave approximation. In the case of flood routing, the last two terms in the momentum equation are often opposite in sign and tend to counteract each other. By including the convective acceleration term and not the local acceleration term, an error is introduced. This error is of greater magnitude than the error that results when both terms are excluded, as in the diffusion wave model. This approach is not often used in flood routing.
- *Dynamic wave equations*—The dynamic wave equations can be applied to a wide range of one-dimensional flow problems, such as dam break flood wave routing, tidal fluctuations, canal distribution, and forecasting water surface elevations and velocities in a river system during a flood. Solution of the full equations is normally accomplished with an explicit or implicit finite difference technique. The equations are solved for incremental times (dt) and incremental distances (dx) along the waterway.

654.0614 Hydraulics input into the stream design process

(a) Determining project scope and level of analysis

Hydraulic engineering contributions to stream design can be viewed as a three-dimensional process. The most important two dimensions are the type of project and the stage of the project.

The third dimension is the constraint of time and/or cost that is not strictly engineering related. The role of the hydraulic engineer in this third dimension is to apply the standards of professional engineering licensure. If time or cost prevents an analysis from meeting professional engineering standards, the engineer must inform project managers and act accordingly.

The level of detail required of a hydraulic analysis falls into one of three categories: rough estimation, standard engineering, and atypical complexity. Generally, the reconnaissance stage of a project requires a rough estimation level of detail, although many standard engineering procedures are not time consuming nor difficult to apply, so that often a reconnaissance stage can be supported with a greater level of detail. For the remaining project stages, standard engineering procedures are minimally required. However, depending on the project particulars, atypical complexity may be necessary.

Each project type, as identified in table 6–2, will have pertinent hydraulic parameters, computations, and an applicable level of detail. The scope of the hydraulic analysis is tied to the project, and each project type generally corresponds with a hydrology type as shown in table 6–3.

When providing hydraulic computations, the designer should also estimate uncertainties, be able to specify their source, and provide confidence limits. Engineering in a stream corridor requires field work. The greater the quantity or precision of results needed, the greater the amount of field data required. Time and human labor cost may be expected to rise accordingly.

Table 6–2 Project dimensions by type and stage of project

Dimension 1	
	Type of project
1	Flood prevention or flood level determination
2	Bed and bank scour prevention, streambank protection
3	New or relocated channel design
4	Design of structures (bridge, culvert, levee, drop, weir)
5	Habitat or vegetation enhancement
6	Flood plain reconnection

Dimension 2	
	Dimension of project
1	Reconnaissance
2	Planning
3	Design
4	Monitoring

Table 6–3 Scope of hydraulic analyses by project type

	Flow level	Major concerns	Project types
1	Low flow	Duration	5
2	Bankfull flow	Duration and frequency	2, 3, 6
3	Overbank flows	Frequency	1
4	Specific flow levels	Frequency	4

(b) Accounting for uncertainty and risk

The hydraulic engineer must always keep in mind the level of certainty inherent in data measurements, computational methods, and information provided by others. For example, the frequency of flows developed by a hydrologist is, at best, a statistical derivation with confidence limits. The hydraulic engineer can inspect the steepness of the frequency curve, as well as the confidence limits to determine the range of flows that should be associated with a given recurrence interval. If the hydrologist had no gage data from which to develop frequency information, the hydrology would probably be considered even less reliable.

As described in this chapter, numerous methods in hydraulic engineering were developed from empirical studies. The designer should know what situations are and are not applicable to a given methodology. Whenever simplified methods are employed, the designer should be aware of the sacrifice in confidence of results.

One typical response in the attempt to minimize the risk due to uncertainty is to use factors of safety and be conservative. However, it is critical that the designer apply factors of safety to the correct calculations and be conservative in the correct aspect of the analysis. To be conservative from a flood control perspective is to design a larger than necessary channel. However, if the goal of the project is to reconnect the flood plain, that designer's conservatism may lead to design failure.

The designer should keep track of each computational attempt to account for uncertainty. In each case, an adjustment should be justified by a description of the source of the uncertainty and reasoning regarding the magnitude of the adjustment. In many cases, a conventional factor of safety will have been established by the field of hydraulic engineering. Standard freeboard heights for channel design are also conventional.

Finally, the hydraulic engineer may wish to more fully document the impact of uncertainties by modeling what-if scenarios, considering extreme values of one or more parameters.

654.0615 Conclusion

This chapter provided an overview of the hydraulic engineering concepts involved in stream design. A number of typical hydraulic computations were provided as examples. This discussion can help all disciplines better understand the role of hydraulics in the stream design process.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 7 Basic Principles of Channel Design

Issued August 2007

Cover photo: Where modification of the stream or channel is needed to achieve restoration goals and objectives, alteration of dimensions, pattern, and profile may be needed, resulting in designs ranging from minimal changes to large-scale rehabilitations.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 7 Basic Principles of Channel Design

Contents

Tables

Figures

Chapter 7 Basic Principles of Channel Design

654.0700 Purpose

Channel design may involve the stabilization or realignment of an existing stream, or it may involve the creation of an entirely new channel. There are a wide variety of sources and techniques for designing stable channels that are available to the designer. These techniques may focus on a variety of open channel design work ranging from natural stream restoration to a strictly structural project. However, these techniques need to be applied to the appropriate conditions and stream types. The purpose of this chapter is to provide a framework for the designer to assess the use and application of several of the analysis and design techniques presented in subsequent chapters. This chapter provides some background which should be useful in the evaluation of these techniques to address specific goals, constraints and conditions. To provide a context for the different design techniques, a clear description of threshold and alluvial channels is presented in this chapter. In addition, a general description of channel design variables and approaches is presented. These broad, and occasionally overlapping, categories of stream types and design approaches can be used to evaluate the appropriateness of the design techniques for a specific objective and site.

654.0701 Overview of channel design

A stable channel is often defined as a channel where the planform, cross section, and longitudinal profile are sustainable over time. While channel migration may not always be acceptable due to project or site constraints, it is important to note that a natural channel can migrate and still be considered stable, in that its overall shape and cross-sectional area do not change appreciably. Design methodologies and approaches may be used to estimate the conditions that may result in such movements. Design features are also often employed to reduce the frequency and magnitude of these changes.

Another common goal for a channel restoration design is that long-term aggradation and/or degradation should be small enough to allow for economical channel maintenance. Ideally, a channel should be self-sustaining and not require any maintenance. Many design methodologies can be used to design a channel which is in balance with the incoming sediment load. However, it is also important for the designer to recognize that manmade, as well as natural channels may aggrade or degrade over time or in response to specific storm events. Sediment impact assessments can be used to quantify what storm events may result in a sediment disequilibrium and to quantify the expected aggradation, so that appropriate maintenance can be budgeted. Design features can also be employed to counteract a tendency for bed degradation.

A variety of applicable open channel analysis and design techniques are available to the designer. The approaches used in open channel design range from those that apply to a natural stream restoration, to those that are more applicable to a strictly structural project. The specifics and details regarding the use and application of several analysis and design techniques are presented in subsequent chapters. This chapter provides a framework in which to evaluate these techniques. While techniques may have the same general objective, the specifics of their applicability should be understood before one approach is chosen over another. Where there is uncertainty regarding the appropriate technique to use, it is recommended that the designer consider several applicable techniques and look for agreement on critical design elements.

Each technique presented and described in this handbook has advantages and disadvantages. One approach may require more certainty in specific background information than another. In other situations, one approach may result in a type of channel which may not satisfy a given ecological goal, while another may result in a more expensive, but potentially more ecologically beneficial project. In addition, different analysis and design techniques are more appropriate for use on specific stream types and systems than on others. For example, some of the techniques are appropriate only for fixed-bed systems, while others are appropriate for mobile-bed systems. While all of the presented techniques have been successfully used, there are many examples where they have been misapplied and have resulted in projects which performed less than ideally.

Many papers and descriptions compare and contrast the different design methods and approaches that are presented in this chapter. The purpose of this document is not to evaluate each of the techniques as being more suitable than others, but to present the user with sufficient information to understand the application of the individual techniques. It is left to the user to review and assess the applicability of each of the techniques to the project site.

654.0702 Channel types

The nature of the interaction of the flows and sediments with the channel boundary should be used in the selection of the appropriate design approach. Channels can be divided into two general categories based on the sediment load and the stability of the channel boundary during normal flow. These two categories are threshold and alluvial channels. The general design approaches for each are defined and contrasted in this chapter. In subsequent chapters, specific design techniques are presented and described. Since there is not always a sharp demarcation between these two very broad categories, transition channels are also described.

(a) Threshold channels

A threshold channel is defined as a channel in which channel boundary material has no significant movement during the design flow. The term threshold is used because the channel geometry is designed such that applied forces from the flow are below the threshold for movement of the boundary material.

A threshold type of channel or stream includes cases where the bed is composed of very coarse material or erosion resistant bedrock. Streams where the boundary materials are remnants of processes no longer active in the stream system may be threshold streams. Examples are streambeds formed by high runoff during the recession of glaciers or dam breaks and streams armored due to reduction in the upstream sediment supply and degradation. Photographs of examples of threshold channels are provided in figures 7–1 through 7–3.

Fine sediment may pass through threshold streams as throughput or wash load. Generally, wash load should not be considered part of the bed-material or sediment load for stability design purposes even if there are temporary deposits on the streambed at low flow. However, throughput or wash load may be an environmental issue.

Threshold channels do not have the ability to quickly adjust their geometry, as do alluvial channels, because the material forming the channel boundary is not erodible within the normal range of flows, and there is no significant exchange between the sediment in transport and the bed. At flows larger than the design flow or

Figure 7–1 Gabion-armored threshold channel

Figure 7–2 Grass-lined threshold channel

Figure 7–3 Bedrock threshold channel

during extreme events, threshold channels may become destabilized for short periods, with harmful morphological impacts. Since threshold channels do not adjust their dimensions to the natural runoff hydrograph, the concept of channel-forming discharge is generally not applicable.

The design goal of a threshold channel design technique is to produce a channel that has positional or engineering stability. As long as the flows in the channel are below the design discharge, the particles that make up the channel boundary are stable, and the section, plan, and profile of the channel should be essentially static over time. The use of threshold design does not necessarily imply the absence of sediment movement, but rather that the transport capacity is sufficiently large to carry the sediment load through the system without meaningful deposition at boundary stresses less than those required to erode (mobilize) the boundary. For this reason, threshold channels are often designed near the erosion threshold of the boundary during design flows to prevent deposition that would change channel characteristics.

The reader should note that in some literature, the term threshold channel refers to a channel that is at the threshold of movement. In this case, these channels are also referred to as incipient motion channels. This defines a situation where the particles in the channel boundary are at the initiation of motion, not some point below movement. However, as defined in this handbook, the boundary of a threshold channel is below this point for flows up to the design discharge, not directly at the threshold of motion.

(b) Alluvial channels

Alluvial streams and channels have bed and banks formed of material transported by the stream under present flow conditions. There is an exchange of material between the inflowing sediment load and the bed and banks of the stream. The sediment transported in an alluvial channel tends to be coarser and of a larger amount than that transported in a threshold channel. Examples of alluvial channels are shown in figures 7–4 through 7–6. Since natural alluvial channels adjust their width, depth, slope, and planform in response to changes in water or sediment discharge, an alluvial channel will not be as static as a threshold channel.

Figure 7–4 Sand-bed alluvial channel

Figure 7–5 Sand and gravel-bed alluvial channel

Figure 7–6 Gravel-bed alluvial channel

Alluvial channel designs require an analysis of channel stability. An alluvial stream is defined as stable when it has the ability to pass the incoming sediment load without significant degradation or aggradation, and when its width, depth, and slope are fairly consistent over time. The design goal of an alluvial channel design technique is often to produce a channel that has dynamic equilibrium or geomorphic stability. Bank erosion and bankline migration are natural processes and may continue in a stable channel. When bankline migration is deemed unacceptable, then engineering solutions must be employed to prevent bank erosion. Bank protection technology is not addressed in this chapter, but a review of issues and design considerations are in NEH654.14.

(c) Transition channels

A clear distinction between threshold and alluvial channels may not always be apparent. One reach of the stream may be alluvial, while another has the characteristics of a threshold channel. A threshold reach can be changed to an alluvial reach by flattening the slope. A stream may be alluvial at low discharges when there is an adequate sediment supply, and then act like a threshold channel at high discharges. Conversely, a channel may function as a threshold stream at low flows, but during very high discharge become mobile. An example is shown in figure 7–7. In these situations, it is often appropriate to apply both threshold and alluvial channel design techniques.

If an armor layer is present, a stream may be a threshold channel at low flows and on the rising limb of a flood hydrograph, but behave as an alluvial channel at high flows when the armor layer is mobilized, and on the falling limb of the flood hydrograph, when sediment is being deposited. Therefore, it is important to evaluate channels through their entire flow range to determine how they will react to natural inflow conditions and how their stability status may change as a function of discharge.

The armor layer of a gravel bed stream is shown in figure 7–8. Note the much finer subsurface bed material exposed when a few cobbles were removed from the armor layer. Armor layer thickness is typically equal to the D_{90} particle size of the subsurface material. Figure 7–9 shows an armor layer that had formed on the delta of a reservoir and then was destroyed when the water level was lowered.

Figure 7–7 Boulder-bed channel that could be a threshold channel or an alluvial channel, depending on the design discharge

Figure 7–8 Subsurface layer exposed after removal of three cobbles from the armour layer

Figure 7–9 Degradation through armor layer

654.0703 Perennial, intermittent, and ephemeral streams

The flow conditions that a channel may experience through the year may also have an influence on the choice of the appropriate channel design technique. Both threshold and alluvial streams may be classified as perennial, intermittent, or ephemeral, depending on the duration of flow over the course of the year. Definitions of these terms are not precise. Following are stream definitions that have been used by the U.S. Geological Survey (USGS) since the early 1920s (Meinzer 1923):

Perennial—A stream that flows continuously. Perennial streams are generally associated with a water table in the localities through which they flow.

Intermittent or seasonal—A stream that flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas.

Ephemeral—A stream that flows only in direct response to precipitation, and whose channel is above the water table at all times.

A perennial stream is one that almost always has some flow. Osterkamp and Hedman (1982) provide a more definitive definition.

> *A perennial stream is a stream that exhibits a measurable surface discharge more than 80 percent of the time.*

Intermittent streams may be differentiated from ephemeral streams in that intermittent streams flow continuously for periods of at least 30 days. An intermittent stream flows only seasonally or sporadically. At times, the flow may infiltrate into the pores of the bed and flow only as ground water. An ephemeral stream generally flows only after a significant rainfall event. Channel processes and morphology are significantly affected by the fact that the discharge is intermittent.

The concept of channel-forming discharge is most applicable to perennial streams. Channel geometry in alluvial intermittent and ephemeral streams is typically a remnant of the last major flow event, rather than a theoretical channel-forming discharge (fig. 7–10). In addition, in ephemeral streams, sediment transport most often occurs as a response to infrequent and flashy hydrologic events. These events cause temporal and spatial episodes of aggradation and degradation and a significantly variable sediment yield. Channel reaches under such flow conditions can be out of phase, and this episodic behavior suggests that ephemeral stream channels may be inherently unstable. Thus, the channel-forming discharge concept may not be applicable.

Figure 7–10 Remnant terraces in an ephemeral stream from previous high-flow events

654.0704 Channel design variables

Traditional channel design methods for fixed-boundary or threshold channels focus on efficient flow conveyance where water surface elevation and velocity are of primary importance. The independent hydraulic design variables are the design discharge and channel roughness. The dependent hydraulic design variables are width, depth, and slope. Channel roughness is a dependent variable if there is a choice of boundary materials. In channel design, these dependent variables are adjusted to achieve the desired hydraulic conditions. Attention is given to the hydraulic losses due to changes in the channel configuration and obstructions such as bridge piers and culverts. Hydraulic design can be accomplished using the energy or momentum equations, in conjunction with a resistance equation such as Manning's equation. The channel boundary is assumed to be immobile at the design discharge, and bed-material sediment inflow is negligible. Traditional methods are applicable for the design of flood control, drainage or irrigation channels lined with a nonerodible material, such as concrete or grass, and for earth channels and ditches with bank protection and little or no sediment inflow. Traditional methods can also be used for design and analysis of natural streams, where the stream boundary is immobile.

Channel design becomes more complicated in alluvial channels, where the bed is mobile and where bed-material sediment inflow is significant. In addition to water surface elevation, efficient transport of sediment becomes a focus in the hydraulic design of alluvial channels. Alluvial streams have the capability to adjust their channel geometry to efficiently transport sediment. The design process seeks to achieve a state of dynamic equilibrium by computing and selecting appropriate values for channel geometry. In some cases, site or project constraints make the ideal channel geometry infeasible. In such cases, erosion control features may be designed or sediment removal maintenance plans implemented.

The independent hydraulic design variables for an alluvial stream include the inflowing discharge hydrograph, bed-material gradation, streambank characteristics, and sediment inflow. The dependent hydraulic design variables for an alluvial stream are width, depth, slope and planform. Hydraulic roughness is generally a function of the bed material, but bank roughness may be considered a dependent variable in some cases. These dependent variables must be selected so that the channel will pass the incoming sediment load without significant degradation or aggradation.

In addition to the energy or momentum equations and a hydraulic resistance equation, a sediment transport equation is needed to calculate appropriate hydraulic geometries. A geomorphic relationship from a reference reach or a selected hydraulic geometry relationship is also required. In some cases, where the existing channel is stable and watershed characteristics are not changing, channel dimensions can be based on a preexisting condition. The design is more challenging when the project reach is unstable due to straightening, channelization, or changing hydrologic or sediment inflow conditions, as is the case in most land use conversion areas. The characteristics of threshold and alluvial channels are summarized in table 7–1.

Table 7–1 Characteristics of threshold and alluvial channels

	Threshold channel	**Alluvial channel**
Channel boundary	Immobile at design discharge	Mobile
Bed-material sediment inflow	Usually small or negligible	Significant
Dependent variables	Width Depth Slope Roughness, if there is a choice of boundary materials	Width Depth Slope Planform Bank roughness Roughness due to obstructions or structures
Independent variables	Design discharge Channel roughness	Design hydrograph Channel-forming discharge Bed-material sediment inflow Bed material Streambank characteristics
Design equations	Energy Momentum Resistance	Energy Momentum Resistance Sediment transport Geomorphic relationship
Design goal with respect to channel stability	Pass the design discharge below the top of bank without mobilizing the boundary	Pass the incoming sediment load without significant aggradation or degradation or planform change

654.0705 Channel design methods and approaches

Channel design approaches can be broadly categorized by their applicability to threshold or alluvial channels. For threshold channels, the recommended design method will provide a stable channel boundary that will not unravel. This is accomplished for a design discharge and a specified channel boundary material. Channel cross-sectional dimensions and channel slope are selected, and velocities and/or shear stresses are calculated iteratively, using the energy or momentum equations and a hydraulic resistance equation, so that calculated values do not exceed acceptable critical values. Hydraulic design methods for threshold channels are well established and available from several sources. The most significant methods are reviewed in NEH654.08. Two methods are recommended for the hydraulic design of threshold channels: the allowable velocity method and the allowable shear stress method. In general, the allowable velocity method is most applicable when the channel will be lined with a variety of different materials, while the allowable shear stress method is often applied in the design of gravel-bed channels. Neither of these methods provides unique solutions for channel dimensions of width, depth, and slope. However, this limitation is not critical to the hydraulic design in terms of stability because the boundary is immobile.

For alluvial channels, hydraulic design methods require sediment transport analysis to ensure sediment continuity through the project reach. The recommended design methodology suggests analytical solutions of resistance and sediment transport equations, in combination with application of fluvial geomorphic principles. When possible, alluvial channels are sized for the channel-forming discharge.

The recommended design method generates a preliminary channel geometry that can transport the incoming water and sediment load for the selected channel-design discharge. Development of this preliminary or initial design geometry is based on a single discharge, the channel-forming discharge. The design philosophy for alluvial channels is to use appropriate fluvial geomorphic principles combined with analytical equations for flow resistance and sediment transport to solve for the dependent design variables of width, depth, slope, and planform. Geomorphic principles that can be used with the analytical equations include analogy methods, hydraulic geometry, and the extremal hypothesis. Project constraints often narrow the range of feasible solutions. Alluvial channel design techniques are addressed in more detail in NEH654.09.

The long-term stability of the preliminary channel design is evaluated using a flow-duration curve or a long-term hydrograph that includes the full range of discharges. Sediment impact analysis is described in NEH654.13. Design adjustments may then be made to the channel design based on issues related to stability, flood effects, and sedimentation. Characteristics of the hydraulic design philosophies for threshold and alluvial channels are shown in table 7–2.

Table 7–2 Hydraulic design philosophies

	Threshold channels	**Alluvial channels**
Design discharges	Maximum design discharge	Channel-forming discharge Flow-duration curve and/or long-term hydrograph
Design criteria	Critical velocity/shear stress	Continuity of sediment
Dependent variables	Width, depth, and slope (roughness if there is a choice of boundary material)	Width, depth, slope, planform, bank roughness, and roughness due to obstructions or structures
Design equations	Energy, momentum, and hydraulic resistance	Energy, momentum, hydraulic resistance, sediment transport, and geomorphic relationship

Some of the analysis, which is based on a threshold assumption, is also used in the design alluvial channel. Some of the degrees of movement that an alluvial channel may undergo may not be permissible. Hard or threshold design techniques may be used to restrict stream movement towards a road or a building, for example. Threshold methods are also used to design stream features such as toe protection, riffles, spurs, barbs, vanes, and deflector dikes. The use and design of these features are described in NEH654.14.

Threshold channels are designed so that the streambed is immobile for the full range of natural discharges, as long as these discharges are below the design flow. In alluvial channels, it is important to determine the discharge at which the streambed begins to move. This can be accomplished using the threshold criteria described in NEH654.08 and is especially important in a channel with an armor layer. Sediment transport capacity dramatically increases when the armor layer is disrupted or destroyed, and the coarse material becomes thoroughly mixed with the substrate material. Stability of vegetated or gravel banks can be determined using allowable velocity methods or shear stress methods. A mobile streambed is not necessarily unstable, but mobile beds require a higher level of analysis to determine stability, within the context of the limitations or requirements of the design.

(a) Analogy method

The analogy method is used to select channel dimensions and is based on the premise that conditions in a reference reach with similar characteristics and watershed conditions can be copied to the project reach. The method can be used for both threshold and alluvial channels, but if used for threshold channel design, bed stability in the project channel should be checked using threshold methods. For alluvial channels, the analogy method is used to select one of the primary dependent design variables of width, depth, or slope (preferably width). The design width is adapted from a selected reference reach, and the remaining two variables are calculated, using hydraulic resistance and sediment transport equations.

Planform can also be determined using the analogy method. The reference reach must be stable and alluvial and have the same channel-forming discharge as the project reach. A stable channel is one in which the stream's planform, cross section, and longitudinal profile are sustainable. Channel features may migrate laterally and longitudinally. The reference reach may be upstream or downstream from the project reach, or in a physiographically similar watershed. The bed and banks in the project and reference reaches must be composed of similar material, and there should be no significant hydrologic, hydraulic, or sediment differences in the reaches.

If a stable predisturbance width and planform can be identified, then the preexisting channel dimensions can be used with the analogy approach. This is feasible if historical width and planform can be determined from mapping, aerial photos, and/or soil borings. This technique is generally not applicable if the watershed water and sediment runoff characteristics or the base level have changed over time.

(b) Hydraulic geometry method

A suitable hydraulic geometry relationship can be used to select a value for one of the dependent variables for the channel-forming discharge. The hydraulic geometry method is similar to the analogy method, but it is more useful because a range of discharges is used. Hydraulic geometry theory is based on the concept that a river system tends to develop in a predictable way, producing an approximate equilibrium between the channel and the inflowing water and sediment (Leopold and Maddock 1953). The theory typically relates a dependent variable, such as width or slope, to an independent or driving variable such as channel-forming discharge or drainage area.

Hydraulic geometry relations are sometimes stratified according to bed-material size, bank vegetation, or bank material type. Rosgen (1998) suggests the use of stream classification as an appropriate tool for differentiating hydraulic geometry relations. Hydraulic geometry relationships are developed from field observations at stable and alluvial cross sections. These relationships were originally used as descriptors of geomorphic trends. Data scatter is expected about the developed curve, even in the same river reach (as described and shown in NEH654.0905. It is important to recognize that this scatter represents a valid range of stable channel configurations due to variables such as geology, vegetation, land use, sediment load and gradation, and runoff characteristics. The transfer of hydraulic geometry relationships developed for one watershed to another watershed should be performed with extreme care. The two watersheds should be similar in historical land use, physiography, geology, hydrologic regime, precipitation, and vegetation.

Both the hydraulic geometry method and the analogy method depend on comparison to channels that are fully adjusted. Specifically, the reference reach, or a channel whose dimensions are used in a hydraulic geometry plot, are not evolving to a different form. If the watershed in which the channel to be designed is likely to change due to changes in water and sediment supply, this assumption can be problematic.

(c) Analytical method

Once one of the dependent design variables (preferably width) is determined using analogy or hydraulic geometry methods, the other two dependent design variables (depth and slope) should be calculated using an analytical, or computational, method. This is accomplished using one of several resistance and sediment transport equations available in the literature. If the resistance and sediment transport equations are solved simultaneously for a specified channel-forming discharge, a family of solutions can be calculated.

The analytical solution for depth and slope that matches the analogy or hydraulic geometry solution for width provides the three dependent design variables. The analytical family of solutions can also be used without the analogy or hydraulic geometry methods to determine the third dependent design variable. The wide range of possible solutions from the analytical calculations can be narrowed by the assigned project constraints. For example, a maximum width constraint might be imposed by right-of-way limits, and a maximum depth constraint might be imposed by flood control considerations. The valley slope would impose a maximum slope constraint. Another approach is to assume that the channel will form its geometry such that the minimum amount of energy is expended. This assumption will provide a unique solution at the minimum slope on the family of solutions.

Characteristics of the analogy, hydraulic geometry, and analytical design methods are summarized in table 7–3.

Table 7–3 Characteristics of analogy, geometry, and analytical hydraulic design methods

	Basis	**Requirements**	**Recommended for determination of**
Analogy	Channel dimensions from a reference reach can be transferred to another location	Reference reach must be stable and alluvial Reference reach must have same channel-forming discharge, valley slope, and similar bed and bank characteristics	Top width of channel-forming discharge channel and planform
Hydraulic geometry	Channel dimensions can be determined from regression relationships with independent variables	Regression curves must be developed from stable and alluvial reaches and from physiographically similar watersheds	Top width of channel-forming discharge channel and planform
Analytical	Depth and sediment transport can be calculated from physically based equations	Estimates of bed-material gradation and resistance coefficients must be obtained	Depth and slope

(d) Hybrid design techniques

Several techniques are available that include a combination of analytical, as well as analogy and hydraulic geometry design methods. Two of these techniques are presented in this handbook.

NEH654.10 presents a two-stage channel design approach for drainage ditches. This is a modification of many of the commonly used threshold design techniques to provide a floodway bench. The intent of this technique is to better mimic alluvial processes by providing a flood plain within the ditch.

NEH654.11 outlines a channel design technique based on the morphological and morphometric qualities of the Rosgen classification system. This approach is often referred to as the Rosgen design approach. The essence for this design approach is based upon measured morphological relations associated with bankfull flow, geomorphic valley type, and geomorphic stream type.

654.0706 Sediment impact assessment

The energy of flowing water constantly reconfigures the physical form of flood plain and stream habitats, primarily through modification of alluvial topography by fluvial action. However, to maintain an equilibrium of channel structure and function, especially in the context of riverine fisheries habitat, natural mechanisms that supply, transport, and deposit watershed materials must remain operative along the river continuum, from the basin to the reach-level scale. Alluvial and threshold channels maintain channel geometries that reflect the quantity of water and the size and characteristics of sediment delivered to them from their drainage basins. Maintenance of channel form and function requires that all of the mass and sizes of sediment supplied to the channel be transported in equilibrium, so that over the long term, the channel neither aggrades nor degrades.

A sediment impact assessment should be conducted for all projects involving changes to the existing channel or the creation of a new channel. This can be accomplished using visual or qualitative assessments for relatively simple projects or by using a numerical model that incorporates solution of the sediment continuity equation for more complex projects. The choice of the appropriate technique to assess the sediment impact of a proposed project includes an assessment of not only the project goals, type of channel, and watershed condition but also an assessment of the impact of project failure. Sediment impact assessments are described in more detail in NEH654.13.

654.0707 Conclusion

The following channel design chapters of this handbook present and describe several systematic hydraulic design methodologies and design techniques. The objective of each of these methodologies is to fit the channel design into the natural system within the physical constraints imposed by other project objectives and constraints. Some techniques are more appropriate for conditions where the design channel boundary is expected to be immobile at design flows, while others are more applicable to conditions where the design channel is expected to be in dynamic equilibrium with its sediment load.

Where appropriately applied, each of the presented design methodologies should be systematic; that is, when used by different engineers with the same project objectives, design results should be similar. However, since each technique is based on different assumptions and is applicable to different conditions, it should not be expected that all of the techniques will result in exactly the same design. The technique or approach that is selected should be appropriate not only for the project goals but also the nature of the sediment-flow exchange with the channel boundary. The physical principles upon which these approaches are based are outlined in the following chapters. The user should evaluate these to determine the applicability to the project specific site. Where there is uncertainty in the nature of the channel and the appropriateness of the design technique, many designers use several techniques and look for agreement on critical design elements.

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Part 654 Stream Restoration Design
National Engineering Handbook

Chapter 8 Threshold Channel Design

Issued August 2007

Cover photo: Threshold channels have erosion-resistant boundaries.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 8 Threshold Channel Design

Contents

Tables

Figures

Chapter 8 Threshold Channel Design

654.0800 Purpose

Threshold channel design techniques are used for rigid boundary systems. In a threshold channel, movement of the channel boundary is minimal or nonexistent for stresses at or below the design flow condition. Therefore, the design approach for a threshold channel is to select a channel configuration where the stress applied during design conditions is below the allowable stress for the channel boundary. Many sources and techniques for designing stable threshold channels are available to the designer. This chapter provides an overview and description of some of the most common threshold channel design techniques. Examples have been provided to illustrate the methods.

654.0801 Introduction

A stable threshold channel has essentially rigid boundaries. The streambed is composed of very coarse material or erosion-resistant bedrock, clay soil, or grass lining. Streams where the boundary materials are remnants of processes no longer active in the stream system may be threshold streams. Examples are streambeds formed by high runoff during the recession of glaciers or dam breaks, streams armored due to degradation, and constructed channels where channel movement is unacceptable for the design flow.

A threshold channel is a channel in which movement of the channel boundary material is negligible during the design flow. The term threshold is used because the applied forces from the flow are below the threshold for movement of the boundary material. Therefore, the channel is assumed to be stable if the design stress is below the critical or recommended stress for the channel boundary. Design issues include assessing the limiting force and estimating the applied force. A requirement for a channel to be considered a threshold channel is that the sediment transport capacity must greatly exceed the inflowing sediment load so that there is no significant exchange of material between the sediment carried by the stream and the bed. Noncohesive material forming the channel boundary must be larger than what the normal range of flows can transport. For boundaries of cohesive materials, minor amounts of detached material can be transported through the system.

Threshold channels, therefore, transport no significant bed-material load. Fine sediment may pass through threshold streams as throughput. In general, this throughput sediment should not be considered part of the stream boundary for stability design purposes, even if there are intermittent small sediment deposits on the streambed at low flow.

An additional requirement for threshold channel design is to maintain a minimum velocity that is sufficient to transport the sediment load through the project reach. This sediment may consist of clays, silts, and fine sands. This is necessary to prevent aggradation in the threshold channel.

Threshold channels differ from movable bed or alluvial channels which show interaction between the incoming sediment load, flow, and channel boundary. In an alluvial channel, the bed and banks are formed from material that is transported by the stream under present flow conditions. The incoming sediment load and bed and bank material of an alluvial channel interact and exchange under design or normal flow conditions. Essentially, the configuration of a threshold channel is fixed under design conditions. An alluvial channel is free to change its shape, pattern, and planform in response to short- or long-term variations in flow and sediment. The design of alluvial channels is addressed in detail in NEH654.09.

Approaches that fall into four general categories for the design of threshold channels are addressed in this chapter. These approaches are the permissible velocity approach, allowable shear stress approach, and allowable tractive power approach. The grass-lined channel design approach, which is a specific case of either the permissible velocity or allowable shear stress approach, is also described. Table 8–1 provides general guidance for selecting the most appropriate design technique. This is a general guide, and there are certainly exceptions. For example, the allowable velocity technique, being the most historical, has been applied more broadly than indicated in table 8–1. Where there is uncertainty regarding the appropriate technique, it is recommended that the designer use several of the most appropriate techniques and look for agreement on critical design elements.

654.0802 Design discharges

Threshold channel design methods are appropriate where sediment inflow is negligible and the proposed channel boundary is to be immobile, even at high flows. Threshold channels do not have the freedom to adjust their geometry under normal flow conditions. Therefore, channel-forming discharge is not necessarily a critical factor in determining channel dimensions in a threshold channel. Design flows are traditionally based, at least in part, on programs and policy decisions.

As described in NEH654.07, the classification of a stream as alluvial or threshold may not be clear. One reach of the stream may be alluvial, while another may have the characteristics of a threshold channel. A threshold stream reach can be changed to an alluvial reach by flattening the slope to induce aggradation or increasing the slope so that the boundary material becomes mobile. At flows larger than the design flow or during extreme events, threshold channels may develop a movable boundary. It is important to evaluate channels through their entire flow range to determine how they will react to natural inflow conditions.

Design of a stream project may involve a hybrid approach. For example, project goals may require that the planform is rigid, while the cross section can vary. In this situation, a design approach might be to

Table 8–1 General guidance for selecting the most appropriate channel design technique

Technique	Significant sediment load and movable channel boundaries	Boundary material smaller than sand size	Boundary material larger than sand size	Boundary material does not act as discrete particles	No baseflow in channel. Climate can support permanent vegetation
Allowable velocity		X			
Allowable shear stress			X		
Tractive power				X	
Grass lined/tractive stress					X
Alluvial channel design techniques	X				

stabilize the grade and toe of a stream in place, and allow the upper bank to adjust naturally. Threshold channel design approaches, such as the use of riprap (NEH654.14), are also used to size stream features such as toe protection, riffles, stream barbs, and deflector dikes.

654.0803 Allowable velocity method

The allowable or permissible velocity approach is typically used with channels that are lined with grass, sand, or earth. Limiting forces for soil bioengineering and manufactured protective linings can also be expressed as permissible velocities.

To design a threshold channel using the allowable velocity method, average channel velocity is calculated for the proposed channel and compared to published allowable velocities for the boundary material. The average channel velocity in the design channel can be determined using a normal depth equation or a computer backwater model. Increased velocities at bends can be accounted for, using applicable charts and equations. Allowable velocities have been determined for a large variety of boundary materials and are provided in many texts and manuals. These tables have primarily been applied to the design of irrigation and drainage canals and were developed from data in relatively straight, uniform channels with depths less than 3 feet. It is common practice to apply allowable velocity data in meandering, nonuniform channels with depths greater than 3 feet, but such application should be done with caution. Allowable velocities can be increased or decreased to account for such irregularities as meandering alignments and increased sediment concentrations, using applicable charts. Allowable velocities are somewhat less than critical velocities so that a factor of safety is included in the values presented.

(a) Calculate average velocity

The first step in applying the allowable velocity design approach is to calculate the average velocity of the existing or proposed channel. Computing the average channel velocity requires a design discharge, cross section, planform alignment, average energy slope, and flow resistance data. If the design channel is a compound channel, it may be necessary to divide the channel into panels and calculate velocities for each panel. In channels with bends, the velocity on the outside of the bend may be significantly higher than the average velocity. Velocity can be calculated using normal depth assumptions or by a more rigorous backwater analysis if a gradually varied flow assumption is more appropriate.

A normal depth calculation is easier than a backwater analysis and can be accomplished using a flow resistance equation such as Manning's. The normal depth assumption is applicable for uniform flow conditions where energy slope, cross-sectional shape, and roughness are relatively constant in the applicable reach. In a natural channel, with a nonuniform cross section, reliability of the normal depth calculation is directly related to the reliability of the input data. Sound engineering judgment is required in the selection of a representative cross section. The cross section should be located in a uniform reach where flow is essentially parallel to the bank line with no reverse flow or eddies. This typically occurs at a crossing or riffle. Determination of the average energy slope can be difficult. If the channel cross section and roughness are relatively uniform, water surface slope can be used. Thalweg slopes and low-flow water surface slopes may not be representative of the energy slope at design flows. Slope estimates should be made over a significant length of the stream (a meander wavelength or 20 channel widths).

A computer program such as the U.S. Army Corps of Engineers (USACE) HEC–RAS can be used to perform these velocity calculations. Such programs allow the designer to account for nonuniform sections and for backwater conditions that may occur behind a bridge or at a constriction. The calculation of hydraulic parameters for both existing and proposed channels is critically important to design. A more complete treatment of the subject is provided in NEH654.06.

Minimum radius of curvature

Caution is recommended in applying this approach on channels with sharp bends. Section 16 of the National Engineering Handbook (U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) 1971) provides guidance for minimum radius of curvature for drainage ditches with very flat topography (slopes less than 0.00114). Table 8–2 provides guidance for channels in stable soil without bank protection. Conditions outside the range of table 8–2 and in erodible soils require use of the more detailed analysis provided in this chapter. The curved channel may require bank protection.

Maximum velocity in bends

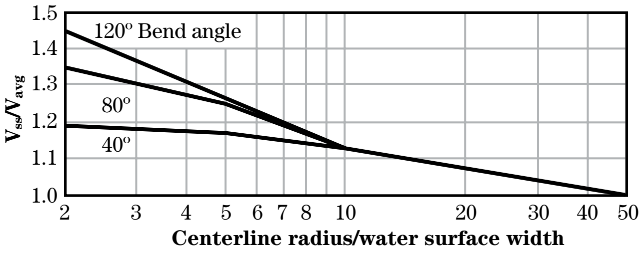
Adjustments to the calculated average channel velocity that account for flow concentration around bends is provided as part of the USACE riprap design method (USACE 1991b.) The method is based on a large body of laboratory data and has been compared to available prototype data (Maynord 1988). The method is applicable to side slopes of 1V:1.5H or flatter. The method calculates a characteristic velocity for side slopes,

Table 8–2 Suggested minimum radius of curvature in stable soils without bank protection

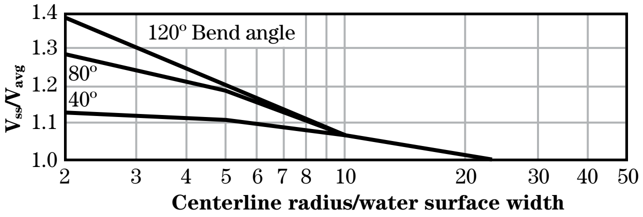
Type of ditch	Slope	Minimum radius of curvature (ft)	Minimum radius of curvature (m)	Approximate degree of curve (degrees)
Small ditches with maximum top width 15 ft (4.6 m)	<0.00057	300	90	19
	0.00057 to 0.00114	400	120	14
Medium-sized ditches with top width 15 to 35 ft (4.6–10.7 m)	<0.00057	500	150	11
	0.00057 to 0.00114	600	180	10
Large ditches with top width >35 ft (10.7 m)	<0.00057	600	180	10
	0.00057 to 0.00114	800	240	7

V_{ss}, which is the depth-averaged local velocity over the side slope at a point 20 percent of the slope length from the toe of the slope. This has been determined to be the part of the side slope that experiences the maximum flow velocity. The ratio V_{ss}/V_{avg}, where V_{avg} is the average channel velocity at the upstream end of the bend, has been determined to be a function of the ratio of the of centerline radius of curvature, R, and the water surface width, W. Figure 8–1 illustrates the relationship for natural channels. Figure 8–2 illustrates the relationship for trapezoidal channels. The data for trapezoidal channels shown in figure 8–2 are based on numerical model calculations described in Bernard (1993). The primary factors affecting velocity distribution in riprap lined bendways are R/W, bend angle, and aspect ratio (bottom width-to-depth). V_{avg}, R, and W should be based on main channel flow only and should not include overbank areas.

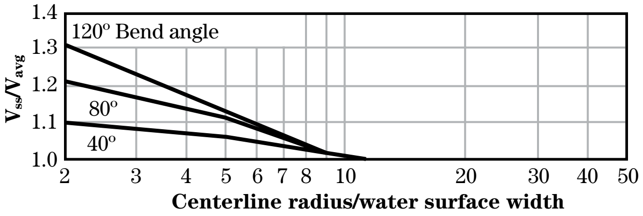
Figure 8–2 Design velocities for trapezoidal channels



Bottom width/depth = 3.3



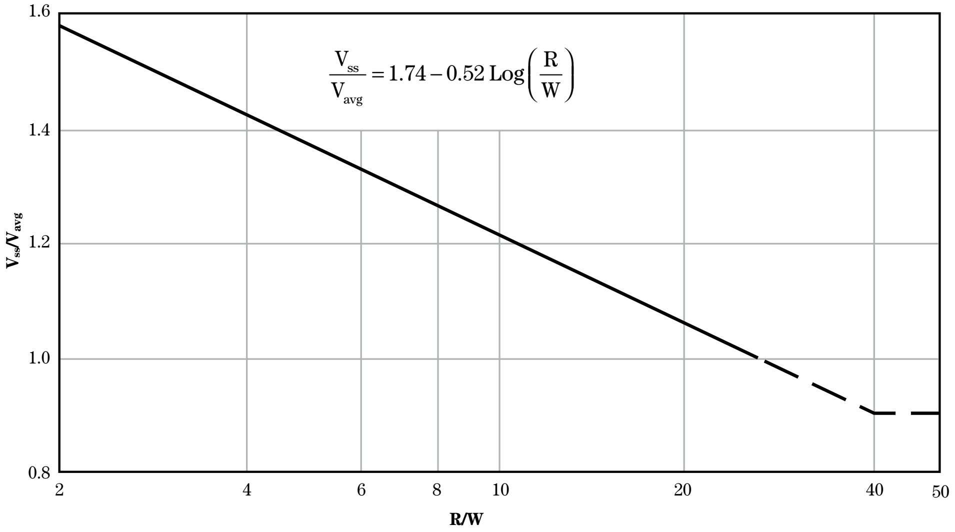
Bottom width/depth = 6.7



Bottom width/depth ≥10

Notes: V_{ss} is depth-averaged velocity at 20% of slope length up from toe, maximum value in bend. Curves based on STREMR model (Bernard 1993), V_{avg} = 6 ft/s, 1V:3H side slopes. n = 0.038, 15 ft depth

Figure 8–1 Design velocities for natural channels. Note: V_{ss} is depth-averaged velocity at 20% of slope length from toe



(b) Determine allowable velocity

The design velocity of the existing or proposed channel must be compared to the allowable velocity for the channel boundary. The allowable velocity is the greatest mean velocity that will not cause the channel boundary to erode. Since the allowable velocity is a design parameter that has a factor of safety, it is somewhat less than the critical velocity (the velocity at incipient motion of the boundary material).

The allowable velocity can be approximated from tables that relate boundary material to allowable velocity, but tabular estimates should be tempered by experience and judgment. In general, older channels have higher allowable velocities because the channel boundary typically becomes stabilized with the deposition of colloidal material in the interstices. Also, a deeper channel will typically have a higher allowable velocity than shallow channels because erosion is a function of the bottom velocity. Bottom velocities in deep channels are less than bottom velocities in shallow channels with the same mean velocity.

Fortier and Scobey (1926) presented a table of maximum permissible velocities for earthen irrigation canals with no vegetation or structural protection. Their work was compiled based on a questionnaire given to a number of experienced irrigation engineers and was recommended for use in 1926 by the Special Committee on Irrigation Research of the American Society of Civil Engineers. This compilation is presented in table 8–3.

USACE (1991b) provides allowable velocity criteria for nonscouring flood control channels in table 8–4.

Theoretical objections to use of average velocity as an erosion criterion can be overcome by using depth as a second independent variable. An example of a velocity-depth-grain size chart from the USACE (1991b) is shown in figure 8–3. This particular chart is intended to correspond to a small degree of bed movement, rather than no movement. Values given in this chart are for approximate guidance only.

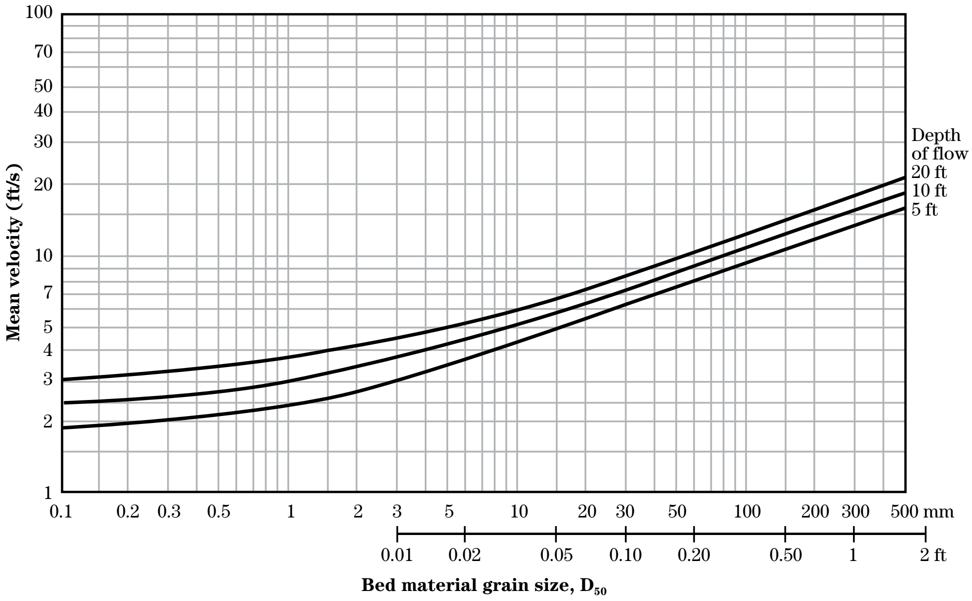
Table 8–3 Maximum permissible canal velocities

	Mean velocity, for straight canals of small slope, after aging with flow depths less than 3 ft (0.9 m)					
	Clear water, no detritus		**Water transporting colloidal silts**		**Water transporting noncolloidal silts, sands, gravels, or rock fragments**	
Original material excavated for canals	**ft/s**	**m/s**	**ft/s**	**m/s**	**ft/s**	**m/s**
Fine sand (noncolloidal)	1.5	0.46	2.5	0.76	1.5	0.46
Sandy loam (noncolloidal)	1.75	0.53	2.5	0.76	2.0	0.61
Silt loam (noncolloidal)	2.0	0.61	3.0	0.91	2.0	0.61
Alluvial silt (noncolloidal)	2.0	0.61	3.5	1.07	2.0	0.61
Ordinary firm loam	2.5	0.76	3.5	1.07	2.25	0.69
Volcanic ash	2.5	0.76	3.5	1.07	2.0	0.61
Stiff clay (very colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Alluvial silt (colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Shales and hardpans	6.0	1.83	6.0	1.83	5.0	1.52
Fine gravel	2.5	0.76	5.0	1.52	3.75	1.14
Graded, loam to cobbles (when noncolloidal)	3.75	1.14	5.0	1.52	5.0	1.52
Graded silt to cobbles (when colloidal)	4.0	1.22	5.5	1.68	5.0	1.52
Coarse gravel (noncolloidal)	4.0	1.22	6.0	1.83	6.5	1.98
Cobbles and shingles	5.0	1.52	5.5	1.68	6.5	1.98

Table 8–4 Allowable velocities

Channel material	Mean channel velocity (ft/s)	(m/s)
Fine sand	2.0	0.61
Coarse sand	4.0	1.22
Fine gravel	6.0	1.83
Earth		
Sandy silt	2.0	0.61
Silt clay	3.5	1.07
Clay	6.0	1.83
Grass-lined earth (slopes <5%)		
Bermudagrass		
Sandy silt	6.0	1.83
Silt clay	8.0	2.44
Kentucky bluegrass		
Sandy silt	5.0	1.52
Silt clay	7.0	2.13
Poor rock (usually sedimentary)	10.0	3.05
Soft sandstone	8.0	2.44
Soft shale	3.5	1.07
Good rock (usually igneous or hard metamorphic)	20.0	6.08

Figure 8–3 Allowable velocity-depth grain chart



(c) Soil Conservation Service allowable velocity approach

Basic allowable velocities may be determined from figure 8–4 (USDA SCS 1977). In this figure, allowable velocities are a function of sediment concentration, grain diameter for noncohesive boundary material, and plasticity index and soil characteristics for cohesive boundary material. Adjustments are given in figure 8–4 to the basic allowable velocity to account for frequency of design flow, alignment, bank slope, depth of flow, and sediment concentration for both discrete particles and cohesive soils. These design charts were compiled from the data of Fortier and Scobey (1926), Lane (1955a), and the Union of Soviet Socialist Republic (USSR) (1936). Soil materials are classified using the Unified Soil Classification System.

Procedure for application of allowable velocity method (USDA SCS 1977)

Step 1 Determine the hydraulics of the system. This includes hydrologic determinations, as well as the stage-discharge relationships for the channel considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream.

Step 3 Determine the concentration of the suspended sediment load entering the reach. This is best accomplished by measurements. Channels with suspended sediment concentrations less than 1,000 parts per million are considered sediment free for this analysis, in that the sediment load is not sufficient to decrease the energy of the stream flow. Sediment-free flows are, therefore, considered to have no effect on channel stability. Channels with suspended sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment-laden flows are considered to enhance stream stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the allowable velocity procedure is applicable using table 8–1.

Step 5 Determine the basic average allowable velocities for the channel from one or more of the available design guidelines (tables 8–3, 8–4, fig. 8–4 (USDA SCS 1977; Federal Interagency Stream Restoration Working Group (FISRWG) 1998)).

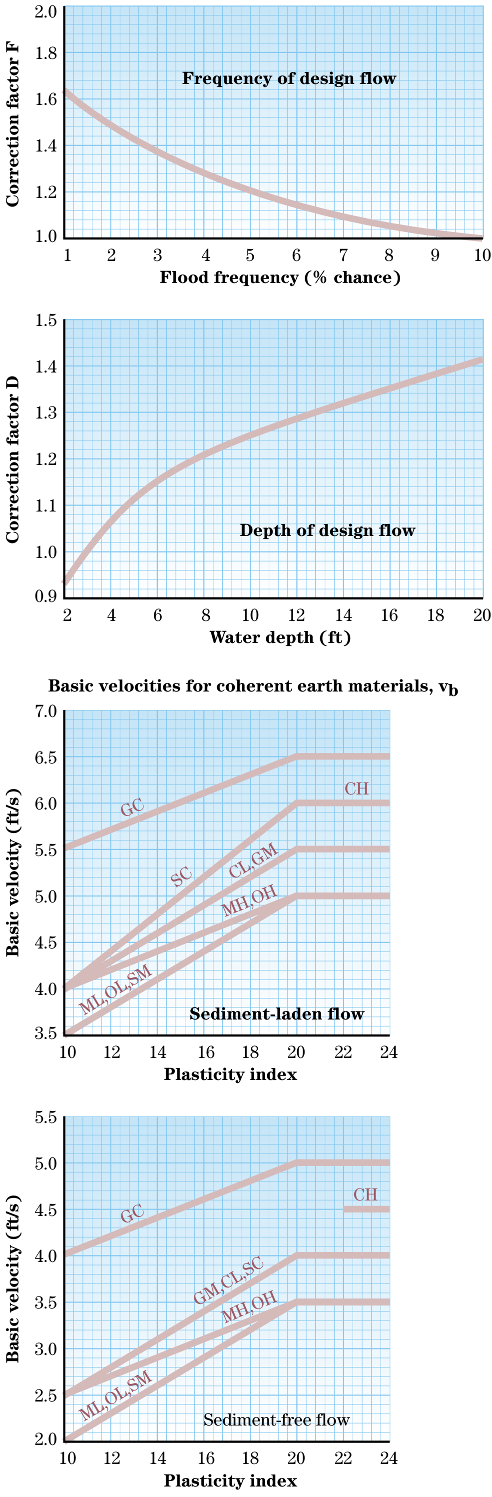
Step 6 Multiply the basic allowable velocity by the appropriate correction factors (fig. 8–4).

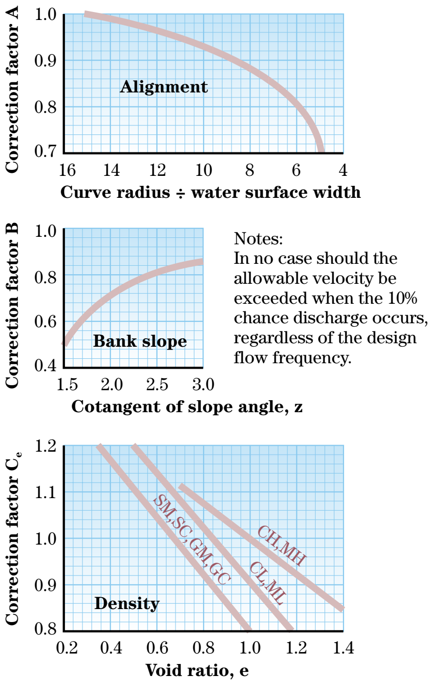
Step 7 Compare the design velocities with the allowable velocities. If the allowable velocities are greater than the design velocities, the design is satisfactory. Otherwise, three options are available:

- Redesign the channel to reduce velocity.
- Provide structural measures (riprap, grade control) to prevent erosion.
- Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

Design of Open Channels, TR–25 (USDA SCS 1977) contains several examples to guide the user through the allowable velocity approach.

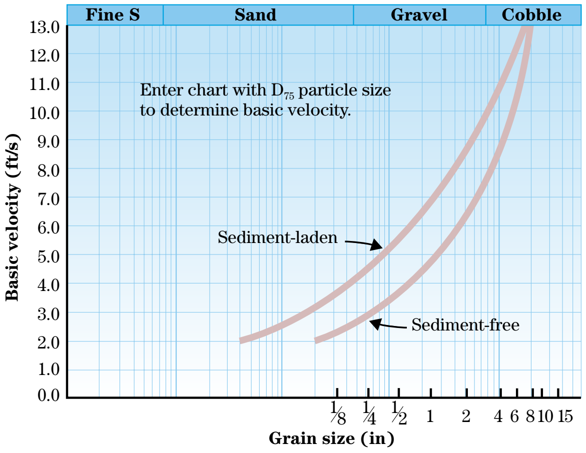
Figure 8–4 Allowable velocities for unprotected earth channels





Notes:
In no case should the allowable velocity be exceeded when the 10% chance discharge occurs, regardless of the design flow frequency.

Basic velocity for discrete particles of earth materials, vb



Enter chart with D_{75} particle size to determine basic velocity.

Allowable velocities for unprotected earth channels	
Channel boundary materials	Allowable velocity
Discrete particles	
Sediment-laden flow	
D_{75} >0.4mm	Basic velocity chart value x D x A x B
D_{75} <0.4mm	2.0 ft/s
Sediment-free flow	
D_{75} >0.2mm	Basic velocity chart value x D x A x B
D_{75} <0.2mm	2.0 ft/s
Coherent earth materials	
PI >10	Basic velocity chart value x D x A x F x C_e
PI <10	2.0 ft/s

Source: USDA Soil Conservation Service, 1977

654.0804 Allowable shear stress approach

The allowable shear approach (sometimes referred to as the tractive stress approach) is typically used with channels that are lined with rock, gravel, or cobbles. Limiting forces for soil bioengineering and manufactured protective linings can also be expressed as allowable shear, as well.

To design a threshold channel using the allowable shear stress approach, the average applied grain bed shear stress is compared to the allowable shear stress for the boundary material. The applied grain bed shear stress can be calculated from the hydraulic parameters determined for the design channel and the characteristics of the channel boundary material. The hydraulic parameters are calculated using the same methods as in the allowable velocity approach. For noncohesive soils, the average allowable shear stress can be calculated using a critical shear stress approach and then adding a factor of safety or by using an empirical equation with a factor of safety included. For cohesive particles, the electrochemical bonds related primarily to clay mineralogy, are the most significant sediment properties that determine allowable shear stress. Although some empirical data are available, laboratory tests to determine allowable shear stress for a specific cohesive soil are preferred.

(a) Calculate applied shear stress

The first step in applying this approach is to calculate the hydraulics of the study reach. The total average shear stress on the boundary can be approximated from equation 8–1, using any consistent units of measurement:

$$\tau_o = \gamma RS \qquad \text{(eq. 8–1)}$$

where:
τ_o = total bed shear stress (lb/ft^2 or N/m^2)
γ = specific weight of water (lb/ft^3 or N/m^3)
R = hydraulic radius (ft or m)
S = energy slope, dimensionless

In wide channels where the width is more than 10 times the depth, R is generally taken to be equal to the depth. Spatial and temporal variation may result in a higher or lower point value for shear stress. The equation approximates average bed shear stress.

The shear stress can also be expressed as a function of the velocity and the ratio of hydraulic radius and boundary roughness. Keulegan (1938) presented such a formula.

$$\tau = \frac{\rho V^2}{\left(\frac{1}{\kappa}\ln\frac{R}{k_s} + 6.25\right)^2} \qquad \text{(eq. 8–2)}$$

where:
V = depth-averaged velocity, ft/s or m/s
ρ = density of water, lb-s^2/ft^4(slugs/ft^3) or kg/m^2
κ = von Karman's constant (usually taken to be 0.4)
k_s = roughness height, ft or m

Actual shear stress values should be calculated for the banks, as well as for the bed of a trapezoidal earth channel. Maximum stresses occur near the center of the bed and at a point on the bank about a third up from the bottom. The designer should note that computer programs such as HEC–RAS may only provide average boundary shear stress in the output. For most trapezoidal sections and depths of flow, bed stress values are somewhat higher than bank stress. Figures 8–5 and 8–6 provide actual shear stress values for the bed and sides of straight trapezoidal channels in coarse grained soil materials.

Grain shear stress

The total applied bed shear stress may be divided into that acting on the grains and that acting on the bedforms. Entrainment and sediment transport are a function only of the grain shear stress; therefore, the grain shear stress is the segment of interest for threshold design. Einstein (1950) determined that the grain shear stress could best be determined by separating total bed shear stress into a grain component and a form component, which are additive. The equation for total bed shear stress is:

$$\tau_o = \tau' + \tau'' = \gamma RS \qquad \text{(eq. 8–3)}$$

where:
τ' = grain shear stress (shear resulting from size of the material on the bed)
τ'' = form shear stress (shear resulting from bed irregularities due to bedforms)

Figure 8–5 Applied maximum shear stress, τ_b, on bed of straight trapezoidal channels relative to an infinitely wide channel, τ_∞

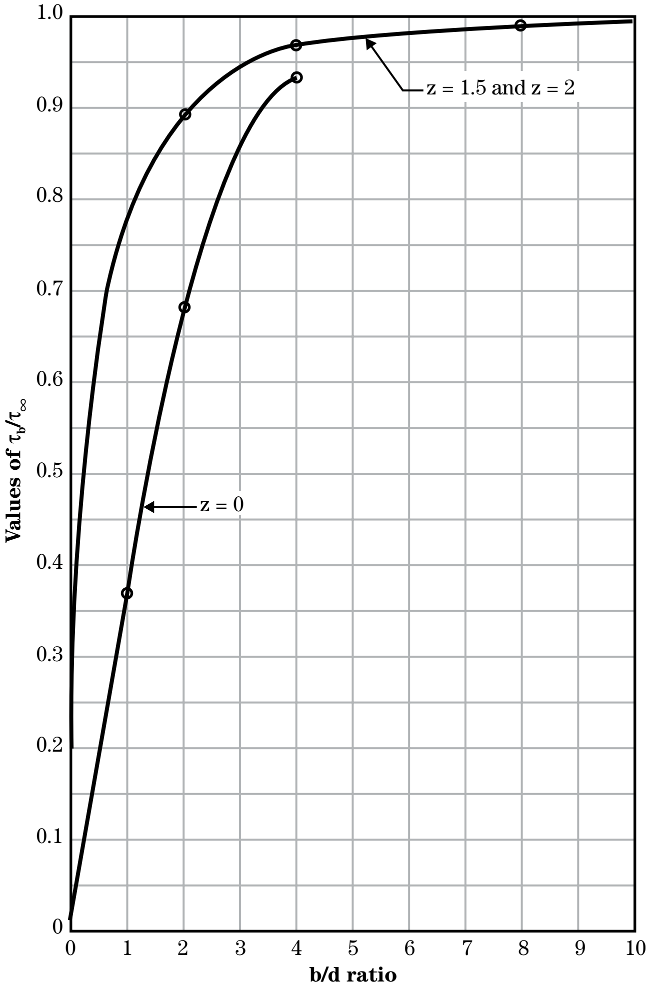
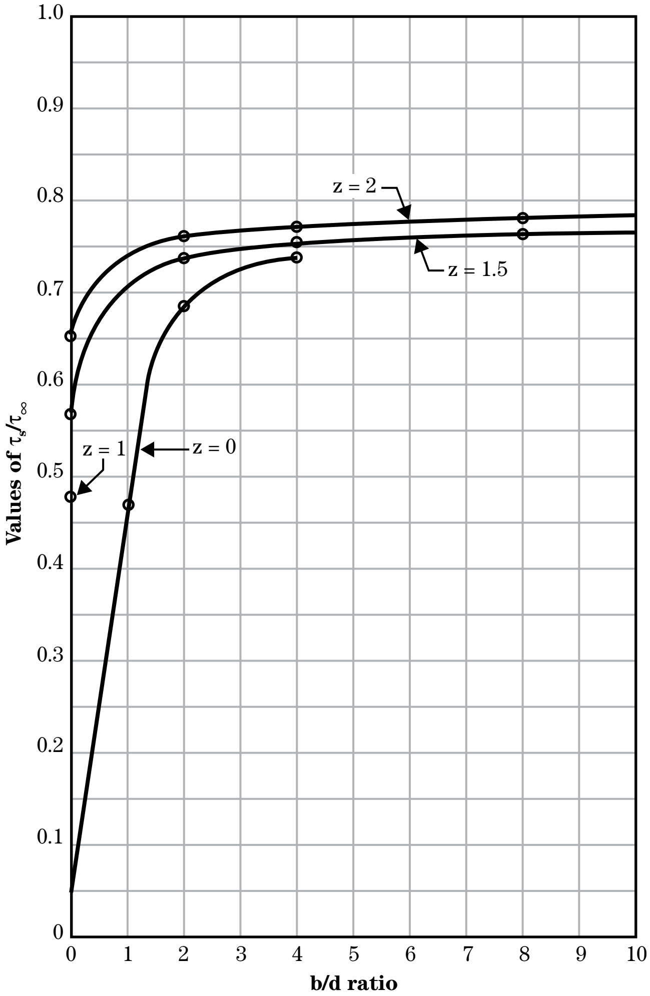


Figure 8–6 Applied maximum shear stress, τ_s, on sides of trapezoidal channels relative to an infinitely wide channel, τ_∞



Note:
b = bottom width
d = depth
z = side slope, zH:1V
τ_∞ = shear stress on a straight, infinitely wide channel
τ_b = applied shear stress on a channel bed
τ_s = applied shear stress on the side of a channel

Einstein also suggested that the hydraulic radius could be divided into grain and form components that are additive. The equations for grain and form shear stress then become:

$$\tau' = \gamma R'S \qquad \text{(eq. 8–4)}$$

$$\tau'' = \gamma R''S \qquad \text{(eq. 8–5)}$$

where:
R' = hydraulic radii associated with the grain roughness
R'' = hydraulic radii associated with the form roughness

These hydraulic radii are conceptual parameters, useful for computational purposes and have no tangible reality. The total bed shear stress can be expressed as:

$$\tau_0 = \gamma R'S + \gamma R''S \qquad \text{(eq. 8–6)}$$

Slope and the specific weight of water are constant so that the solution is to solve for one of the *R* components. The grain shear stress can be calculated with the Limerinos equation, using any consistent units of measurements.

$$\frac{V}{U'_*} = 3.28 + 5.66\log_{10}\frac{R'}{D_{84}} \qquad \text{(eq. 8–7)}$$

$$U'_* = \sqrt{gR'S} \qquad \text{(eq. 8–8)}$$

where:
V = average velocity (ft/s or m/s)
U'_* = grain shear velocity (ft/s or m/s)
D_{84} = particle size for which 84% of the sediment mixture is finer (ft or m)
g = acceleration of gravity (ft/s^2 or m/s^2)

Limerinos (1970) developed his equation using data from gravel-bed streams. Limerinos' hydraulic radii ranged between 1 and 6 feet; D_{84} ranged between 1.5 and 250 millimeters. This equation was confirmed for plane bed sand-bed streams by Burkham and Dawdy (1976). The equation can be solved iteratively for R' and τ', when average velocity, slope, and D_{84} are known.

Whenever the streambanks contribute significantly to the total channel roughness, the applied shear stress to the banks must be accounted for. This is accomplished using the sidewall correction procedure, which separates total roughness into bed and bank roughness and conceptually divides the cross-sectional area into additive components. The procedure is based on the assumption that the average velocity and energy gradient are the same in all segments of the cross section.

$$A_{total} = A_b + A_w \qquad \text{(eq. 8–9)}$$

$$A_{total} = P_bR_b + P_wR_w \qquad \text{(eq. 8–10)}$$

where:
A = cross-sectional area (ft^2 or m^2)
P = perimeter (ft or m)

Subscripts b and w are associated with the bed and wall (or banks), respectively. Note that the hydraulic radius is not additive with this formulation, as it was with R' and R''. Using Manning's equation, with a known average velocity, slope, and roughness coefficient, the hydraulic radius associated with the banks can be calculated:

$$\frac{V}{\text{CME } S^{\frac{1}{2}}} = \frac{R^{\frac{2}{3}}}{n} = \frac{R_w^{\frac{2}{3}}}{n_w} \qquad \text{(eq. 8–11)}$$

$$R_w = \left(n_w \frac{V}{\text{CME } S^{\frac{1}{2}}}\right)^{\frac{3}{2}} \qquad \text{(eq. 8–12)}$$

where:
CME =1.486 in English units and 1.0 in SI units

Total hydraulic radius and shear stress, considering grain, form, and bank roughness, can be expressed by equations 8–13 and 8–14:

$$R_{total} = \frac{P_b\left(R' + R''\right) + P_wR_w}{P_{total}} \qquad \text{(eq. 8–13)}$$

$$\tau_{total} = \gamma S\left(\frac{P_b\left(R' + R''\right) + P_wR_w}{P_{total}}\right) \qquad \text{(eq. 8–14)}$$

Lane's tractive force method

Lane (1952) developed an analytical design approach for calculation of the applied grain shear stress and the shear distribution in trapezoidal channels. The tractive force, or applied shear force, is the force that the water exerts on the wetted perimeter of a channel due to the motion of the water. Lane determined that in most irrigation canals, the tractive force near the middle of the channel closely approaches

$$\gamma d S_o$$

where:

γ = specific weight of water

d = depth

S_o = bed slope assuming uniform flow

He also determined that the maximum tractive force on the side slopes was approximately 0.75 $\gamma d S_o$. Lane also found that the side slopes of the channel affected the maximum allowable shear stress. He developed an adjustment factor, K, to account for the side slope effects. Detailed information on the tractive force approach is found in Design of Open Channels, TR–25 (USDA SCS 1977) and Chow (1959). A summary of the method follows.

When the boundary of the channel consists of coarse-grained discrete particles, Lane (1952) determined that the grain roughness, n_s, could be determined as a function of the D_{75} of the boundary material. Applied grain shear stress can then be calculated using Manning's equation. The D_{75} range for which Lane found this relationship to be applicable was between 0.25 inches (6.35 mm) and 5.0 inches (127 mm). This is similar to determining the grain shear stress using the Limerinos equation.

$$n_s = \frac{D_{75}^{\frac{1}{6}}}{39} \text{ with } D_{75} \text{ expressed in inches} \qquad \text{(eq. 8–15)}$$

$$n_s = \frac{D_{75}^{\frac{1}{6}}}{66.9} \text{ with } D_{75} \text{ expressed in millimeters} \qquad \text{(eq. 8–16)}$$

The grain roughness is combined with other roughness elements to determine the total Manning's roughness coefficient, *n*. The friction slope associated with grain roughness, S_t, can then be calculated using equation 8–17:

$$S_t = \left(\frac{n_s}{n}\right)^2 S_e \qquad \text{(eq. 8–17)}$$

where:

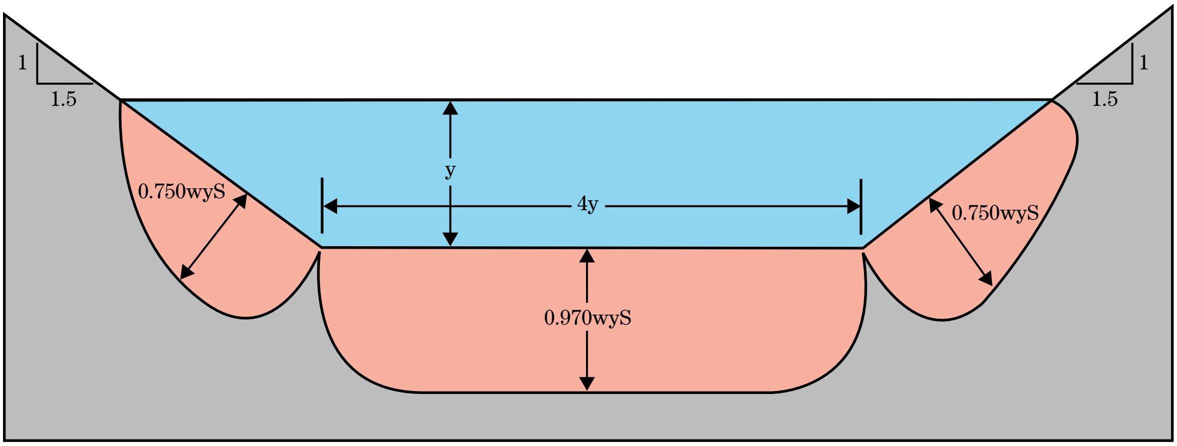
S_e = total friction slope determined from Manning's equation

The applied shear stress acting on the grains in an infinitely wide channel is then calculated from equation 8–18.

$$\tau_\infty = \gamma d S_t \qquad \text{(eq. 8–18)}$$

In open channels, the applied shear stresses are not distributed uniformly along the perimeter as is shown in figure 8–7 (Lane 1952). Laboratory experiments and field observations have indicated that in trapezoidal channels the stresses are very small near the water surface and corners of the channel. In straight chan-

Figure 8–7 Lateral distribution of shear stress in a trapezoidal channel



w=specific weight of water, y=depth, and S=slope nels, the maximum shear stress occurs on the bed near the center of the channel. The maximum shear stress on the banks occurs about a third the way up the bank from the bed. Figures 8–5 and 8–6 can be used to determine the shear stress distribution in a trapezoidal channel, relative to the applied shear stress in an infinitely wide channel with the same depth of flow and energy slope (USDA SCS 1977).

The magnitude of applied shear stresses is not uniform in turbulent flow. Calculations using traditional equations provide an average value of shear stress. In design, therefore, a factor of safety is typically applied to account for this fluctuation. This fluctuation may also be addressed in certain design approaches using probability methods presented later in this chapter.

Applied shear stress on curved reaches

Curved channels have higher maximum shear stresses than straight channels. Maximum stress occurs on the inside bank in the upstream portion of the curve and on the outer bank in the downstream portion of the curve. The smaller the radius of curvature, the more the stress increases along the curved reach. Maximum applied shear stress in a channel with a single curve also occurs on the inside bank in the upstream portion of the curve and near the outer bank downstream from the curve. Compounding of curves in a channel complicates the flow pattern and causes a compounding of the maximum applied shear stress. Figure 8–8 gives values of maximum applied shear stress based on judgment coupled with very limited experimental data (USDA SCS 1977). It does not show the effect of depth of flow and length of curve, and its use is only justified until more accurate information is obtained. Figure 8–9, with a similar degree of accuracy, gives the maximum applied shear stresses at various distances downstream from the curve (USDA SCS 1977). The designer should note that these adjustments are similar to rules of thumb.

(b) Calculate allowable shear stress

The applied shear stress must be compared to the allowable shear stress. Shear stress at initiation of motion can be calculated from an empirically derived relationship between dimensionless shear stress (Shields parameter), τ^*, and grain Reynolds number, R^*. The dimensionless shear stress is defined as the ratio of the critical shear stress (shear stress at the initiation of particle motion) and product of the grain diameter and the submerged specific weight of the particle. The grain Reynolds number is defined as the ratio of the product of shear velocity and grain diameter to kinematic viscosity. Shields parameter and grain Reynolds number are dimensionless and can be used with any consistent units of measurement. The relationship between τ^* and R^* represents an average curve drawn through scattered data points that were determined experimentally from flumes or rivers. Therefore, a wide range in recommended values exists for the Shields parameter, depending on how the experiment was conducted and the nature of the bed material being evaluated.

Once τ^* has been assigned, the critical shear stress for a particle having a diameter, D, is calculated from equation 8–19.

$$\tau_c = \tau^*\left(\gamma_s - \gamma\right)D \qquad \text{(eq. 8–19)}$$

where:

τ^* = Shields parameter, dimensionless
R^* = grain Reynolds number = u^*d/ν, dimensionless
τ_c = critical shear stress (lb/ft^2 or N/m^2)
γ_s = specific weight of sediment (lb/ft^3 or N/m^3)
γ = specific weight of water (lb/ft^3 or N/m^3)
D = particle diameter (ft or m)
u^* = shear velocity = $(gRS)^{1/2}$ (ft/s or m/s)
ν = kinematic viscosity of the fluid (ft^2/s or m^2/s)
g = acceleration of gravity (ft/s^2 or m/s^2)

Shields (1936) obtained his critical values for τ^* experimentally using uniform bed material and measuring sediment transport at decreasing levels of bed shear stress, and then extrapolating to zero transport. The Shields curve is shown in figure 8–10 (USACE 1995c). Shields' data suggest that τ^* varies with R^* until the grain Reynolds number exceeds 400. At larger values of R^*, τ^* is independent of R^* and is commonly taken to be 0.06. The Shields curve may be expressed as an equation, useful for computer programming and spreadsheet analysis.

$$\tau^* = 0.22\beta + 0.06\times10^{-7.7\beta} \qquad \text{(eq. 8–20)}$$

$$\beta = \left(\frac{1}{\nu}\sqrt{\left(\frac{\gamma_s-\gamma}{\gamma}\right)gD^3}\right)^{-0.6} \qquad \text{(eq. 8–21)}$$

The Shields diagram is the classic method for determining critical shear stress. However, subsequent

Figure 8–8 Applied maximum applied shear stress, τ_{bs} and τ_{sc} on bed and sides of trapezoidal channels in a curved reach

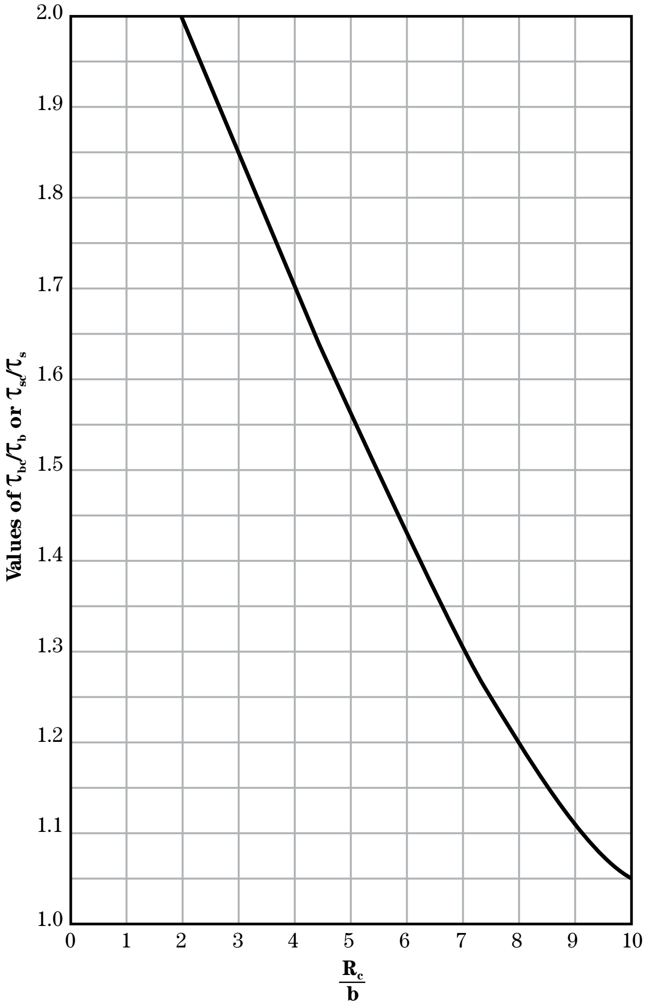
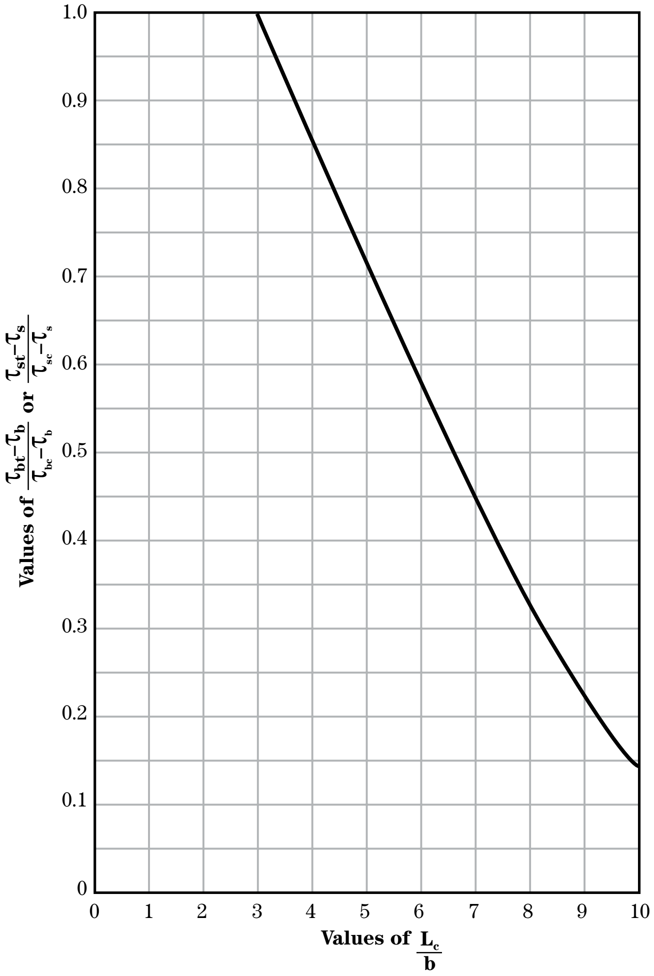


Figure 8–9 Applied maximum applied shear stress, τ_{bt} and τ_{st} on bed and sides of trapezoidal channels in straight reaches immediately downstream from curved reaches



Note:
R_c = radius of curvature
b = bottom width
d = channel depth
L_c = length of curve
τ_b = applied shear stress on a channel bed
τ_s = applied shear stress on the side of a channel
τ_{bc} = applied shear stress on channel bed in a curve
τ_{sc} = applied shear stress on channel side in a curve
τ_{bt} = applied shear stress on channel bed immediately downstream of a curve
τ_{st} = applied shear stress on channel side immediately downstream of a curve

work identified three significant problems associated with the curve itself. First, the procedure did not account for the bedforms that developed with sediment transport. Second, the critical dimensionless shear stress is based on the average sediment transport of numerous particles and does not account for the sporadic entrainment of individual particles at very low shear stresses. Thirdly, critical dimensionless shear stress for particles in a sediment mixture may be different from that for the same size particle in a uniform bed material. In general, for purposes of design of threshold channels, in which no bed movement is a requirement, the Shields curve will underestimate the critical dimensionless shear stress and is not recommended unless a factor of safety is added.

Adjustment for bedforms

Gessler (1971) determined that Shields did not separate grain shear stress from bedform shear stress in his experimental flume data analysis. Bedforms developed with sediment transport for the fine-grained bed material in some of Shields flume data. Since a portion of the total applied shear stress is required to overcome the bedform roughness, the calculated dimensionless shear stress would be too high for a natural bed with no bedforms. Gessler reanalyzed Shields' data so that the critical Shields parameter represented only the grain shear stress (fig. 8–11). This curve is more appropriate for determining critical shear stress in plane bed streams with relatively uniform bed gradations. With fully turbulent flow (R* >400), typical of gravel-bed streams, τ* is commonly taken to be 0.047 using Gessler's curve.

Figure 8–11 Gessler's reformulation of Shields diagram. τ is critical grain shear stress and k is grain diameter.

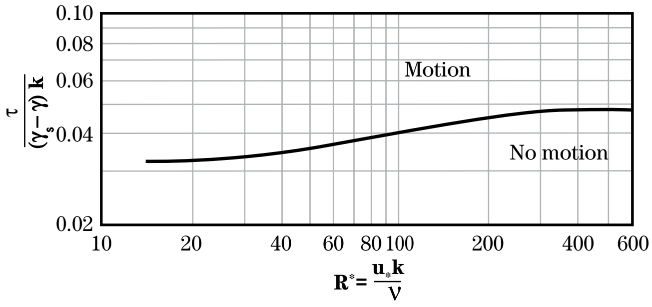
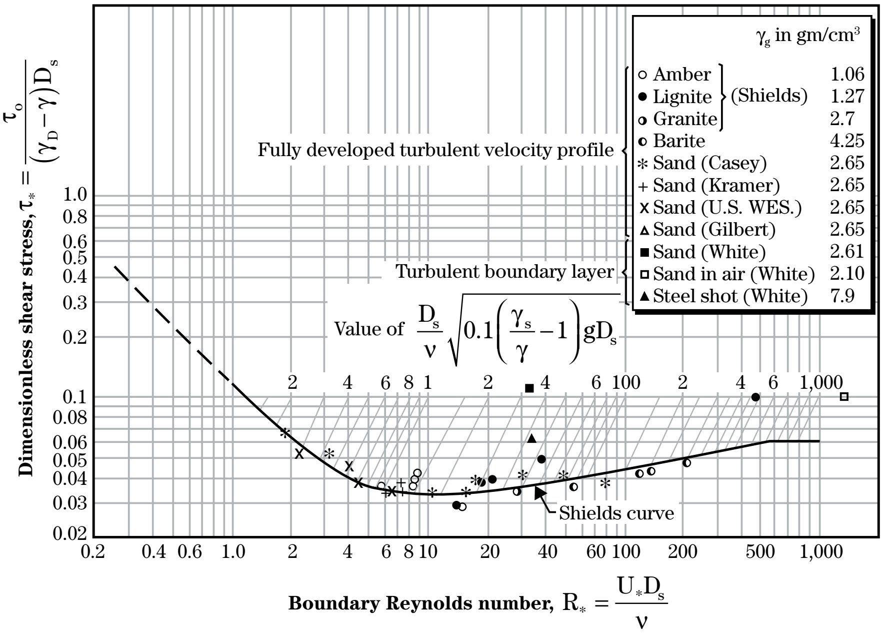


Figure 8–10 Shields curve



Adjustment for mixtures

Natural streambeds seldom have uniform bed gradations. The critical bed shear stress equation must be modified for mixtures. There are two approaches: one is to select a τ* that is characteristic of mixtures; the other is to select a percent finer grain size that is characteristic of initiation of motion. Meyer-Peter and Muller (1948) and Gessler (1971) determined that when R* >400, the critical Shields parameter for sediment mixtures was about 0.047 when median grain size was used. Neill (1968) determined from his data that in gravel mixtures, most particles became mobile when τ* was 0.030, when median grain size was used for D. Andrews (1983) found a slight difference in τ* for different grain sizes in a mixture, and presented the equation 8–22:

$$\tau_i^* = 0.0834\left(\frac{D_i}{D_{50}}\right)^{-0.872} \qquad \text{(eq. 8–22)}$$

where:

subscript, i =Shields parameter and grain size for size class i

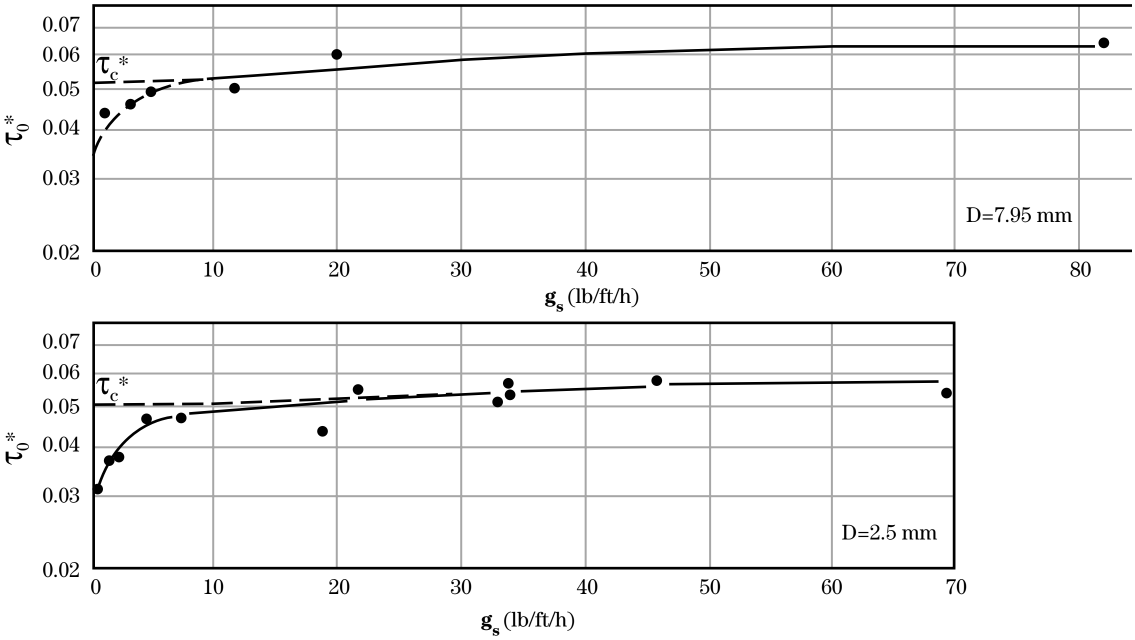
D_{50} =median diameter of the subsurface material

The minimum value for τ* was found to be 0.020. According to Andrews, the critical shear stress for individual particles has a very small range; therefore, the entire bed becomes mobilized at nearly the same shear stress. However, Wilcock (1998) and Wilcock and McArdell (1993) have demonstrated that this near-equal mobility result applies only to unimodal sediments with a small to modest standard deviation. In coarse beds with a wide range of sizes (especially mixtures of sand and gravel), the fines may begin to move at flows much smaller than the coarse grains.

Gessler's concept for particle stability

Critical shear stress is difficult to define because entrainment is sporadic at low shear stresses caused by bursts of turbulence. Due to the difficulty in defining initiation of motion in a flume, the Shields curve was developed by extrapolating measured sediment transport rates back to zero. Unfortunately, the relationship between the Shields parameter and sediment transport is not linear at low shear stresses. This phenomenon was demonstrated by Paintal (1971) (fig. 8–12). Note that the extrapolated critical dimensionless shear stress was about 0.05, but the actual critical dimensionless shear stress was 0.03.

Figure 8–12 Variation in Shields parameter with decreasing sediment load



Gessler (1971) developed a probability approach to the initiation of motion for sediment mixtures. He reasoned that due to the random orientation of grains and the random strength of turbulence on the bed, for a given set of hydraulic conditions, part of the grains of a given size will move, while others of the same size may remain in place. Gessler assumed that the critical Shields parameter represents an average condition, where about half the grains of a uniform material will remain stable and half will move. It follows then that when the critical shear stress was equal to the bed shear stress, there was a 50 percent chance for a given particle to move. Using experimental flume data, he developed a probability function, p, dependent on τ_c/τ where τ_c varied with bed size class (fig. 8–13). He determined that the probability function had a normal distribution, and that the standard deviation (slope of the probability curve) was a function primarily of turbulence intensity, and equal to 0.057. Gessler found the effect of grain-size orientation to be negligible. The standard deviation also accounts for hiding effects; that is, no attempt was made to separate hiding from the overall process. Gessler's analysis demonstrates that there can be entrainment of particles, even when the applied shear stress is less than the critical shear stress; and that not all particles of a given size class on the bed will necessarily be entrained, until the applied shear stress exceeds the critical shear stress by a factor of 2. The design implications of this work are:

- If near-complete immobility is desired in the project design, the Shields parameter used to determine critical shear stress should be on the order of half the typically assigned value.
- To assure complete mobility of the bed (fully alluvial conditions), the applied grain shear stress should be twice the critical shear stress.

The inherent dangers of using 50 percent or 200 percent of critical shear stress are that the channel could aggrade or incise.

Gessler used the probability approach to determine if the bed surface layer of a channel was stable (immobile). He suggested that the mean value of the probabilities for the bed surface to stay in place should be a good indicator of stability:

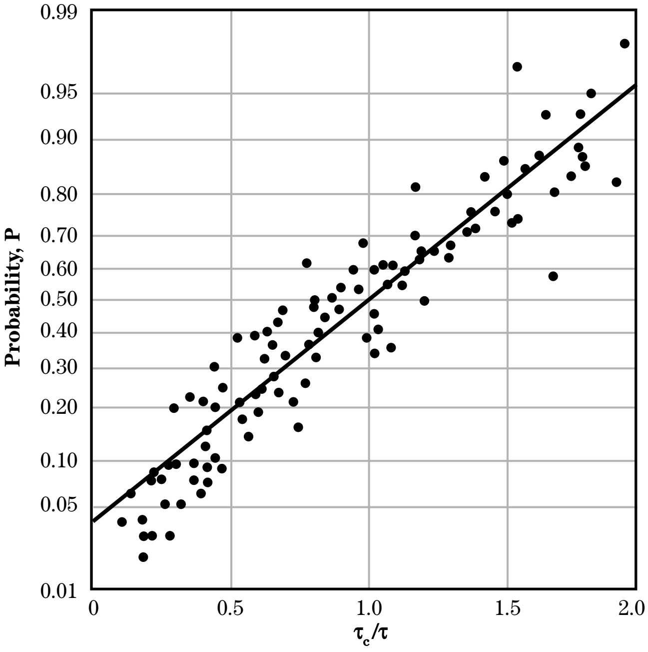
$$\bar{P} = \frac{\int_{i_{min}}^{i_{max}} P^2 f_i D_i}{\int_{i_{min}}^{i_{max}} P f_i D_i} \qquad \text{(eq. 8–23)}$$

where:
$\bar{P}$ = probability function for the mixture (depends on the frequency of all grain sizes in the underlying material)
f_i = fraction of grain size i

If the gradation of the channel bed is known, τ_c for each size class is determined from figure 8–11, and P for each size class is determined from figure 8–13. $\bar{P}$ can then be calculated from equation 8–23. Gessler suggested that when $\bar{P}$ was less than 0.65, the bed was unstable.

The probability concept was presented in an empirical fashion by Buffington and Montgomery (1997). They analyzed critical shear stress data from many investigators and suggested ranges for the critical Shields parameter. For visually base data, where initiation of motion was determined by investigator observation, Buffington and Montgomery suggested a range for τ^* between 0.073 and 0.030 for fully rough, turbulent flow ($R^* > 400$). They concluded that less emphasis should be placed on choosing a universal value for τ^*, while more emphasis should be placed on choosing defendable values for particular applications. Buffington and Montgomery also provided the compiled data

Figure 8–13 Probability of grains to stay on the bed



from many investigators, including data from natural streams.

Lane's method for coarse grained soils

Lane (1955a) concentrated on the force exerted over a given surface area of the channel, rather than the force exerted on a single particle, as in the Shields parameter and Gessler approaches. He also built in a factor of safety to the critical shear stress, so that his equation more appropriately can be called an allowable shear stress equation. This factor of safety accounts for the shear stress fluctuations in turbulent flow.

For boundaries with coarse-grained discrete soil particles, where the D_{75} is between 0.25 and 5.00 inches (6.35 and 127 mm), the allowable shear stress on the channel bottom, τ_{ab}, can be approximated using equation 8–24 proposed by Lane.

$$\tau_{ab} = 0.4\,D_{75} \qquad \text{(eq. 8–24)}$$

where:

D_{75} = particle size for which 75% of the sediment is smaller (in)

τ_{ab} = allowable shear stress on channel bottom (lb/ft^2)

The allowable shear stress for the channel sides, τ_{as}, is less than that of the same material in the bed of the channel because the gravity force aids the applied shear stress in moving the materials. For channel sides composed of soil particles behaving as discrete single grain materials, considering the effect of the side slope, z, and the angle of repose, ϕ, with the horizontal, the allowable shear stress is:

$$\tau_{as} = 0.4K\,D_{75} \qquad \text{(eq. 8–25)}$$

where:

$$K = \sqrt{\frac{z^2 - \cot^2\phi}{1+z^2}} \qquad \text{(eq. 8–26)}$$

The angle of repose for various degrees of particle angularity can be determined from figure 8–14 (Lane 1952). When the unit weight, γ_s, of the boundary material greater than D_{75} is significantly different from 160 pounds per cubic foot, the allowable shear stresses, τ_{ab} and τ_{as}, should be multiplied by the factor T.

$$T = \frac{\gamma_s - \gamma}{97.8} \qquad \text{(eq. 8–27)}$$

where:

units of γ are in lb/ft^3

Figure 8–15 (from TR–25) provides adjustment values for allowable bank stress in trapezoidal channels, based on angle of repose and side slope steepness. The allowable stress for the channel sides is thought to be less than that of the same material in the bed because the gravity force adds to the stress in moving the materials.

Lane's method for fine-grained soils

Allowable shear stress in fine-grained soils (D_{75} <6.3 mm) can be determined from figure 8–16 (Lane 1955a). The curves relate the median grain size of the soils to the allowable shear stress. The curve labeled as high sediment content is to be used when the stream under consideration carries a load of 20,000 parts per million by weight or more of fine suspended sediment. The curve labeled low sediment content is to be used for streams carrying up to 2,000 parts per million by weight of fine suspended sediment. The curve labeled clear water is for flows with less than 1,000 parts per million.

When 5 millimeters <D_{50} <6.3 millimeters, use the allowable shear stress for 5 millimeters shown on the chart. When D_{50} is less than 0.1 millimeter and is still noncohesive, use the allowable shear stress for values of 0.1 millimeter.

Cohesive materials

The allowable shear stress concept has been applied to semicohesive and cohesive soils, but values do not correlate well with standard geotechnical parameters because resistance to erosion is affected by such factors as water chemistry, history of exposure to flows, and weathering. Analysis of experience with local channels and laboratory testing of local materials are generally recommended. Figure 8–17 gives an example of allowable shear stresses (tractive forces) for a range of cohesive materials, but where possible, values should be compared against the results of field observation or laboratory testing. The curves in figure 8–17 are converted from USSR (1936) permissible velocity data from straight channels with an average depth of 3 feet. The figure is reported in Chow (1959) and USACE (1991b). The basic soil textural class can be determined as a function of the percentages of clay, silt, and sand in the soil using the soil triangle in figure 8–18 (USDA SCS 1994).

Figure 8–14 Angle of repose for noncohesive material

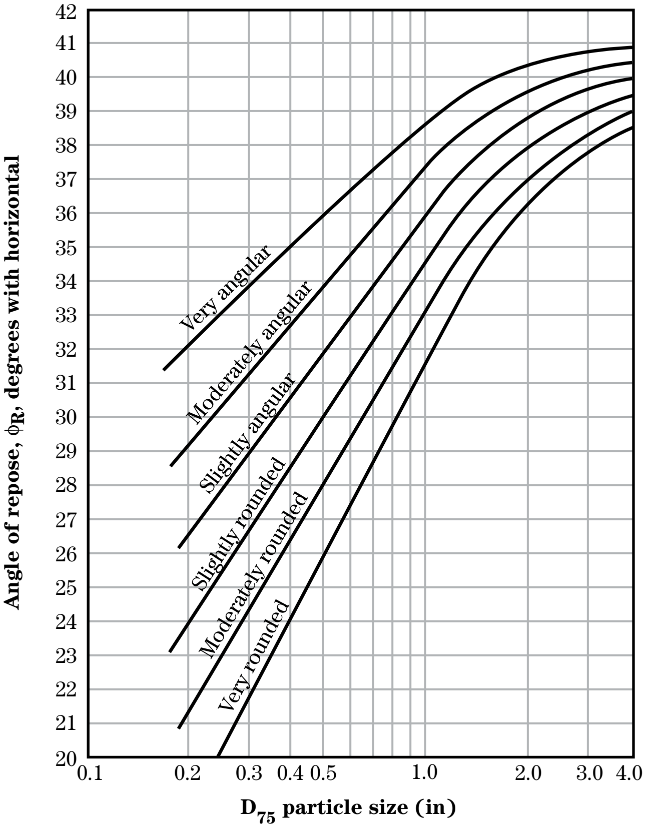


Figure 8–15 K values for allowable stress, sides of trapezoidal channels

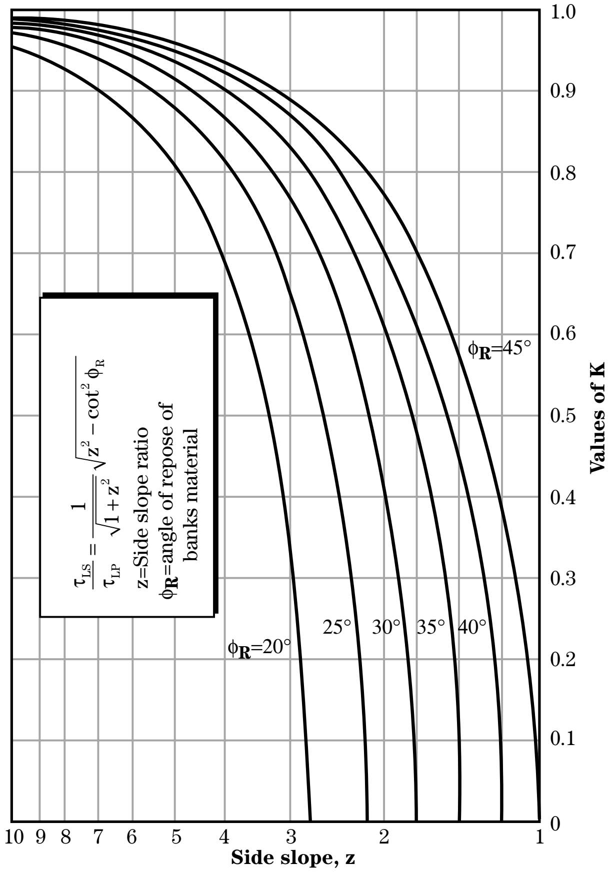


Figure 8–16 Allowable shear stress for granular material in straight trapezoidal channels

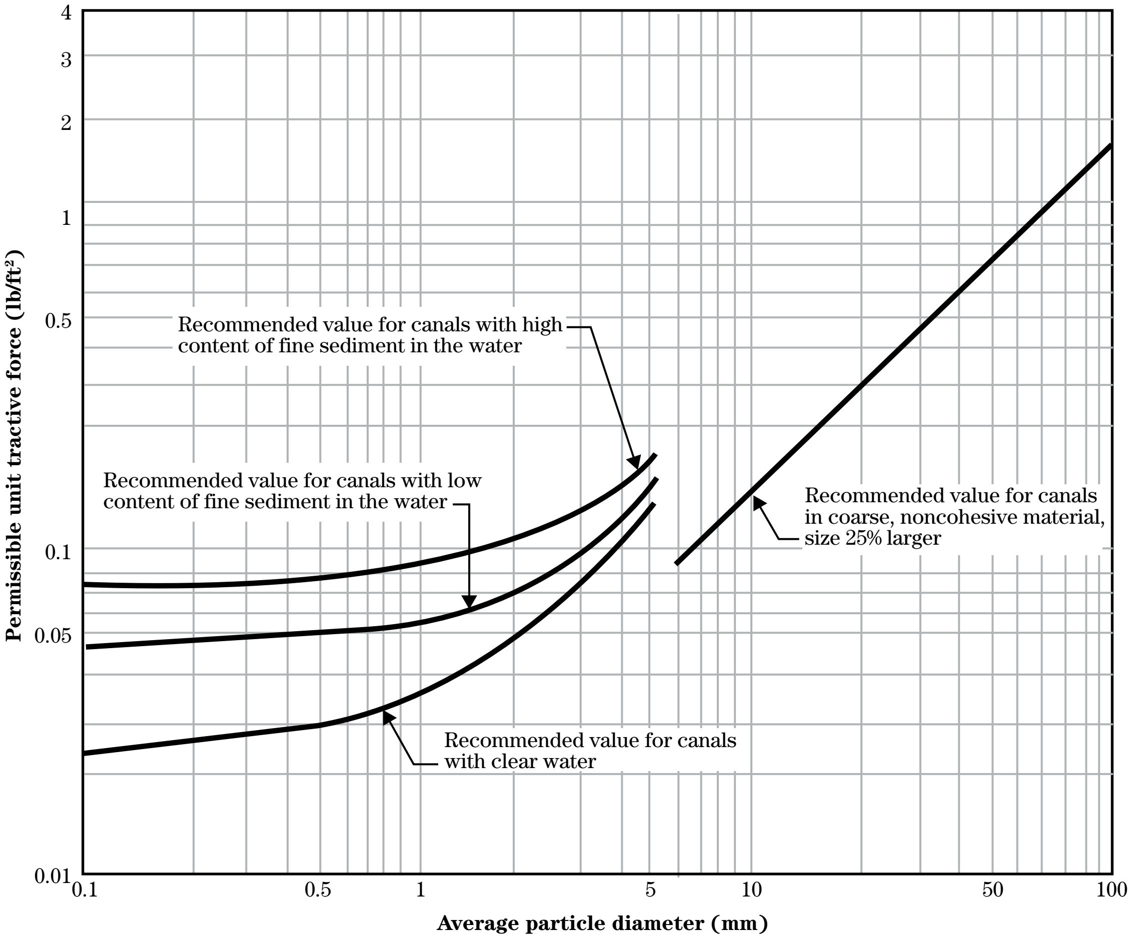


Figure 8–17 Allowable shear stress in cohesive material in straight trapezoidal channels

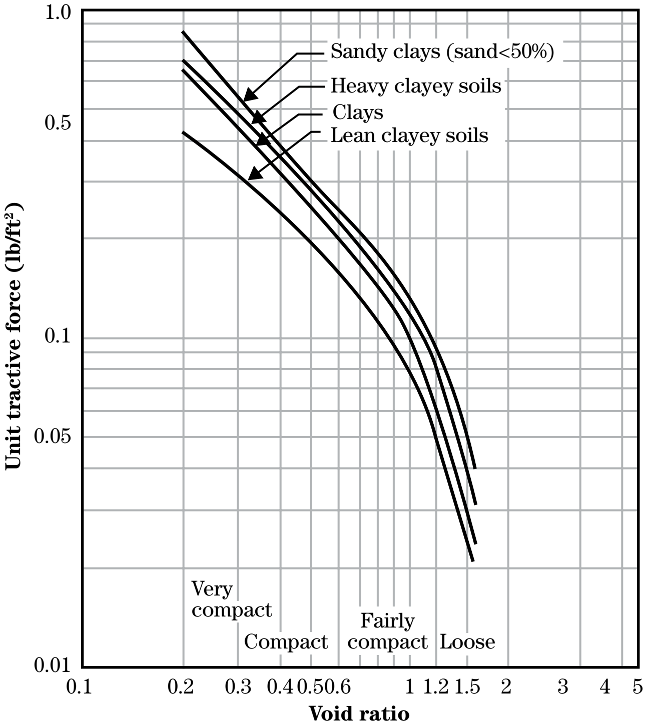
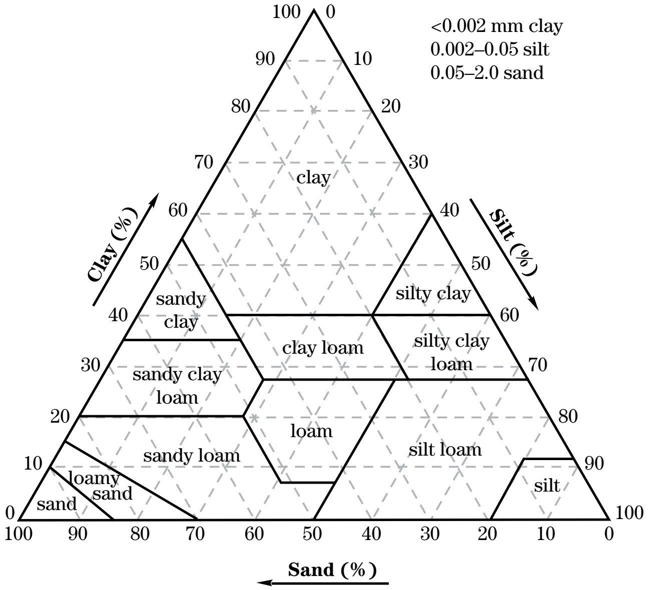


Figure 8–18 USDA textural classification chart



(c) Procedure for application of allowable shear stress method

Application of the allowable shear stress method requires first the determination of shear stress in the design channel and then comparison of the design shear stress to allowable shear stress for the boundary material. The allowable shear stress may be determined by one of three methods: Shields parameter approach, Gessler (1971) probability approach, or Lane tractive force method (Lane 1952). The characteristics of each method are summarized in table 8–5.

The use of the tractive force method to design earth channels involves the following steps modified from those found in TR–25, Design of Open Channels (USDA SCS 1977).

Step 1 Determine the hydraulics of the channel. This includes the hydrologic determinations, as well as the stage-discharge relationships for the channel being considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream.

Step 3 Determine the concentration of the suspended fine sediment load entering the reach. This is best accomplished by measurements. Channels with suspended fine sediment concentrations less than 1,000 parts per million are considered sediment free. Sediment-free flows are considered to have no effect on channel stability. Channels with suspended fine sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment-laden flows are considered to enhance sediment stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the allowable shear stress approach is applicable. Use table 8–1.

Step 5 Compute the applied shear stress on the boundary of the channel being studied. For noncohesive bed materials, grain shear stress can be calculated using the Limerinos equation or the Lane equation. If the Shields parameter or Gessler probability methods are used, calculate the grain shear stress using the Limerinos equation and the D_{84} of the boundary material. A factor of safety should be added to this calculated grain shear stress if the Shields parameter approach is to be used. If the tractive force method is used, calculate grain shear stress using Lane's equation with the D_{75} of the boundary material. Lane's equation already accounts for the factor of safety, so there is no need to increase the calculated applied shear stress. If the bed material is cohesive, use the total shear stress as the applied shear stress. Use (with caution) figures 8–8 and 8–9 to determine applied shear stress on the outside of bends.

Step 6 Check the ability of the soil materials forming the channel boundary to resist the computed applied shear stress. If the Shields parameter method is used, determine an appropriate Shields parameter and calculate critical shear

Table 8–5 Characteristics of methods to determine allowable shear stress

	Theoretical basis	**Bed characteristics**	**Safety factor**	**Basis for coefficients**
Shields parameter	The force on a single particle that initiates sediment motion	Noncohesive	No	Flumes and channels
Gessler probability	Probability distribution of force on a particle mixture	Noncohesive	Yes	Flume
Lane	Force on surface area	Separate equations and charts for coarse and fine-grained, noncohesive materials and cohesive material	Yes	Channels

stress. If the Gessler probability method is used, calculate critical shear stress for each size class in the mixture using figure 8–11. Then calculate the probability for each size class to stay in place, using figure 8–13. Finally, calculate the probability function for the bed mixture using Gessler's equation. For Lane's coarse-grained soils method, use Lane's equations with D_{75} to calculate allowable shear stress on the channel bottom and the channel slide slope. Lane's K factor for side slope allowable shear stress can also be adapted for use with the Shields parameter and Gessler probability methods. For Lane's method for fine-grained soils use figure 8–16 with the D_{50} and wash load sediment concentration to determine allowable shear stress. For cohesive materials, allowable shear stress should be determined by laboratory testing. Approximate values of allowable shear stress based on soil properties can be determined from figure 8–17.

Step 7 Compare the design shear stress with the allowable shear stress. If the allowable shear stress is greater than the design shear stress, the design is satisfactory. Otherwise, three options are available:

- Redesign the channel to reduce shear stress.
- Provide structural measures (riprap, grade control) to prevent erosion.
- Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

Step 8 Do a performance check to determine at what discharge the allowable shear stress is exceeded and the bed becomes alluvial.

(d) Limitations and cautions

For channels with substantial bed-material sediment load, aggradation of the design channel could be a problem in a channel designed using allowable velocity or allowable shear stress methods. A minimum velocity or shear stress must be determined that ensures sediment transport through the design reach, in addition to the allowable value. The minimum permissible velocity that prevents deposition is a function of the sediment concentration and the sediment transport capacity of the channel. Generally, for irrigation canal design, a mean velocity of 2 to 3 feet per second may be used safely, when the sediment load in the channel is small (Chow 1959).

In bends and meandering channels, bank erosion and migration may occur even if average velocities and shear stresses are well below allowable values.

An allowable velocity or shear stress analysis will not in itself define completely the channel design because it can be satisfied by a wide range of width, depth, and slope combinations. The design, therefore, must be supplemented by additional guidelines for slope, width, or cross-sectional shape. Usually, the slope will be predetermined within narrow limits, and practicable limits of width-to-depth ratio will be indicated by the existing channel.

The distinction between incipient motion and allowable velocity and shear stress must be remembered. Velocity and shear stress at incipient motion, when the particles on the bed begin to be entrained, are less than allowable velocity and shear stress used in design. Allowable values must include an allowance for the fluctuation of velocity and shear stress caused by turbulence. Channels should be designed using criteria that include some factor of safety beyond incipient motion.

It is important to remember that not all of the shear stress applied on the channel bottom is actually available to erode the channel bed. In sand channels especially, the bed is normally covered with bedforms, which dissipate some of the shear stress. Bedforms and irregularities also occur in many channels with coarser beds. Then it is necessary to use more complex approaches that involve separating the total applied shear stress into two or more parts, where only the shear stress associated with the roughness of the sediment grains must be less than the allowable shear stress.

Example: Allowable shear stress design

Given: A proposed flood channel has a bottom width of 8 feet, side slopes of 2H:1V, and energy slope of 0.00085. The channel will flow at a normal depth of 4 feet, a velocity of 3.2 foot per second, and a discharge of 200 cubic feet per second. The soils are slightly angular sandy gravels, with D_{75} of 0.75 inches. Manning's coefficient for the entire channel is estimated at 0.025. The channel has a curve with radius of curvature of 40 feet.

Problem: Check stability using allowable shear stress approach.

Solution:

Step 1 Calculate actual stresses on bed, sides, and curve.

a. Reference stress, τ_∞

$$\tau_\infty = \gamma d S_e \left(\frac{n_t}{n}\right)^2$$

$$n_t = \frac{\left(D_{75}\right)^{\frac{1}{6}}}{39} = 0.0244$$

$$\tau_\infty = (62.4)(4)(0.00085)\left(\frac{0.0244}{0.025}\right)^2 = 0.2021 \text{ lb/ft}^2$$

b. Actual stress on channel bed, τ_b

$$\tau_b = \tau_\infty \left(\frac{\tau_b}{\tau_\infty}\right)$$

Using figure 8–5,

$$\frac{b}{d} = \frac{8}{4} = 2 \text{ and } z=2$$

$$\frac{\tau_b}{\tau_\infty} = 0.89$$

$$\tau_b = (0.2021)(0.89) = 0.1799$$

c. Actual stress on channel bed, curved reach, τ_{bc}

$$\tau_{bc} = \tau_b \left(\frac{\tau_{bc}}{\tau_b}\right)$$

Using figure 8–8:

$$\frac{R_c}{b} = \frac{40}{8} = 5$$

$$\frac{\tau_{bc}}{\tau_b} = 1.56$$

$$\tau_{bc} = (0.1799)(1.56) = 0.281 \text{ lb/ft}^2$$

d. Actual stress on channel sides, τ_s

$$\tau_s = \tau_\infty \left(\frac{\tau_s}{\tau_\infty}\right)$$

Using figure 8–6: $\frac{b}{d} = \frac{8}{4} = 2$ and z=2

$$\frac{\tau_s}{\tau_\infty} = 0.76$$

$$\tau_s = (0.2021)(0.76) = 0.154 \text{ lb/ft}^2$$

e. Actual stress on channel sides, curved reach, τ_{sc}

$$\tau_{sc} = \tau_s \left(\frac{\tau_{sc}}{\tau_s}\right)$$

$$\tau_s = (0.2021)(0.76) = 0.154 \text{ lb/ft}^2$$

Step 2 Calculate allowable stresses on beds and sides, τ_{Lb} and τ_{Ls}.

a. Allowable stress on bed, τ_{Lb}

$\tau_{Lb} = 0.4\ D_{75}$
$= (0.4)\ (0.75) = 0.3 \text{ lb/ft}^2$

b. $\tau_{Ls} = 0.4\ D_{75}K$

For K:

Use figure 8–14 and $D_{75} = 0.75$ in:

$\Phi_R = 34.3^\circ$ for subangular

Use figure 8–15, z = 2 and $\Phi_R = 34.3^\circ$:

K = 0.6

$\tau_{Ls} = 0.4\ (0.75)\ (0.6) = 0.18 \text{ lb/ft}^2$

Step 3 Compare actual with allowable stress for stability check.

$\tau_b = 0.1799$, $\tau_{bc} = 0.281 < \tau_{Lb} = 0.3 \text{ lb/ft}^2$ (OK)

$\tau_s = 0.154 < \tau_{Ls} = 0.18 \text{ lb/ft}^2 < \tau_{sc} = 0.24$

Therefore, for the channel to be considered to be stable, the curved reach needs a change in the hydraulics, less curvature, and/or some sort of armoring of the banks.

654.0805 Tractive power method

The tractive power method was developed by the NRCS (formally SCS) in the western United States in the 1960s to evaluate the stability of channels in cemented and partially lithified (hardened) soils. In this approach, the aggregate stability of saturated soils is assessed by use of the unconfined compression test. Field observations of several channels were evaluated against the unconfined compression strength of soil samples taken from the same channels. The results are shown in figure 8–19. Soils in channels with unconfined compression strength versus tractive power that plot above and to the left of the S-line have questionable resistance to erosion. Soils in channels with unconfined compression strength versus tractive power that plot below and to the right of the S-line can be expected to effectively resist the erosive efforts of the stream flow.

Tractive power is defined as the product of mean velocity and tractive stress. Tractive stress is calculated using the Lane method for the appropriate soil characteristics.

The use of the tractive power method to design earth channels involves the following steps modified from those found in TR–25, Design of Open Channels (USDA SCS 1977).

Step 1 Determine the hydraulics of the channel. This includes the hydrologic determinations, as well as the stage-discharge relationships for the channel being considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream. This includes the saturated unconfined compressive strength.

S*tep 3* Determine the concentration of the suspended sediment load entering the reach. This is best accomplished by measurements. Channels with suspended sediment concentrations less than 1,000 parts per million are considered sediment free. Sediment free flows are considered to have no effect on channel stability. Channels with suspended sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment laden flows are considered to enhance sediment stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the tractive power method is applicable. Use table 8–1.

Step 5 Compute the tractive power on the boundary of the channel being studied. Use velocity from step one. Calculate applied tractive force using the appropriate equation based on the boundary characteristics. For noncohesive bed materials, grain shear stress can be calculated using the Limerinos equation or Lane equation. If the bed material is cohesive, use the total shear stress as the applied shear stress. Use (with caution) figures 8–8 and 8–9 to determine applied shear stress on the outside of bends.

Step 6 Check the ability of the soil materials forming the channel boundary to resist the computed applied shear stress, using figure 8–19. If the combination of tractive power and unconfined compressive strength plots below the S-line, the design is satisfactory. Otherwise, three options are available:

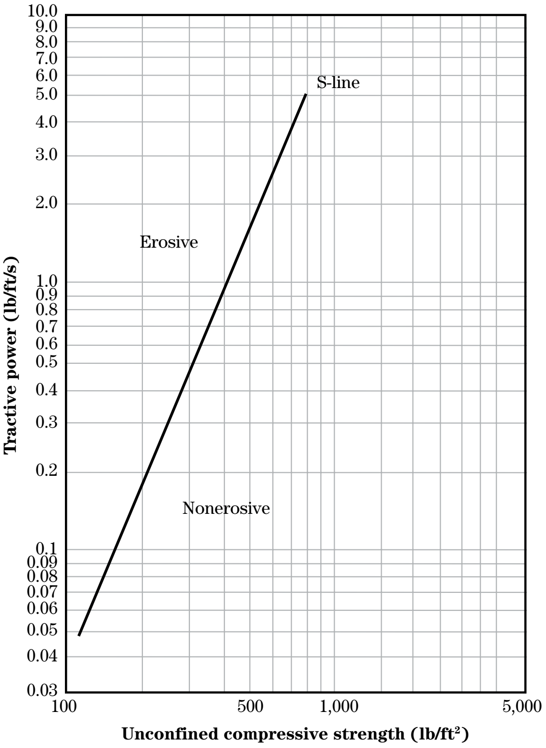
a. Redesign the channel to reduce tractive power.

b. Provide structural measures (riprap, grade control) to prevent erosion.

c. Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

Step 7 Do a performance check to determine at what discharge the allowable tractive power is exceeded and the bed becomes alluvial.

Figure 8–19 Unconfined strength and tractive power as related to channel stability



654.0806 Grass-lined channels

In channels where climate and soils can support permanent vegetation and baseflow does not exist, grass channel lining may be used to provide protection to erodible soil boundaries. Grass linings have been widely used to protect agricultural waterways, floodways, urban drainageways, and reservoir auxiliary spillways. The material in this section is derived from USDA Agricultural Handbook (AH) 667 (Temple et al. 1987), which has extended the concepts of SCS TP–61 (USDA SCS 1954).

(a) Allowable velocity

The method follows a similar format to the allowable or permissible velocity method described earlier. However, there are some important differences in how the allowable velocity is calculated. The allowable velocity is defined as the velocity that can be sustained for a reasonable length of time. Recommended allowable velocities for different vegetal covers, channel slopes, and soil conditions are shown in table 8–6.

Table 8–6 Allowable velocities for channels lined with grass

Cover	Slope range percent	Allowable velocity (ft/s)	
		Erosion-resistant soils	Easily eroded soils
Bermudagrass	0–5 5–10 >10	8 7 6	6 5 4
Buffalograss, Kentucky bluegrass, smooth brome, blue grama	0–5 5–10 >10	7 6 5	5 4 3
Grass mixture	0–5 5–10	5 4	4 3
	Not recommended on slopes greater than 10%		
Lespedeza sericea, weeping lovegrass, ischaemum (yellow bluestem), kudzu, alfalfa, crabgrass	0–5	3.5	2.5
	Not recommended on slopes greater than 5%, except for side slopes in a compound channel		
Annuals—used on mild slopes or as temporary protection until permanent covers are established, common lespedeza, Sudangrass	0–5	3.5	2.5
	Not recommended for slopes greater than 5%		

Climate, soil conditions, and stability are all important factors in the selection of grass type for the channel lining. Grasses that grow in bunches, such as alfalfa, lespedeza, and kudzu, tend to concentrate flow at the bed surface. Although this characteristic may be helpful in discouraging sediment deposition, from a stability standpoint, these grasses are not suitable on steep slopes. For slopes greater than 5 percent, only fine, uniformly distributed sod-forming grasses, such as bermudagrass, Kentucky bluegrass, and smooth brome, are recommended for lining on the channel bottom. Sod-forming grasses tend to spread and may be objectionable in some cases. The upper side slope and channel berms may be planted with grasses, such as weeping lovegrass, that do not spread as easily.

Manning's roughness coefficients were also determined for the grasses tested at the USDA Agricultural Research Service (ARS) Laboratory, Stillwater, Oklahoma. Roughness was determined to be a function of the grass type, product of velocity (V), and hydraulic radius (R). Maximum VR values tested were about 20 square feet per second. These roughness values should be used to calculate the average velocity for the design channel. Average curves for five degrees of flow retardance are shown in figure 8–20 (USDA SCS 1954). Descriptions of the grasses tested and their degree of retardance are given in table 8–7.

(b) Allowable shear stress

Design criteria for grass-lined channels are provided in USDA AH 667 (Temple et al. 1987). This allowable shear stress method is based on a reanalysis of available data, largely SCS TP–61 data, and a better understanding of the interaction of the flow with a vegetated boundary. The method is still semiempirical, but it improves the separation of independent variables in the design relations. Combining this method with appropriate soil erodibility relations results in an improved design procedure that is more flexible than the allowable velocity method. The allowable shear stress design method is also consistent with current nonvegetated channel design practices.

Vegetative linings can fail with increased shear stress, either by particle detachment or failure of individual vegetal elements. For soils most often encountered in practice, particle detachment begins at levels of total

Figure 8–20 Manning's roughness coefficients for grass-lined channels

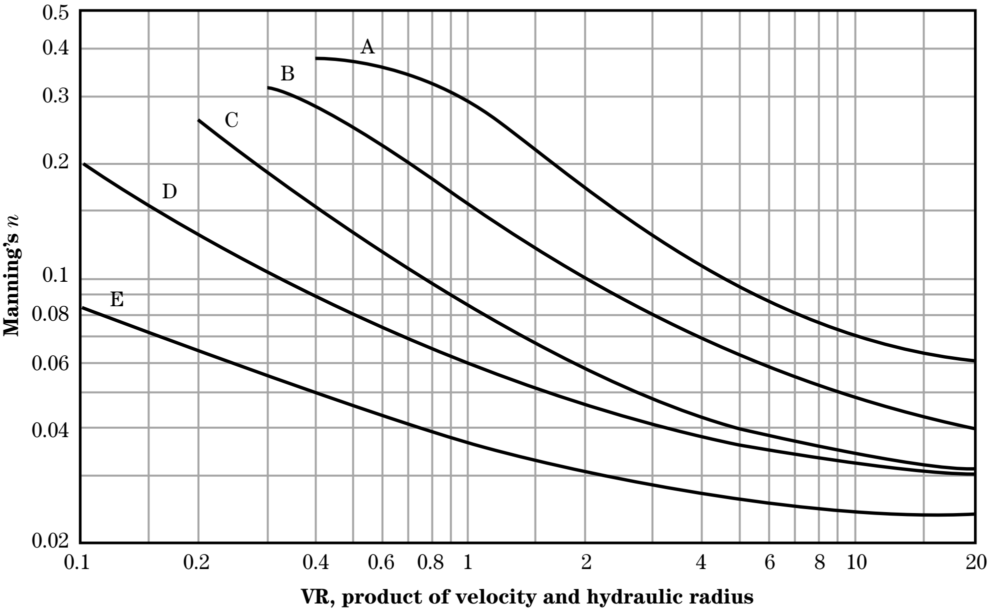


Table 8–7 Classification of degree of retardance for various kinds of grasses

Retardance	**Cover**	**Condition**
A—Very high	Weeping lovegrass	Excellent stand, tall (average 30 in)
	Yellow bluestem	Excellent stand, tall (average 36 in)
B—High	Kudzu	Very dense growth, uncut
	Bermudagrass	Good stand, tall (average 12 in)
	Native grass mixture (little bluestem, blue grama, and other long and short Midwest grasses)	Good stand, unmowed
	Weeping lovegrass	Good stand, tall (average 24 in)
	Lespedeza sericea	Good stand, not woody, tall (average 19 in)
	Alfalfa	Good stand, uncut, (average 11 in)
	Weeping lovegrass	Good stand, mowed (average 13 in)
	Kudzu	Dense growth, uncut
	Blue grama	Good stand, uncut (average 13 in)
C—Moderate	Crabgrass	Fair stand, uncut (10–48 in)
	Bermudagrass	Good stand, mowed (average 6 in)
	Common lespedeza	Good stand, uncut (average 11 in)
	Grass-legume mixture—summer (orchardgrass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (6–8 in)
	Centipede grass	Very dense cover (average 6 in)
	Kentucky bluegrass	Good stand, headed (6–12 in)
D—Low	Bermudagrass	Good stand, cut to 2.5 in
	Common lespedeza	Excellent stand, uncut, (average 4.5 in)
	Buffalo grass	Good stand, uncut (3–6 in)
	Grass-legume mixture—fall, spring (orchardgrass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (4–5 in)
	Lespedeza sericea	After cutting to 2 in
E—Very low	Bermudagrass	Good stand, cut to 1.5 in
	Bermudagrass	Burned stubble

shear stress low enough to be withstood by the vegetation without significant damage. When this occurs, the vegetation is undercut, and the weakest vegetation is removed. This leads to decreases in the density and uniformity of the remaining vegetative cover, which in turn leads to greater stresses at the boundary and a rapid failure of the protection. Failure progresses in much the same fashion in very resistant soils where the vegetal elements may sustain damage before the effective stress at the boundary becomes large enough to detach soil particles of aggregates. Damage to the vegetal cover in the form of removal of young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems, results in an increase in effective stress on the boundary until conditions critical to erosion are exceeded. The ensuing erosion further weakens the cover and unraveling occurs. This characteristic of rapid unraveling of the channel lining once a weak point has developed, combined with the variability of vegetative covers, forces the design criteria presented in Agricultural Handbook (AH) 667 to be conservative. Therefore, a design factor of safety is built into the procedure.

The AH 667 procedure assumes that the allowable soil stress is the same for vegetated channels as for unlined channels, for which the tractive force is a suitable design parameter. For effective shear stress to be the sole stability parameter, detachment, rather than sediment transport processes must dominate stability considerations. This means that sediment deposition and sediment transport as bed-material load must be negligible.

(c) Species selection, establishment, and maintenance of grass-lined channels

The selection of grass species for use in channels for erosion control is based on site-specific factors:

- soil texture
- depth of the underlying material
- management requirements of vegetation
- climate
- slope
- type of structure or engineering design
- invasiveness of grass species and downstream impacts

Expected flow rate, availability of seed, ease of stand establishment, species or vegetative growth habit, plant cover, and persistence of established species are other factors that must be considered in selecting the appropriate grass to meet conditions critical to channel stability.

Chapter 2 of AH 667 (Temple et al. 1987) addresses the essential agronomic considerations in selecting, establishing, and maintaining grass channel linings.

(d) Determination of channel design parameters

The independent hydraulic variables governing the stability of a grass-lined open channel are the channel geometry and slope, erodibility of the soil boundary, and properties of the grass lining that relate to flow retardance potential and boundary protection.

Stability design of a grass-lined open channel using the effective stress approach requires the determination of two vegetal parameters. The first is the retardance curve index, C_I, which describes the potential of the vegetal cover to develop flow resistance. The second is the vegetal cover index, C_F, which describes the degree to which the vegetal cover prevents high velocities and stresses at the soil-water interface.

The retardance curve index can be determined from the dimensionless equation (eq. 8–28) where any consistent units of measurement can be used.

$$C_I = 2.5\left(h\sqrt{M}\right)^{\frac{1}{3}} \qquad \text{(eq. 8–28)}$$

where:
h = the representative stem length
M = the stem density in stems per unit area

The stem length will usually need to be estimated directly from knowledge of the vegetal conditions at the time of anticipated maximum flow. Table 8–8 may be used as a guide for the grass species most commonly encountered (Temple et al. 1987). When two or more grasses with widely differing growth characteristics are involved, the representative stem length is determined as the root mean square of the individual stem lengths. The reference stem densities contained in table 8–9 may be used as a guide in estimating M when more direct information is unavailable. The values in

Table 8–8 Characteristics of selected grass species for use in channels and waterways

Grass species	Height at maturity	
	(ft)	(m)
Cool-season grasses		
Creeping foxtail	3–4	0.9–1.2
Crested wheatgrass	2–3	0.6–0.9
Green needlegrass	3–4	0.9–1.2
Russian wild rye	3–4	0.9–1.2
Smooth bromegrass	3–4	0.9–1.2
Tall fescue	3–4	0.9–1.2
Tall wheatgrass		1.2–1.5
Western wheatgrass	2–3	0.6–0.9
Warm-season grasses		
Bermudagrass	3/4–2	0.2–0.6
Big bluestem	4–6	1.2–1.8
Blue grama	1–2	0.3–0.6
Buffalograss	1/3–1	0.1–0.3
Green spangletop	3–4	0.9–1.2
Indiangrass	5–6	1.5–1.8
Klein grass	3–4	0.9–1.2
Little bluestem	3–4	0.9–1.2
Plains bristlegrass	1–2	0.3–0.6
Sand bluestem	5–6	1.5–1.8
Sideoats grama	2–3	0.6–0.9
Switchgrass	4–5	1.2–1.5
Vine mesquitegrass	1–2	0.3–0.6
Weeping lovegrass	3–4	0.9–1.2
Old World bluestems		
Caucasian bluestem	4–5	1.2–1.5
Ganada yellow bluestem	3–4	0.9–1.2

Table 8–9 Retardance curve index by SCS retardance class

SCS retardance class	Retardance curve index
A	10.0
B	7.64
C	5.60
D	4.44
E	2.88

this table were obtained from a review of the available qualitative descriptions and stem counts reported by researchers studying channel resistance and stability.

Since cover conditions vary from year to year and season to season, it is recommended that an upper and lower bound be determined for C_I. The lower bound should be used in stability computations, and the upper bound should be used to determine channel capacity. Some practitioners find that the use of SCS retardance class (table 8–9) is a preferable approach.

The vegetal cover index, C_F, depends primarily on the density and uniformity of density in the immediate vicinity of the soil boundary. Because this parameter is associated with the prevention of local erosion damage which may lead to channel unraveling, the cover factor should represent the weakest area in a reach, rather than the average for the cover species. Recommended values for the cover factor are presented in table 8–10. Values in this table do not account for such considerations as maintenance practices or uniformity of soil fertility or moisture. Therefore, appropriate engineering judgment should be used in its application.

Table 8–10 Properties of grass channel linings values (apply to good uniform stands of each cover)

Cover factor (C_F)	Covers tested	Reference stem density (stems/ft^2)	Reference stem density (stems/m^2)
0.90	Bermudagrass	500	5,380
	Centipede grass	500	5,380
0.87	Buffalograss	400	4,300
	Kentucky bluegrass	350	3,770
	Blue grama	350	3,770
0.75	Grass mixture	200	2,150
0.50	Weeping lovegrass	350	3,770
	Yellow bluestem	250	2,690
0.50	Alfalfa	500	5,380
	Lespedeza sericea	300	3,280
0.50	Common lespedeza	150	1,610
	Sudangrass	50	538

Multiply the stem densities given by 1/3, 2/3, 1, 4/3, and 5/3 for poor, fair, good, very good, and excellent covers, respectively. Reduce the C_F by 20% for fair stands and 50% for poor stands.

Two soil parameters are required for application of effective stress concepts to the stability design of lined or unlined channels having an erodible soil boundary: soil grain roughness, n_s, and allowable effective stress, τ_a. When the effective stress approach is used, the soil parameters are the same for both lined and unlined channels with negligible bed-material sediment transport.

Soil grain roughness is defined as the roughness associated with particles or aggregates of a size that can be independently moved by the flow at incipient channel failure. For noncohesive soils, the soil grain roughness and effective shear stress are both a function of the D_{75} grain size. When D_{75} is greater than 1.3 millimeter, the soil is considered coarse grained. When D_{75} is less than 1.3 millimeter, the soil is considered fine grained. Fine-grained roughness is considered to have a constant value of 0.0156. Fine-grained effective shear stress is taken to have a constant value of 0.02 pound per square foot. Coarse-grained shear stress and roughness are given in figures 8–21 and 8–22.

A soil grain roughness of 0.0156 is assigned to all cohesive soils. The allowable effective stresses are a function of the unified soil classification system soil type, the plasticity index, and the void ratio. The basic allowable shear stress, τ_{ab}, is determined from the plasticity index and soil classification, and then adjusted by the void ratio correction factor, C_e, using the following equation:

$$\tau_a = \tau_{ab} C_e^2 \qquad \text{(eq. 8–29)}$$

The basic allowable effective stress can be determined from figure 8–23 and the void ratio correction factor from figure 8–24. These two figures were developed directly from the allowable velocity curves in AH 667. Stress partitioning (slope partitioning) is essential to application of figures 8–21 to 8–24, with or without vegetation (Temple et al. 1987).

(e) General design procedure

Use the basic shear stress equation to determine effective shear stress on the soil beneath the vegetation. Use any consistent units of measurement.

$$\tau_e = \gamma d S \left(1 - C_F\right)\left(\frac{n_s}{n}\right)^2 \qquad \text{(eq. 8–30)}$$

where:

τ_e = effective shear stress exerted on the soil beneath vegetation (lb/ft^2 or N/m^2)
γ = specific weight of water (lb/ft^3 or N/m^3)
d = maximum depth of flow in the cross section (ft or m)
S = energy slope, dimensionless
C_F = vegetation cover factor (0 for unlined channel), dimensionless
n_s = grain roughness of underlying soil, typically taken as dimensionless
n = roughness coefficient of vegetation, typically taken as dimensionless

The flow depth is used instead of the hydraulic radius because this will result in the maximum local shear stress, rather than the average shear stress. The cover factor is a function of the grass and stem density. Roughness coefficients are standard Manning's roughness values; n_s can be determined from figure 8–22, n can be determined from the old SCS curves (fig. 8–20) or from the following equation.

$$n_R = \exp\left\{C_I\left[0.0133\left(\ln R_v\right)^2 - 0.0954 \ln R_v + 0.297\right] - 4.16\right\} \qquad \text{(eq. 8–31)}$$

where:

R_v = (VR/ν) x 10^{-5} (this dimensionless term reduces to VR for practical application in English units)
V = channel velocity (ft/s or m/s)
R = hydraulic radius (ft or m)
Limited to $0.0025 C_I^{2.5} < R_v < 36$

A reference value of Manning's resistance coefficient, $n_{R,}$ is applicable to vegetation established on relatively smoothly graded fine-grained soil.

If vegetated channel liner mats are used, manufacturer-supplied roughness coefficients for particular mats may be used in the equation.

Maximum allowable shear stress, τ_{va}, in pound per square foot is determined as a function of the retardance curve index, C_I. Very little information is available for vegetal performance under very high stresses and this relation is believed to be conservative.

$$\tau_{va} = 0.75 C_I \qquad \text{(eq. 8–32)}$$

Figure 8–21 Allowable shear stress for noncohesive soils

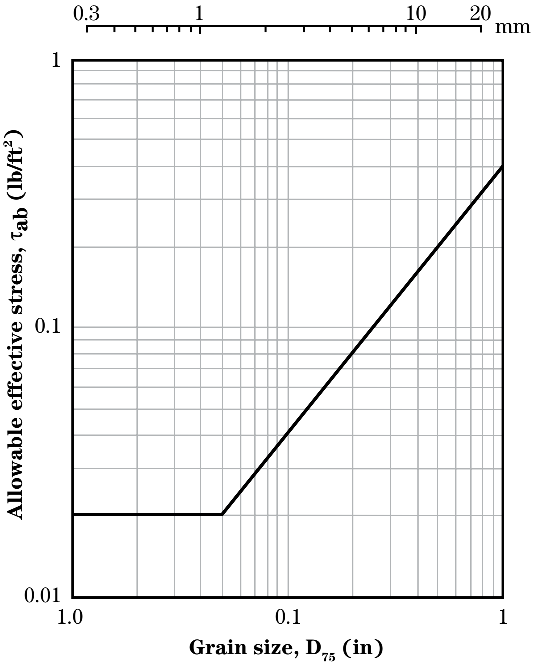


Figure 8–22 Soil grain roughness for noncohesive soils

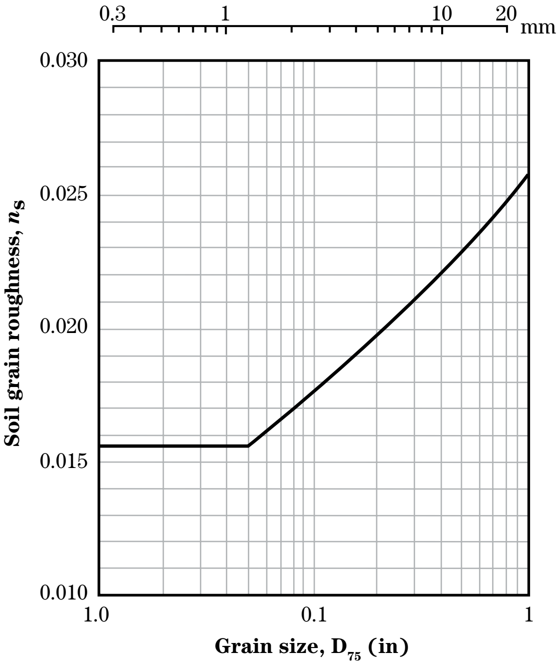


Figure 8–23 Basic allowable shear stress for cohesive soils

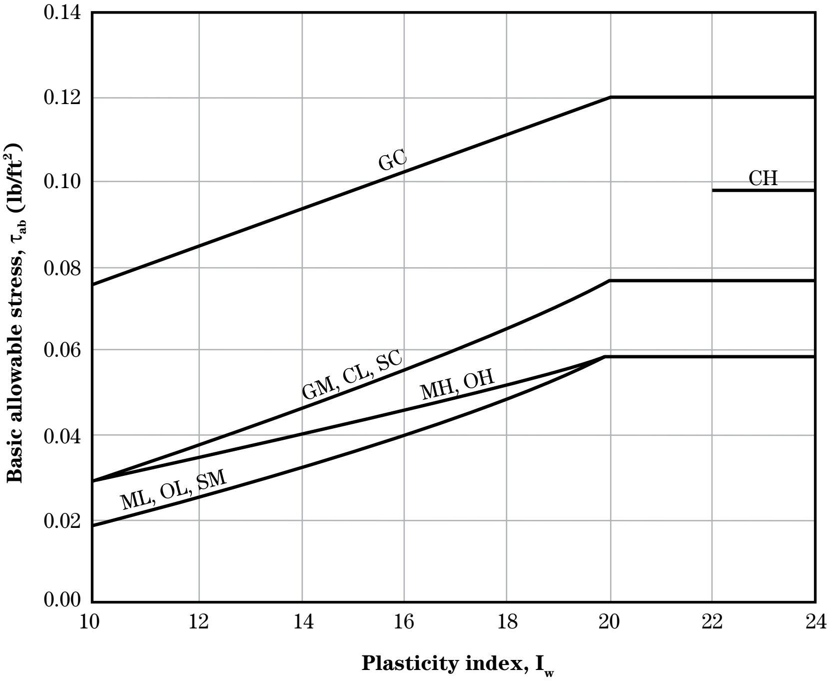
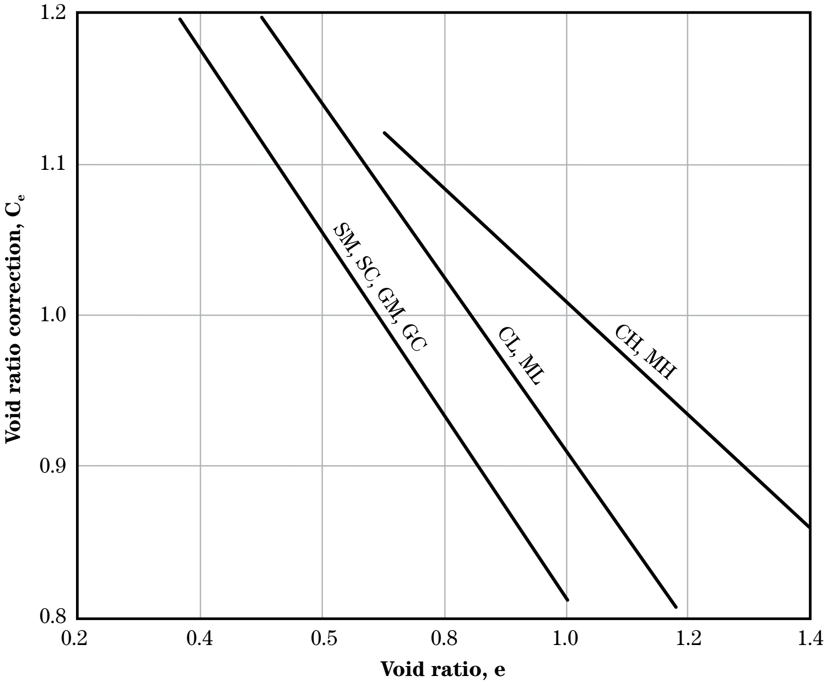


Figure 8–24 Void ratio correction factor for cohesive soils



Example problem: Threshold channel design of a grass-lined channel

Given: A vegetated floodway is to be constructed to bypass flood flows around an urban area. HEC–RAS computer program has been used to analyze the hydraulics of a preliminary design. The proposed floodway has a trapezoidal shape with bottom width of 50 feet and side slopes of 3H:1V. The floodway n value is 0.03. The floodway will have straight and curved reaches with radii of curvature equal to 300 feet. Energy slopes range from 0.00026 to 0.00060, with respective maximum flow depths of 11.0 feet and 10.5 feet.

Soils laboratory test data indicate that the floodway will be excavated into a CL soil, with plasticity index greater than 20, and void ratio of 1.2. Planned vegetation is a grass mixture of brome and Kentucky bluegrasses. Vegetation is expected to be maintained at a fair stand, equivalent to a retardance class of D.

Determine: Allowable stresses and actual stresses and compare.

Solution:

Step 1 Determine allowable stresses. Note that different references subscript the symbol for stress, τ, differently. TR–25 refers to allowable stress with the symbol, τ_L; the L stands for limiting.

a. Allowable soil stress

Basic allowable soil stress,

$\tau_{ab} = 0.076$ lb/ft^2 (fig. 8–23; CL soil and plasticity index, $I_w > 20$)

Void ratio correction factor, $C_e = 1.48 - 0.57e$

$C_e = 0.8$ (fig. 8–24; void ratio, e = 1.2)

Allowable soil stress, $\tau_a = \tau_{ab}\,C^2_e$

$\tau_a = 0.076\ (0.8)^2 = 0.0486$ lb/ft^2

b. Allowable vegetal stress

$C_I = 4.44$ (table 8–9), retardance class of D)

$\tau_{va} = 0.75\ C_I$

$\tau_{va} = 0.75\ (4.44) = 3.33$ lb/ft^2

Step 2 Determine actual stresses (straight reaches). Note that TR–25 refers to actual stress with the symbol, τ, subscripted for bed, sides.

a. Actual soil stress

$$\tau_e = \gamma dS\left(1 - C_F\right)\left(\frac{n_s}{n}\right)^2$$

For minimum slope of 0.00026 and d = 11.0 ft

γ = 62.4 lb/ft^3

n = 0.0156 (note TR–25 uses the symbol n_t)

C_F = 0.75 (0.8) = 0.6 (table 8–10; reduced 20% for fair stand of grass)

n = 0.03 (for the entire channel)

$\tau_e = (62.4)\ (11.0)\ (0.00026)\ (1 - .6)(0.0156/0.03)^2$

$\tau_e = 0.0193$ lb/ft^2 ,which is less than the allowable soil stress of 0.0486 lb/ft^2

For maximum slope of 0.0006 and d = 10.5 ft

$\tau_e = (62.4)\ (10.5)\ (0.0006)\ (1 - 0.6)\ 0.0156/0.03)^2$

$\tau_e = 0.0425$ lb/ft^2, which is less than the allow able soil stress of 0.0486 lb/ft^2

b. Actual vegetal stress

$$\tau_v = \left(\gamma dS_e\right) - \tau_e$$

For minimum slope,

$\tau_v = (62.4)(11.0)(0.00026) - (0.0193)$

$\tau_v = 0.1592$ lb/ft^2

For maximum slope,

$\tau_v = (62.4)(10.5)(0.0006) - (0.0425)$

$\tau_v = 0.3506$ lb/ft^2

which is less than the allowable vegetal stress of 3.33 pounds per square foot.

Example problem: Threshold channel design of a grass-lined channel—Continued

Step 3 Determine actual soil stress (curved reaches), τ_{ec}.

For minimum slope of 0.00026,

$$\frac{w}{r_c} = \frac{\text{water width}}{\text{radius of curvature}}$$

$$\frac{w}{r_c} = \frac{\left[(11.0)(5)(2)+50\right]}{300} = 0.533$$

$$\frac{\tau_{ec}}{\tau_e} = 2.1$$

$$\tau_{ec} = 2.1(0.0193) = 0.0405 \text{ lb/ft}^2$$

which is less than the allowable soil stress of 0.0486 lb/ft^2

For maximum slope of 0.0006,

$$\frac{w}{r_c} = \frac{\left[(10.5)(5)(2)+50\right]}{300} = 0.517$$

$$\frac{\tau_{ec}}{\tau_e} = 2.05$$

$$\tau_{ec} = 2.05(0.0425) = 0.0870 \text{ lb/ft}^2$$

which is greater than the allowable soil stress of 0.0486 pounds per square foot. The curve sections with energy slope of 0.0006 should be considered for change of planform (less curvature or flatter energy slope) or armoring.

654.0807 Allowable velocity and shear stress for channel lining materials

Allowable velocity and allowable shear stress values for a number of different channel lining materials are presented in table 8–11. Data in the table were compiled from many sources by Fischenich (2001b). Information for specific soil bioengineering practices is provided in NEH654 TS14I. Ranges of allowable velocity and shear stress, therefore, are presented in the table. For manufactured products, the designer should consult the manufacturer's guidelines to determine thresholds for a specific product.

The values in table 8–11 relate to cross-sectional averaged values. The data typically come from flumes where the flow is uniform and does not exhibit the same level of turbulence as natural channels. The recommended values are empirically derived. The designer should consider modifying tabular values based on site-specific conditions such as duration of flow, soils, temperature, debris, ice load in the stream, and plant species, as well as channel shape and planform (Hoag and Fripp 2002). To account for some of these differences, Fischenich recommends that a factor of safety of between 1.2 and 1.3 be applied to the tabular values.

The allowable limits of velocity and shear stress published by manufacturers for various products are typically developed from studies using short durations. Studies have shown that extended flow duration reduces the erosion resistance of many types of erosion control products as shown in figure 8–25. Fischenich (2001b) recommends a factor of safety be applied when flow duration exceeds a couple of hours.

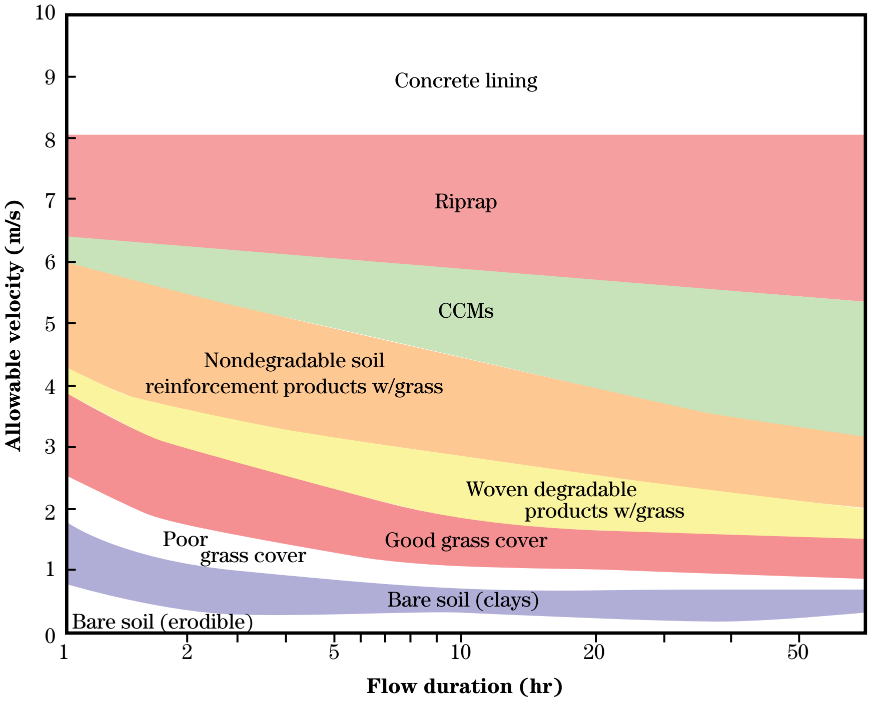
Table 8–11 Allowable velocity and shear stress for selected lining materials[1/]

Boundary category	Boundary type	Allowable velocity (ft/s)	Allowable shear stress (lb/ft^2)	Citation(s)
Temporary degradable reinforced erosion control products (RECP)	Jute net	1–2.5	0.45	B, E, F
	Straw with net	1–3	1.5–1.65	B, E, F
	Coconut fiber with net	3–4	2.25	B, F
	Fiberglass roving	2.5–7	2	B, E, F
Nondegradable RECP	Unvegetated	5–7	3	B, D, F
	Partially established	7.5–15	4–6	B, D, F
	Fully vegetated	8–21	8	C, F
Hard surface	Gabions	1–19	10	A
	Concrete	>18	12.5	E

1/ Ranges of values generally reflect multiple sources of data or different testing conditions

(Goff 1999)
(Gray and Sotir 1996)
(Julien 1995)
(Kouwen, Li, and Simons 1980)
(Norman 1975)
(TXDOT 1999)

Figure 8–25 Effect of flow duration on allowable velocities for various channel linings



*For slopes <5%

654.0808 Basic steps for threshold channel design in stream restoration projects

The following step-by-step procedure for design of natural threshold channels is from American Society of Civil Engineers (ASCE) Manual 54 (ASCE 2006). This method is applicable when width, depth, and slope are design variables; for example, slope can be varied and is not dictated by geology or other constraints. Although the procedure is presented as a series of linear steps, the actual design process is iterative, and design variables should be refined as the process proceeds from preliminary to final results. This method provides only the average channel cross-sectional dimensions. Channel variability in width and depth, and riffles and pools may be added later. Threshold methods should be used to determine the stability of the channel in areas where velocity and shear stress are increased, such as constrictions and riffles.

Step 1 Determine design bed-material gradation/ channel boundary.

Determine the design bed-material gradation and the design discharge. The design discharge is the maximum flow at which channel stability is required. Channel-forming discharge theory is not generally used as the design flow for threshold channel design because the boundary of the channel will be immobile, and natural fluvial process will not be able to adjust channel dimensions.

Step 2 Determine preliminary width.

Use hydraulic geometry or regime formula (described in the NEH654.09 on alluvial channel design) with the design discharge to compute a preliminary average flow width. It is appropriate to use hydraulic geometry theory in threshold channels, even though the boundary is immobile. This is because natural flow processes will tend to form helical cells of specific widths; if the channel is too wide, ineffective flow areas will develop in the channel. If wash load is available in the stream, it may become trapped in these ineffective flow areas, and the channel will eventually narrow, even though the boundaries are immobile, and the calculated average velocity is sufficient to move the wash load.

Step 3 Estimate critical shear stress/velocity.

Using the design bed-material size gradation, estimate the critical bed stress. This may be determined using a Shields parameter approach with a factor of safety, the Gessler probability approach, or the Lane tractive force approach. If the allowable velocity approach is used, determine the allowable velocity from published tables.

Step 4 Determine flow resistance (Manning's n).

Use the bed-material size, estimated channel sinuosity, bank vegetation, and flow depth to estimate a flow resistance coefficient. The Cowan (1956) method is applicable for channels with multiple sources of roughness. If resistance due to bars and bedforms are not important, formulas such as those proposed by Limerinos (1970) or Hey (1979) may be used to compute resistance coefficients. Bathurst (1997) provides a review of flow resistance equations and their proper application.

Step 5 Calculate depth and slope.

Using the continuity equation and a uniform flow equation, compute the average depth and bed slope needed to pass the design discharge. Sinuosity may be computed by dividing the valley slope by the bed slope. Adjustment of the flow resistance coefficient for sinuosity and reiteration may be required.

Step 6 Determine planform.

Planform is a function of the sinuosity and meander wavelength. Although threshold channels are not self forming, it is appropriate to use the same techniques outlined in NEH654.09 on alluvial channels to determine planform in threshold channels.

Step 7 Assess for failure and sediment impact.

After the threshold channel design is complete, an assessment of failure should be made. This involves determination of the discharge at which the allowable velocity or shear stress would be exceeded. Confirmation should be made that the channel boundary will not become active, in which case alluvial design techniques should be examined. In addition, the possible impacts of sediment deposition should be assessed. More information on sediment impact assessments is provided in NEH654.13.

Example problem: Threshold channel design

Given:

Valley slope = 0.007 (this is the maximum possible slope)

Bed material D_{50} = 45 mm = 0.148 ft

Bed material D_{75} = 55 mm = 2.17 in

Bed material D_{84} = 60 mm = 0.197 ft

Channel side slope = 3H:1V

Specific weight of sediment = 165 lb/ft^3

Water temperature = 68 °F

Design discharge is 25-year storm = 400 ft^3/s

Problem:

Design a threshold channel to convey the design discharge.

Note: There is no unique solution with the given design constraints.

Step 1 Estimate channel width using hydraulic geometry equation (fig. 9–9, NEH654.09):

$$W = 2.03Q^{0.5}$$
$$W = 2.03(400)^{0.5}$$
$$W = 41 \text{ ft}$$

Note from figure 9–9 in NEH654.09 that widths between 22 and 74 feet are within the 90 percent single response confidence bands. If there are width constraints on the project design they may be applied here. If there are minimum depth requirements, a narrower width may be necessary. It should also be noted that the figure refers to measurements of top width. However, the difference between the top and bottom width is within the error bounds. This example will proceed with the mean width of 41 feet.

Step 2 Determine critical Shields parameter (fig. 8–10):

Initially, assume fully turbulent rough flow where grain Reynolds number >400.

$$\tau^* = 0.047$$

Step 3 Calculate critical shear stress:

$$\tau_c = \tau^*(\gamma_s - \gamma_w)D_{50}$$
$$\tau_c = (0.047)(165 \text{ lb/ft}^3 - 62.4 \text{ lb/ft}^3)(0.148 \text{ ft})$$
$$\tau_c = 0.714 \text{ lb/ft}^2$$

Step 3a. Calculate critical shear stress using the Lane equation:

$$\tau_{ab} = 0.4D_{75}$$
$$\tau_{ab} = 0.4(2.17)$$
$$\tau_{ab} = 0.868 \text{ lb/ft}^2$$

Note that the Lane equation provides a higher critical shear stress. This information will be useful in evaluating the sensitivity of the final design channel.

Step 4 Calculate depth when applied shear stress equal to critical shear stress:

$$d = \frac{\tau_c}{\gamma S}$$
$$d = \frac{(0.714 \text{ lb/ft}^2)}{(62.4 \text{ lb/ft}^2)(0.007)}$$
$$d = 1.63 \text{ ft}$$

Step 5 Calculate area and hydraulic radius for channel:

$$A = d(dz + W)$$
$$A = (1.63)[1.63(3) + 41]$$
$$A = 74.8 \text{ ft}^2$$

$$R = \frac{A}{P} = \frac{A}{\left(W + 2d\sqrt{1+z^2}\right)}$$
$$R = \frac{74.8}{\left[41 + 2(1.63)\sqrt{1+3^2}\right]}$$
$$R = 1.46 \text{ ft}$$

Example problem: Threshold channel design—Continued

Step 6 Check for fully rough flow:

$$R^* = \frac{D_{50}\sqrt{gRS}}{\upsilon}$$

$$R^* = \frac{[0.148]\left[\left(32.2\ \text{ft/s}^2\right)(1.46\ \text{ft})(.007)\right]^{0.5}}{1.082\times10^{-5}\ \text{ft}^2/\text{s}}$$

$$R^* = 7{,}850$$

R* is greater than 400, therefore, fully rough flow assumption was OK.

Step 7 Calculate Manning's roughness coefficient:

Since this is a gravel-bed stream, assume no form loss and use the Limerinos equation:

$$n = \frac{0.0926R^{\frac{1}{6}}}{1.16 + 2.03\log\frac{R}{D_{84}}}$$

$$n = \frac{(0.0926)(1.46)^{\frac{1}{6}}}{\left[1.16 + 2.03\log\left(\frac{1.46}{0.197}\right)\right]}$$

$$n = \frac{(0.0926)(1.46)^{\frac{1}{6}}}{\left[1.16 + 2.03\log\left(\frac{1.46\ \text{ft}}{0.197\ \text{ft}}\right)\right]}$$

$$n = .0337$$

Step 8 Calculate velocity and discharge:

$$V = \frac{1.49}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$$

$$V = \frac{(1.49)(1.46)^{\frac{2}{3}}(.007)^{\frac{1}{2}}}{(.0337)}$$

$$V = 4.76\ \text{ft/s}$$

$$Q = VA = (4.76\ \text{ft/s})\left(74.8\ \text{ft}^2\right)$$

$$Q = 356\ \text{ft}^3/\text{s}$$

Step 9 Modify slope until design discharge is achieved.

This iterative process can be achieved using a spreadsheet similar to the one shown in figure 8–26. The slope is decreased until the design discharge can be conveyed, without exceeding the critical shear stress. The calculated maximum slope is 0.00643. The channel planform would have a sinuosity of 1.09. The spreadsheet can also be used to evaluate the sensitivity of the solution. For example, if Gessler's criterion is applied that a stable bed should have a probability of 0.65 for the grains to stay in place, the critical shear stress is divided by 1.25 (fig. 8–13). This yields a maximum slope of 0.00473 and a sinuosity of 1.48. The solution is very sensitive to the critical shear stress. An alternative to adjusting the channel slope is to adjust the channel width between limits of the 90 percent single response confidence limits.

If movement of the bed material in this channel is a concern, select the solution where the probability of the grains on the bed to stay in place is 0.65.

Base width = 41 ft
Depth = 1.93 ft
Slope = 0.0047
Sinuosity = 1.48

As a final check, the designer should assess if the incoming sediment load can be transported through the design channel without depositing. If there is a significant incoming bed-material load, this is not a threshold channel, and alluvial channel design methods should be used. This sediment assessment is addressed in more detail in NEH654.13.

Example problem: Threshold channel design—Continued

Figure 8–26 Spreadsheet calculations for threshold channel using critical shear stress

Valley slope	**0.007**
Width	**41 ft**
Side slope	**3**
Critical shear	**0.714 lb/ft^2**
D_{84}	**0.197 ft**

Iteration	**Slope**	**Sinuosity**	**Max depth (ft)**	**Area (ft^2)**	**R (ft)**	***n***	**Velocity (ft/s)**	**Discharge (ft^3/s)**
1	0.007	1.00	1.63	75.0	1.46	0.0337	4.76	357
2	0.0065	1.08	1.76	81.5	1.56	0.0334	4.84	394
3	0.0064	1.09	1.79	82.9	1.58	0.0333	4.86	403
4	0.00642	1.09	1.78	82.6	1.58	0.0334	4.86	401
5	0.00643	1.09	1.78	82.5	1.58	0.0334	4.85	400

Spreadsheet calculations for threshold channel using 0.8 times critical shear stress

Critical shear	**0.571 lb/ft^2**

Iteration	**Slope**	**Sinuosity**	**Max depth (ft)**	**Area (ft^2)**	**R (ft)**	***n***	**Velocity (ft/s)**	**Discharge (ft^3/s)**
1	0.007	1.00	1.31	58.7	1.19	0.0347	4.04	237
2	0.005	1.40	1.83	85.1	1.62	0.0333	4.37	372
3	0.004	1.75	2.29	109.5	1.97	0.0325	4.56	500
4	0.0046	1.52	1.99	93.4	1.74	0.0330	4.44	415
5	0.0047	1.49	1.95	91.2	1.71	0.0330	4.42	403
6	0.00473	1.48	1.93	90.5	1.70	0.0331	4.42	400

654.0809 Conclusion

Channels cut through bedrock or coarse bed materials, grass-lined channels, and channels with cohesive beds may be designed using threshold methods. Typically, bed-material sediment transport is negligible in a threshold channel, although fine sediments that do not interchange with the bed (wash load) may be transported through the channel. The objective of the threshold channel design procedure is to ensure that the design hydraulic parameters are less than the allowable values for the channel boundary. To provide a factor of safety, allowable design variables are typically less than the critical values for the boundary material used. Average channel velocity and shear stress are the hydraulic parameters typically used for threshold channel design. As with any stream restoration, stabilization or creation, the application of design techniques should be done with caution. In many circumstances, several techniques should be examined. For channels designed using threshold assumptions and procedures, the designer must confirm that deposition or erosion will not change the boundary conditions and result in alluvial channel behavior.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654 Stream Restoration Design
National Engineering Handbook

Chapter 9 Alluvial Channel Design

Issued August 2007

Cover photo: In an alluvial channel, there is a continual exchange of the channel boundary material with the flow.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 9 Alluvial Channel Design

Contents

Tables

Figures

Chapter 9 Alluvial Channel Design

654.0900 Purpose

Alluvial channel design techniques are generally used for movable boundary systems and streams with beds and banks made of unconsolidated sediment particles. In an alluvial channel, there is a continual exchange of the channel boundary material with the flow. Therefore, the design of an alluvial channel as part of a restoration project requires an assessment of sediment continuity and channel performance for a range of flows. A wide variety of sources and techniques are available to the designer for designing stable alluvial channels. This chapter provides an overview and discussion of some of the most common alluvial channel design techniques. The use and application of regime, analogy, hydraulic geometry, and analytical methods are presented and described. Examples have been provided to illustrate the methods.

654.0901 Introduction

The channel geometry and flow conditions in an alluvial stream are interrelated. The river's shape and size are determined by the river itself through the processes of erosion, sediment transport, sedimentation, and resuspension. Alluvial rivers are free to adjust section, pattern, and profile in response to hydraulic changes. Alluvial streams flow through channels with bed and banks made of sediments transported by the stream under-current conditions. In alluvial streams, the independent variables that drive the hydraulic design of the channel are discharge, sediment inflow, and bed and bank-material composition. The dependent or design variables are width, depth, slope, and planform.

Alluvial channel design approaches fall into five general categories: regime, analogy, hydraulic geometry, extremal, and analytical methods. Each method has its advantages and disadvantages, depending on the stream reach being restored.

A summary of alluvial channel design methods described in this chapter is presented in table 9–1. The table summarizes the basic theory and assumptions behind each method, input requirements for using the method, and basic limitations associated with each method. Table 9–1 is a general guide, recognizing that exceptions will be encountered. Designs can become complex, especially in wood-dominated systems or when some of the necessary input data is contradictory or missing. When there is uncertainty regarding the appropriate technique, it is recommended that the designer use several of what appear to be the most appropriate techniques and look for agreement on critical design elements.

Table 9–1 Characteristics of alluvial channel hydraulic design methods

Design method	Theory and assumptions	Requirements	Limitations
Regime	Dependent channel dimensions of width, depth, and slope can be determined from regression relationships with independent variables of channel-forming discharge, bed gradation, and sediment-inflow concentration. Based on the assumption that alluvial canals will evolve to the same stable channel dimensions, given the same independent driving variables	Channel-forming discharge and inflowing sediment concentration must be estimated. Bed and bank characteristics must be determined from field evaluations	Applicability is limited to channels similar to those used to develop the regression equations. Most of the data came from irrigation canals. Froude numbers should be less than 0.3, sediment transport low, and discharge relatively uniform, similar to flow in canals
Analogy	Channel dimensions from a reference reach can be transferred to another location. Based on the assumption that alluvial streams will evolve to the same stable channel dimensions, given the same independent driving variables	Reference reach must be stable and alluvial. Reference reach must have same channel-forming discharge, valley slope, and similar bed and bank characteristics. Watershed conditions must be similar	Difficult to find a suitable reference reach, especially in developed watersheds. Dependent design variables from the reference reach must be used as a combined set
Hydraulic geometry	Dependent channel dimensions of width, depth, and slope can be determined from regression relationships with independent variables. Independent variables may include one or more of the following: channel-forming discharge, drainage area, bed gradation, bank conditions, or sediment-inflow concentration. Based on the assumption that alluvial streams will evolve to the same stable channel dimensions, given the same one or two independent driving variables	Regression curves must be developed from stable and alluvial reaches and from physiographically similar watersheds. Channel-forming discharge must be estimated. Bed and bank characteristics must be determined from field evaluations	Applicability is limited to channels similar to those used to develop the regression equations. There is a high degree of uncertainty associated with the assumptions that (1) channel dimensions can be determined by a single independent variable; and (2) and with the determination of the channel-forming discharge. Design is only for the channel-forming discharge. Modifications may be required to convey higher flows. Sediment transport is typically low

Table 9–1 Characteristics of alluvial channel hydraulic design methods—Continued

Design method	Theory and assumptions	Requirements	Limitations
Extremal hypothesis	Alluvial channels will adjust channel dimensions so that energy expenditure is minimized. Depth and sediment transport can be calculated from physically based equations including continuity, hydraulic resistance and sediment transport. Typically, these equations are based on the assumptions of fully turbulent, hydraulically rough and gradually varied flow	Channel-forming discharge and inflowing sediment concentration must be estimated. Estimates of bed-material gradation and resistance coefficients must be obtained. Appropriate hydraulic resistance and sediment transport equations must be solved simultaneously, which requires a computer program or detailed spreadsheet analysis	Support for the extremal hypothesis is divided. Many stable alluvial channels exist at conditions different from the computed extremal condition
Analytical	Depth and sediment transport can be calculated from physically based equations including continuity, hydraulic resistance, and sediment transport. Typically, based on the assumptions of fully turbulent, hydraulically rough, gradually varied flow	Channel-forming discharge and inflowing sediment concentration must be estimated. Bank characteristics must be determined from field evaluations. Estimates of bed-material gradation and resistance coefficients must be obtained. Appropriate hydraulic resistance and sediment transport equations must be solved simultaneously, which requires a computer program or detailed spreadsheet analysis	A family of solutions is obtained from the hydraulic resistance and sediment transport equations. Another method must be used to obtain the third independent variable

654.0902 Alluvial channel design variables

Alluvial channels are different from threshold channels in that the channel boundary is mobile, and sediment transport is significant. The National Engineering Handbook (NEH) 654.08 presents a basic overview of threshold channel design techniques. In an alluvial channel design, stability depends on both the channel geometry and composition of the boundary materials. Alluvial channels are capable of adjustment. Stable natural alluvial channels typically form their geometry by moving boundary material. Channel-forming discharge is typically used to determine preliminary channel dimensions, but the full range of expected discharges should be used to determine final dimensions. The hydraulic design variables of width, depth, slope, and planform are the primary dependent variables in an alluvial channel (table 9–2). Their magnitudes are determined by the independent variables of sediment inflow, water inflow, and bank composition. The downstream water surface elevation is an independent variable that could have a significant effect on the dependent variables in some cases. Boundary resistance along the channel banks and sometimes along the bed can be both dependent and/or independent, depending on local circumstances.

Design of alluvial irrigation canals has traditionally been accomplished using regime methods. Regime methods rely on regression equations that are used to determine the dependent variables. The independent variables of discharge and sediment concentration are single-valued functions and, therefore, are applicable to cases where the discharge is relatively uniform with time. Regime methods are applicable for low-energy systems with low sediment transport.

Table 9–2 Alluvial channel design variables

Dependent variables	Independent variables
Width	Sediment inflow
Depth	Water inflow
Slope	Bank composition
Planform	

The design philosophy for an alluvial channel to be designed as a natural stream, as part of a restoration project, is to employ both geomorphic principles and physically based analytical techniques to determine the design variables. Average magnitudes for width, depth, and slope are determined first. Planform and other features such as riffles, pools, and habitat enhancement structures are added later. The initial or preliminary average channel geometry is determined using a single channel-forming discharge.

Sizing the channel for the channel-forming discharge promotes channel stability. Project constraints may not allow the channel geometry to fit the dimensions suggested by the channel-forming discharge, but an effort should be made to be as close as possible to the stable channel geometry to reduce project maintenance costs. Later in the design process, a full range of discharges is used to evaluate the channel design and emulate the full range of natural discharges. The initial design, however, may need to be adjusted.

Analytical techniques are employed to ensure that the combinations of design variables are compatible. With three unknowns, three equations are required to determine the magnitude of each design variable. A hydraulic resistance equation, such as Manning's equation, can be one design equation. A sediment transport equation, such as Meyer-Peter and Müller's equation can be the second design equation. Resistance and sediment transport equations are well established and can be used with a reasonable level of confidence in the design process. One additional equation is needed. Four alternatives are considered to determine this third equation: analogy methods, hydraulic geometry relationships, constraint of one of the variables, or adopting an extremal hypothesis.

654.0903 Regime methods

Regime methods were introduced by British engineers in the late nineteenth century to design and operate extensive irrigation systems in India. These canals were excavated into fine sand-bed material and carried their design discharge within the channel. Sediment entered the canals through the canal head works. The objective of channel design was to set the channel dimensions so that the inflowing sediment load would be passed without significant scour or deposition. Channels that carried their design flow without significant degradation or aggradation were said to be in regime. Data collected from these regime channels were used to develop relationships between hydraulic and sediment variables deemed to be significant. Most regime formulations include relationships to calculate channel width, depth, and slope as functions of channel-forming (or dominant) discharge and bed-material size.

One of the major deficiencies of the regime approach is that the equations often contain empirical coefficients that must be estimated primarily using judgment and experience. Regime equations are typically regression equations. They should not be used in cases where the discharge, sediment transport, bed gradations, and channel characteristics of the project channel are significantly different from those used in the development of the regime relationships. In general, regime relationships are applicable to flows at low Froude numbers, in the ripple-dune regime, with low sediment transport, and relatively uniform discharges. Since many of these equations were developed using canals where the flows remain in the channel, they do not reflect the effects of flood plain flows in the channel formation and maintenance in a natural channel. In short, since this theory is based on steady, uniform flows in canals, a sole application of it to unsteady, nonuniform rivers is not necessarily an optimum design method, given other alternatives.

(a) Blench regime equations

Stable channel dimensions may be calculated using the Blench regime equations. These regime equations are also addressed in American Society of Civil Engineers (ASCE) Manual 54 (ASCE 2006). The data used to develop the Blench regression equations came from Indian canals with sand beds and slightly cohesive-to-cohesive banks. The sediment inflow was affected by sediment exclusion and/or ejection structures and was generally less than 30 milligrams per liter (Federal Interagency Stream Restoration Working Group (FISRWG) 1998). The equations were intended for design of canals with sand beds. The basic three channel dimensions—width, depth, and slope—are calculated as a function of bed-material grain size, channel-forming discharge, bed-material sediment concentration, and bank composition. The regression equations are not dimensionless and must be used with the units used in their derivation.

$$d = \left(\frac{F_S Q}{F_B^2}\right)^{\frac{1}{3}}$$

$$W = \left(\frac{F_B Q}{F_S}\right)^{0.5}$$

$$F_B = 1.9\sqrt{D_{50}}$$

$$S = \frac{F_B^{0.875}}{\frac{3.63g}{\upsilon^{0.25}} W^{0.25} d^{0.125} \left(1 + \frac{C}{2,330}\right)} \qquad \text{(eq. 9–1)}$$

where:

W = channel width (ft)
F_B = bed factor
F_S = side factor
Q = water discharge (ft^3/s)
D_{50} = median grain size of bed material (mm)
d = depth (ft)
S = slope
C = bed-material sediment concentration (ppm)
g = acceleration of gravity (ft/s^2)
υ = kinematic viscosity (ft^2/s)

The results are true regime values only if Q is the channel-forming discharge. However, a width, depth, and slope may be calculated for any discharge by these equations.

Blench suggested that the following values be used for the side factor:

F_S = 0.10 for friable banks
F_S = 0.20 for silty, clay, loam banks
F_S = 0.30 for tough clay banks

(b) Modified regime method

The modified regime method was introduced by Simons and Albertson (1963) and is based on data from canals in India and the United States. Simons and Albertson expanded the range of conditions used in development of previous regime equations, reducing reliance on empirical coefficients. This method is also addressed in Design of Open Channels, TR–25 (U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) (1977). Regime canals in California's Imperial Valley, the San Luis Valley in Colorado, and canals in Wyoming, Colorado, and Nebraska, were used to develop the equations. Limits of data sets used to derive the modified regime equations are given in table 9–3 (FISRWG 1998). Three sets of equations were developed for three classes of channels based on the composition of streambed and streambanks. The need for computing bed, bank, or sediment concentration factors is eliminated. Inflowing sediment concentration is not an independent variable. The equations are presented in table 9–4. These are not dimensionless equations and must be used with the units used in their derivation.

The following relationships between channel geometry and slope are applicable to all three channel types.

$$\begin{aligned} d &= 1.23R && (1 < R < 7) \\ d &= 2.11 + 0.934R && (7 < R < 12) \\ W &= 0.9P \\ W &= 0.92TW - 2.0 \end{aligned} \qquad \text{(eq. 9–2)}$$

where:
Q = channel-forming discharge (ft^3/s)
P = perimeter (ft)
R = hydraulic radius (ft)
A = channel cross-sectional area (ft^2)
V = mean channel velocity (ft/s)
W = average channel width (ft)
d = average flow depth (ft)
TW = channel top width (ft)

According to Simons and Albertson, the channel Froude number must be less than 0.3 to avoid excessive scour.

Procedure for application of the modified regime method

Step 1 Determine the channel-forming discharge. Use methods outlined in NEH654.05. The channel-forming discharge is the primary independent variable in the modified regime equations.

Step 2 Determine the character of the bed and bank materials. Determine characteristics for both the design reach and the upstream reach. Classify the boundary materials as either sand bed and sand banks, sand bed and cohesive banks, or cohesive bed and cohesive banks. Coefficients for the modified regime equations are determined from the boundary classification.

Step 3 Calculate sediment transport rate. Select an appropriate sediment transport equation, and calculate inflow to the design reach.

Step 4 Check to see if the modified regime approach is applicable. Use table 9–1.

Step 5 Determine the channel geometry and acceptable safe slope using the modified regime equations. Use table 9–4.

Step 6 Check the slope calculated with the modified regime equations. Use Manning's equation with a realistic roughness coefficient and cross-sectional geometry consistent with that determined in step 4.

After channel dimensions have been determined, it is prudent to evaluate the sediment transport capacity of the design reach and compare it to the upstream supply reach. This can be accomplished by calculating sediment transport capacity in the two reaches, using an appropriate sediment transport equation. More detail on how to make this evaluation is given in NEH654.13, which addresses sediment budget analysis.

Table 9–3 Limits of data sets used to derive Simons and Albertson modified regime equations

Data source	Median bed-material size (mm)	Banks	Discharge (ft^3/s)	Sediment concentration (ppm)	Slope (L/L)	Bedforms
United States and Indian canals	0.318 to 0.465	Sand	100 to 400	<500	0.000135 to 0.000388	Ripple to dunes
	0.06 to 0.46	Cohesive	5 to 88,300	<500	0.000059 to 0.00034	Ripples to dunes
	Cohesive 0.029 to 0.36	Cohesive	137 to 510	<500	0.000063 to 0.000114	Ripples to dunes

Table 9–4 Coefficients for modified regime equations

Q (ft^3/s)	Sand bed and sand banks	Sand bed and cohesive banks	Cohesive bed and cohesive banks
P (ft) = $C_1Q^{0.512}$	3.30	2.51	2.12
R (ft) = $C_2Q^{0.361}$	0.37	0.43	0.51
A (ft^2) = $C_3Q^{0.873}$	1.22	1.08	1.08
V (ft/s) = $C_4 (R^2S)^{1/3}$	13.9	16.1	16.0
W/d = $C_5 Q^{0.151}$	6.5	4.3	3.0

Note: * A soil is classed as cohesive if the plasticity index is >7

Example 1: Modified regime method

Given: The channel has a sand bed and cohesive banks. The channel-forming discharge is 600 ft^3/s. Use 2H:1V side slopes and $n = 0.022$.

Problem: Design a stable trapezoidal channel using the modified regime approach.

Solution:

Step 1 Compute the channel perimeter, P:

$$P = 2.51Q^{0.512}$$
$$P = (2.51)(600)^{0.512}$$
$$P = 66.4 \text{ ft} \qquad \text{(eq. 9–3)}$$

Step 2 Compute the hydraulic radius, R:

$$R = 0.43Q^{0.361}$$
$$R = (0.43)(600)^{0.361}$$
$$R = 4.33 \text{ ft} \qquad \text{(eq. 9–4)}$$

Step 3 Compute the flow area, A:

$$A = PR$$
$$A = (66.4)(4.33)$$
$$A = 288 \text{ ft}^2 \qquad \text{(eq. 9–5)}$$

or

$$A = 1.08Q^{0.873}$$
$$A = (108)(600)^{0.873}$$
$$A = 288 \text{ ft}^2 \qquad \text{(eq. 9–6)}$$

Step 4 Compute mean velocity, V:

$$V = \frac{Q}{A}$$
$$V = \frac{(600)}{(288)}$$
$$V = 2.08 \text{ ft/s} \qquad \text{(eq. 9–7)}$$

Step 5 Compute the depth, d:

When $R < 7$ ft

$$d = 1.23R$$
$$d = (1.23)(4.33)$$
$$d = 5.33 \text{ ft} \qquad \text{(eq. 9–8)}$$

Step 6 Compute the Froude number:

$$F = \frac{V}{(gd)^{0.5}}$$
$$F = \frac{(2.08)}{\left[(32.2)(5.33)\right]^{0.5}}$$
$$F = 0.159$$
$$F < 0.3 \qquad \text{(eq. 9–9)}$$

therefore, design meets this requirement for stability.

Step 7 Compute bottom width, BW:

$$W = 0.9P$$
$$W = 0.9(66.4)$$
$$W = 59.8 \text{ ft}$$
$$W = 0.92TW - 2.0$$
$$59.8 = 0.92TW - 2.0$$
$$TW = 67.2 \text{ ft} \qquad \text{(eq. 9–10)}$$

For 2H: 1V side slopes

$$BW = 67.2 - (2)(2)(5.33)$$
$$BW = 45.9 \text{ ft} \qquad \text{(eq. 9–11)}$$

Step 8 Calculate the width-to-depth ratio, W/d:

$$\frac{W}{d} = 4.3Q^{0.151}$$
$$\frac{W}{d} = 4.3(600)^{0.151}$$
$$\frac{W}{d} = 11.3 \qquad \text{(eq. 9–12)}$$

Example 1: Modified regime method—Continued

Step 9 Calculate regime slope and regime hydraulic roughness coefficient:

$$V = C_4\left(R^2 S\right)^{\frac{1}{3}} \qquad \text{(table 9-4)}$$

$$2.08 = 16.1\left[\left(4.33\right)^2 S\right]^{\frac{1}{3}}$$

$$S = 0.000115$$

$$n = 1.486AR^{\frac{2}{3}}\frac{S^{\frac{1}{2}}}{Q} \qquad \text{(Manning's equati}$$

$$n = \left(1.486\right)\left(288\right)\left(4.33\right)^{\frac{2}{3}}\frac{\left(0.000115\right)^{\frac{1}{2}}}{\left(600\right)}$$

$$n = 0.020$$

(eq. 9–13)

Step 10 Calculate the channel slope assuming uniform flow:

$$S = \frac{\left(Qn\right)^2}{\left(2.208A^2R^{\frac{4}{3}}\right)}$$

$$S = \frac{\left[\left(600\right)\left(0.022\right)\right]^2}{\left[2.208\left(288\right)^2\left(4.33\right)^{\frac{4}{3}}\right]}$$

$$S = 0.000135$$

(eq. 9–14)

Step 11 Select the channel design slope:

At this point in the design process, the designer must decide if there is more confidence in the regime hydraulic roughness coefficient, 0.020, or the assigned hydraulic roughness coefficient, 0.022. If it can be demonstrated that the regime relationship for slope fits existing data in channels physiographically similar to the design channel, the engineer might choose the regime slope. Without such calibration data, there is less uncertainty related to assigning a roughness coefficient and using the slope from the uniform flow equation.

For example:

S = 0.000135 (from step 10)

d = 5.3 ft (from step 5)

BW = 45 ft (from step 7)

Step 12 After channel dimensions have been determined, calculate the sediment transport capacity of the design reach, and compare it to the upstream supply reach. If the sediment transport capacity of the supply reach is greater than the sediment transport capacity of the design channel, either sediment removal must be provided for, or the design must be modified. This step is described in more detail in NEH654.13.

654.0904 Analogy method and reference reaches

Estimates for stable channel design width, depth, and slope in an alluvial channel can be made using channel dimensions from a similar stable channel. The channel reach from which the design dimensions are taken is frequently called a reference reach. The concept is that alluvial streams will evolve to the same stable channel dimensions, given the same independent driving hydraulic variables. To apply the analogy method, the bed and bank materials, sediment inflow, slope, valley type, and annual discharge hydrograph should be close to the same in both the design and reference reaches. When these conditions exist, the reference reach is said to be physiographically similar to the design reach. All three dependent hydraulic design dimensions from the reference reach must be used in the design reach to maintain physiographic similarity. Given these constraints, it can be difficult to find a suitable reference reach, especially in urban or developed watersheds. However, while locating a suitable reference reach can be problematic, many stream restorations have been planned, measured, and designed using this approach.

A reference reach is a site that is able to transport sediments and detritus from its contributing watershed drainage area, while maintaining a consistent profile, dimension, and plan view, over time. The reference reach with the highest level of confidence would be the existing channel in the project reach or just upstream or downstream from the project reach. If the existing channel is used as a reference reach, the channel must be stable, and there should be no significant recent or future changes in the watershed. Urbanization in the watershed can significantly change both the inflow hydrograph and the sediment inflow. The analogy method is inappropriate for streams where the entire fluvial system, or a significant part of it, is in disequilibrium.

A stable historic channel can sometimes be used as a reference reach to obtain estimates for the dependent design variables of channel width and planform. This is feasible if historical width and planform information can be determined from mapping, aerial photos, and/or soil borings. However, this technique is not applicable if the watershed sediment yield and runoff characteristics have changed over time. It cannot be assumed that the historically stable channel dimensions will continue to be stable with different water and sediment inflow.

An existing pristine or pre-settlement reach may also be used as an analog or reference reach. These reaches are rare, but can sometimes be found on USDA Forest Service or National Park Service land, as well as undeveloped portions of less developed countries. However, the use of these analogs is hindered by the same issues as for the historic channels. As a result, their use is generally not feasible to use in the vast majority of stream restoration projects, unless restoration to the pristine pre-settlement condition is the project goal.

In practice, several reference reaches with relatively similar channel-forming discharges may be used to develop a range of solutions for a single dependent design variable, typically, width. Analytical methods can then be employed to determine the other dependent design variables. Other design features such as planform, riffle and pool spacing, riffle widths, and pool depths can be determined using the reference reaches. The reference reaches must be stable and alluvial. The bed and banks in both the project and reference reaches must be composed of similar sediments. There should be no significant differences in watershed hydrology, channel flows, sediment inflow, or bed-material load between the project and reference reaches.

(a) Limitations of analogy method

It can be very difficult to find a stable alluvial reference reach with characteristics physiographically similar to the reach to be restored. The independent driving variables of sediment inflow, bed and bank material, and channel-forming discharge must be similar. The dependent design variables of slope, depth, and width must be taken together as a set.

654.0905 Hydraulic geometry method

Hydraulic geometry theory is an extension of regime theory. Regime theory was developed to design canals. Hydraulic geometry was developed for analysis of natural streams and rivers. Hydraulic geometry theory is based on the concept that a river system tends to develop in a predictable way, producing an approximate equilibrium between the channel and the inflowing water and sediment (Leopold and Maddock 1953). The theory typically relates a dependent variable, such as width, to an independent or driving variable, such as discharge or drainage area. Herein lies the primary weaknesses of hydraulic geometry theory—dependent hydraulic design variables are assumed to be related only to a single independent design variable and not to any other design variables.

To help overcome this deficiency, hydraulic geometry relationships are sometimes stratified according to bed-material size, bank vegetation, or bank material type. Rosgen (1998) suggests stream classification as an appropriate tool for differentiating hydraulic geometry relationships. Hydraulic geometry relationships are developed from field observations at stable and alluvial channel cross sections and were originally used as descriptors of geomorphically adjusted channel forms. As design tools, hydraulic geometry relationships may be useful for preliminary or trial selection of the stable channel width. Hydraulic geometry relationships for depth and slope are, however, less reliable and not recommended for final channel design.

A hydraulic geometry relationship for width can be developed for a specific river, watershed, or for streams with similar physiographic characteristics. Data scatter is expected about the developed curve, even in the same river reach. An example of a hydraulic geometry relationship between bankfull discharge and bankfull water surface width developed for a mountainous watershed can be found in Emmett (1975). Emmett collected data at 39 gaging stations in the Salmon River Drainage Basin, Idaho. The relationship between bankfull discharge and bankfull width is shown in figure 9–1. Emmett's mean regression line had a regression coefficient (r^2) of 0.92. Nevertheless, a wide range of bankfull widths were found for any specific bankfull discharge. The data scatter indicates that for a bankfull discharge of 200 cubic feet per second, the bankfull width could reasonably range between 15 and 45 feet. This range does not necessarily indicate instability or different physiographic conditions, but rather the wide range of possible stable widths for a given channel-forming discharge. Some other examples of regional hydraulic geometry studies are Leopold and Maddock (1953); Dunne and Leopold (1978); Charlton, Brown, and Benson (1978); Bray (1982); and Hey and Thorne (1986). Additional guidance for application of hydraulic geometry methods is provided in FISRWG (1998). Table 9–5 provides the range of data used to derive the hydraulic geometry width predictors for gravel-bed rivers shown in table 9–6 (FISRWG 1998; Soar and Thorne 2001).

The more dissimilar the stream and watershed characteristics are in stream reaches used to develop a hydraulic geometry relationship, the greater the expected data scatter around the regression line, and the less reliable the results. It is important to recognize that this scatter represents a valid range of stable channel configurations due to variables such as geology, vegetation, land use, sediment load and gradation, runoff characteristics, and in some geographic areas, woody debris. The composition of the bank is very important in the determination of a stable channel width. The presence and percentage of cohesive sediment in the bank and/or the amount of vegetation on the bank significantly affect the stable alluvial channel width (Schumm 1977; Hey and Thorne 1986).

Figure 9–1 Hydraulic geometry relationship for width for the Upper Salmon River Basin, ID

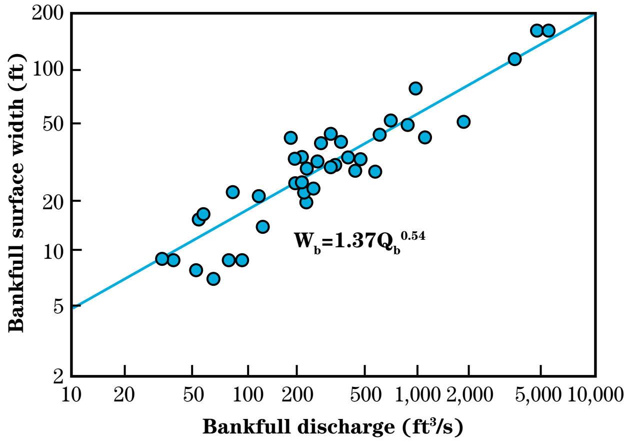


Table 9–5 Limits of data sets used to derive hydraulic geometry equation

Reference	Data source	Median bed material size (mm)	Banks	Discharge (ft^3/s)	Sediment concentration (ppm)	Slope (L/L)	Bed forms
Nixon (1959)	U.K. rivers	Gravel		700–18,000	Not measured		
Kellerhalls (1967)	U.S., Canadian, and Swiss rivers of low sinuosity, and laboratory	7–265 bed armored	Noncohesive	1.1–70,600	Negligible	0.00017–0.0131	Plane
Emmett (1975)	Salmon River, ID	11–58	Cohesive, sand and gravel	40–5,100		0.0009–0.0006	
Charlton, Brown, and Benson (1978)	Meandering U.K. rivers	33–113	Sand or gravel	95–5,500	Negligible	0.0009–0.0137	
Bray (1982)	Sinuous Canadian rivers	1.9–145		194–138,400	Mobile bed	0.00022–0.015	
Parker (1982)	British rivers Alberta–single Alberta–braided		Cohesive Little cohesion No cohesion	100–21,200 400–200,000	Active bed	0.0007–0.015 0.0002–0.015 0.0025–0.015	
Hey and Thorne (1986)	Meandering U.K. rivers	14–176	Cohesive and composite	138–15,000	Computed 0–535	0.0012–0.021	

Table 9–6 Hydraulic geometry width equations for gravel-bed rivers

$$W = aQ^b$$

Reference	Data source	Coefficient a W = m Q = m^3/s	Coefficient a W = ft Q = ft^3/s	Exponent b
Nixon (1959)	U.K.	2.99	1.65	0.5
Kellerhalls (1967)	U.S., Canada, Switzerland	3.26	1.80	0.5
Bray (1973, 1982)*	Canada	3.83	1.90	0.53
Emmett (1975)	Salmon River, ID	2.86	1.37	0.54
Charlton, Brown, and Benson (1978)	U.K.			
	Type A	3.74	2.47	0.45
	Type A_G	3.37–4.86	2.22–3.21	0.45
	Type A_T	2.62–4.11	1.73–2.71	0.45
	Type B	2.43	1.85	0.41
Parker (1982)	U.K. single channel; cohesive or vegetated banks	3.73	2.50	0.446
	Alberta single channel; little cohesion in banks	5.86	3.99	0.441
	Alberta braided; no cohesion in banks	7.08	5.25	0.417
Hey and Thorne (1986)	U.K. rivers			
	Type I	4.33	2.39	0.50
	Type II	3.33	1.84	0.50
	Type III	2.73	1.51	0.50
	Type IV	2.34	1.29	0.50

* Bankfull discharge equated to 2-year recurrence interval discharge

Note:
Type A = low sediment load
Type A_G = low sediment load and grass-lined banks
Type A_T = low sediment load and tree-lined banks
Type B = appreciable sediment load
Type I = grassy banks with no trees or shrubs
Type II = 1 to 5 percent tree/shrub cover
Type III = 5 to 50 percent tree/shrub cover
Type IV = greater than 50 percent tree-shrub cover or incised into flood plain

When a hydraulic geometry relationship is to be used for a channel design, the first choice is to use one developed from stable alluvial reaches of the project stream. It is required that the stable reaches used to develop the relationship have similar physiographic conditions to each other and the project reach. If there are no stable reaches, or if the range of discharges is insufficient, a second choice is to use other streams or tributaries in the same watershed to develop the hydraulic geometry relationship.

The third choice is to use regional relationships developed for other watersheds in the same physiographic region. The transfer of hydraulic geometry relationships developed for one watershed to another watershed should be performed with care. The two watersheds should be similar in historical land use, physiography, hydrologic regime, precipitation, and vegetation. For example, relationships developed for pristine watersheds should not be transferred to urban watersheds. Relationships developed for areas with snowmelt hydrology should not be transferred to areas dominated by convective storms. Since discharge is the variable that shapes the channel, relationships based on discharge can be transferred with more confidence than those based on drainage area, which is basically a surrogate for discharge.

Urbanized streams present particular problems in both the development and the application of hydraulic geometry relationships. Land use and runoff characteristics usually vary greatly, even within a single watershed. The multiplicity of humanmade structures, such as storm sewers, bridge openings, culverts and stormwater management facilities, and amount of impervious pavement changes the amount, duration, and timing of flows. This would be expected to greatly increase data variability. These factors make discharge more poorly correlated with drainage area and, therefore, would make discharge the better choice than drainage area as an independent variable. Locating stable, alluvial reaches in urban or developed watersheds may be difficult.

In all cases, it must be remembered that data used to develop hydraulic geometry relationships should come from stable reaches and that the watersheds and channel boundary conditions should be similar to the project channel.

(a) Procedure for developing hydraulic geometry relationships

Step 1 Locate gaging stations with long-term records. Making sure that the record is homogeneous (temporally consistent watershed conditions) as described in NEH654.05, calculate an annual peak frequency curve and a flow-duration curve. Preferably, these gaging stations will be on physiographically similar reaches of the same river as the project. A second choice is physiographically similar reaches of streams in physiographically similar watersheds. Make sure that discharge ranges are significantly greater and less than the design reach. Do not rely solely on regional relationships or drainage area versus discharge plots. These are already empirical and may not be appropriate for deriving new relationships.

Step 2 Locate stable alluvial channel reaches that can be associated with the gaging stations. Survey a typical channel cross section or several cross sections in the reach. Determine average channel top width at bankfull flow and average channel depth. Rosgen (1998) suggests gathering data from a reach length associated with two meander wavelengths or 20 top widths. Estimate channel hydraulic roughness. Using surveys or contour maps determine average channel bed slope. If the channel slope is discontinuous, use the cross sections to develop a backwater model, and calculate average energy slope. Determine bankfull discharge by using a normal depth equation or a backwater model.

Step 3 Note channel characteristics. Characteristics such as bank material composition, bed-material gradation, and bank vegetation are of interest. These characteristics may be used to ensure the physiographic similarity of the stream or to develop more refined hydraulic geometry relationships.

Step 4 Determine the channel-forming discharge. Determine the 2-year peak discharge from the annual peak frequency curve. Calculate the effective discharge using the flow-duration curve and a sediment transport curve. Determine the bankfull discharge from field measurements and backwater calculations. From these three discharges, estimate the channel-forming discharge as described in NEH654.05.

Step 5 Develop regression curve. Plot the measured channel top width versus the channel-forming discharge, and develop a power regression curve through the data. Plot confidence limits. The final plot should include the data so that the natural range of data can be observed.

(b) Generalized width predictors

Lacking data to develop more reliable hydraulic geometry relationships, generalized width predictors for various river types with different bank characteristics have been developed (Copeland et al. 2001) and are presented in figures 9–2 through 9–11. The range of data used in the development of these equations is shown in table 9–7 (Soar and Thorne 2001).

These predictors include confidence limits and may be used for general guidance when stream or watershed specific data cannot be obtained.

(c) Hydraulic geometry for meandering sand-bed rivers

Hydraulic geometry width predictors (fig. 9–2) were developed from data collected from 58 meandering sand-bed rivers in the United States (Copeland et al. 2001). These rivers were located mostly in Indiana, Illinois, Iowa, Kansas, Oklahoma, Texas, Arkansas, Louisiana, Mississippi, Kentucky, Virginia, North Carolina, and South Carolina (fig. 9–3).

Sufficient data were collected to determine both bankfull discharge and effective discharge. Data were collected from stable reaches, so bankfull discharge should be the most reliable approximator for the channel-forming discharge. In many of these meandering sand-bed rivers, the effective discharge was significantly less than the bankfull discharge. For design purposes, the bankfull discharge was used to define the width predictor. The data were divided into two sets: type T1, where there was less than 50 percent tree cover on the banks (fig. 9–4) and type T2, where there was greater than 50 percent tree cover on the banks (fig. 9–5).

Figures 9–6 and 9–7 are examples of rivers used in the development of the sand-bed hydraulic geometry relations. All sites were tree-lined to some degree; therefore, the predictors should not be used for grass-lined or thinly vegetated banks. The percentage of silt and clay in the banks was not found to be statistically significant in affecting width for these rivers, possibly because the root-binding properties of the trees were more significant in stabilizing the bank than cohesive forces.

Table 9–7 Limits of data sets used to derive generalized hydraulic geometry equations

River type	Median bed material mm	Banks	Discharge ft^3/s	Sediment concentration ppm	Slope
United States meandering sand-bed rivers	0.12–1.63	Cohesive and noncohesive	630–48,300	Significant	0.00007–0.00088
United States gravel-bed rivers	3–122	Variable	39–18,000	Negligible	0.00062–0.024
United Kingdom gravel-bed rivers	14–176	Variable	95–23,000	Negligible	0.00036–0.0021

Figure 9–2 Best-fit hydraulic geometry relationships for width for U.S. sand-bed rivers with banks typed according to density of tree cover

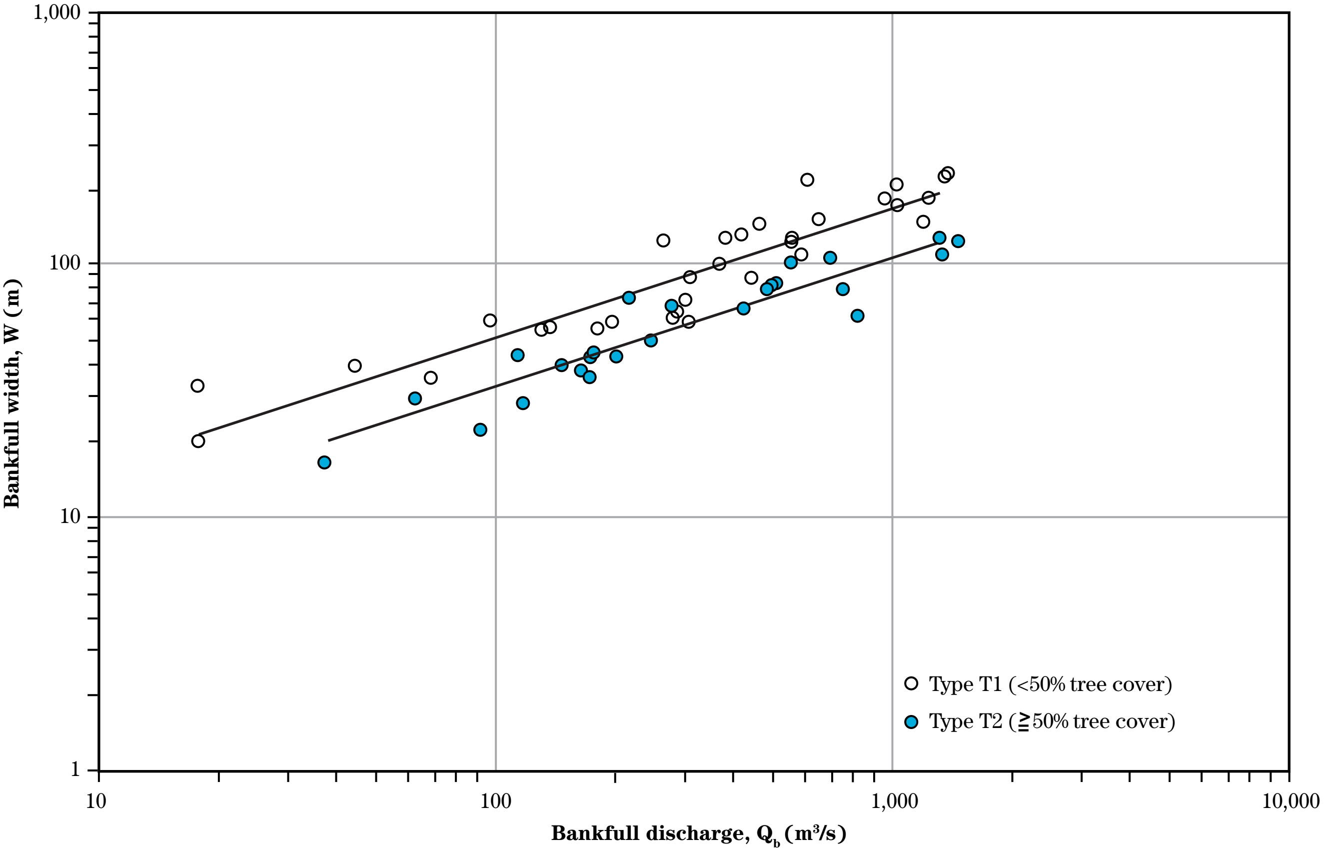


Figure 9–3 Sites used to develop U.S. sand-bed river hydraulic geometry relationships

Figure 9–4 Confidence intervals applied to the hydraulic geometry equation for width based on 32 sand-bed rivers with less than 50% tree cover on the banks (T1). SI units – m and m^3/s (English units – ft and ft^3/s)

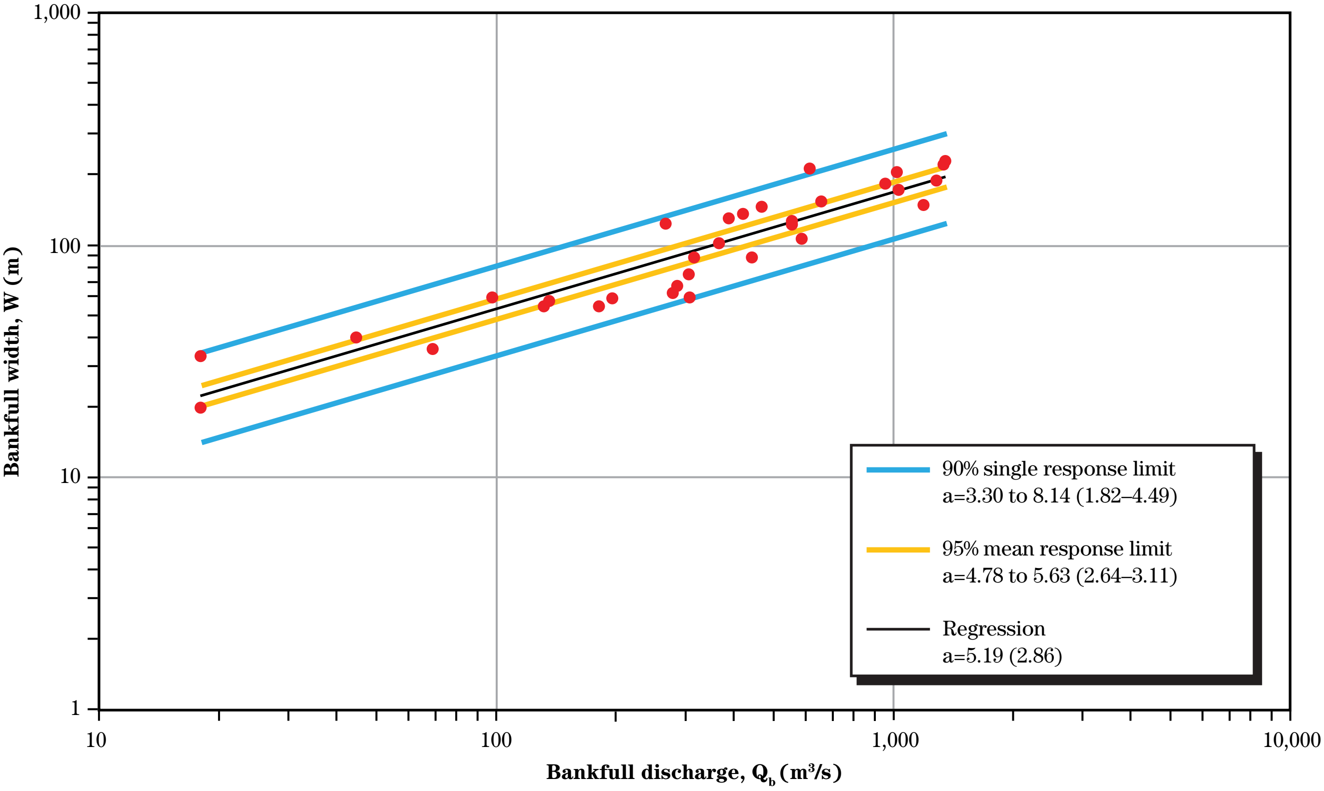


Figure 9–5 Confidence intervals applied to the width hydraulic geometry equation based on 26 sand-bed rivers with at least 50% tree cover on the banks (T2). SI units – m and m^3/s (English units ft and ft^3/s)

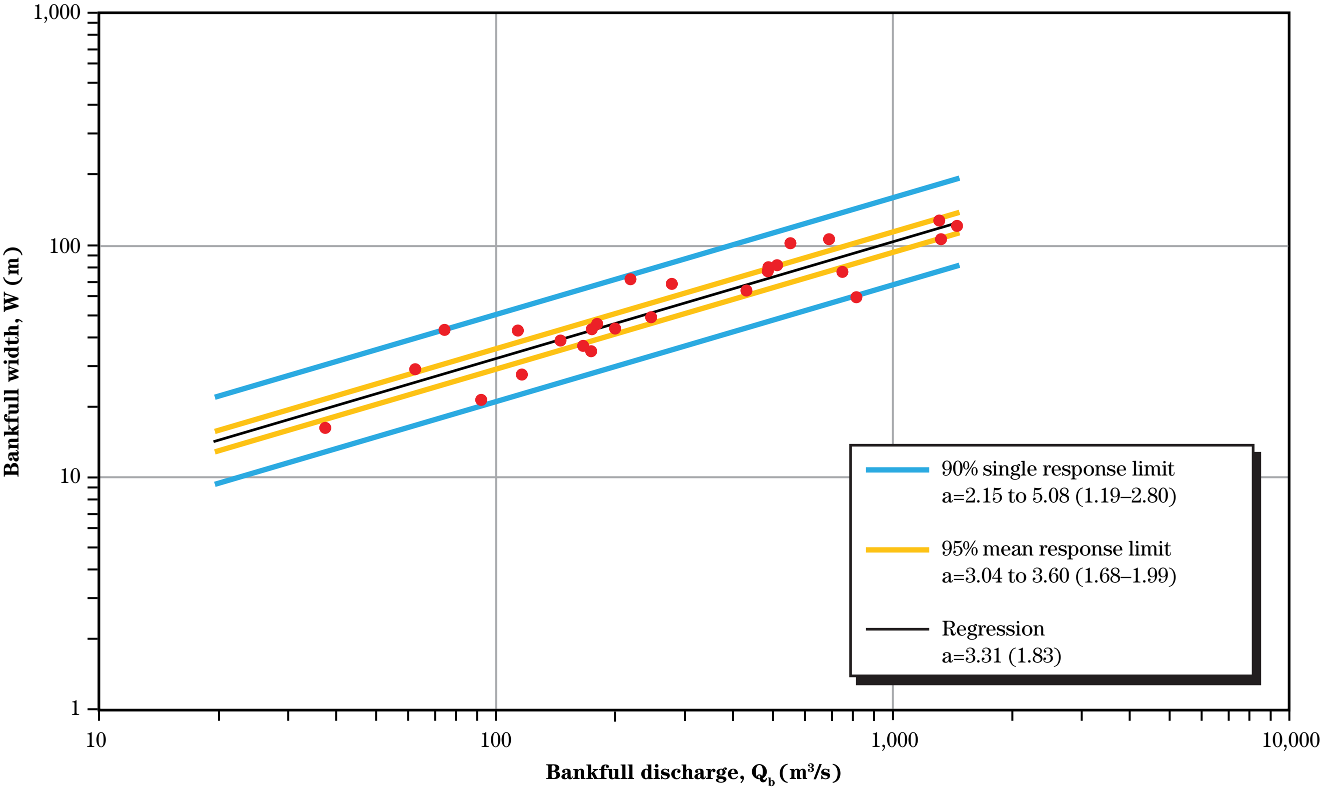


Figure 9–6 Type 1 bankline (T1), less than 50% tree cover

Figure 9–7 Type 2 bankline (T2), greater than 50% tree cover

The hydraulic geometry width predictor is expressed by the general equation:

$$W = aQ^b \qquad \text{(eq. 9–15)}$$

where:
W = channel top width
Q = channel-forming discharge
a = see table 9–8
b = see table 9–8

The hydraulic geometry width predictors each include two sets of confidence bands. The 95 percent mean response limit provides the band in which one can be 95 percent confident that the mean value of the width will occur. This is the confidence interval for the regression line and provides the range of average values of width that can be expected for a given discharge. The 90 percent single response limit provides the envelope curves that contain 90 percent of the data points. This is the confidence interval for an individual predicted value and provides the engineer with the range of possible widths that have been observed to correspond to a given discharge. The confidence interval on an individual predicted value is wider than the confidence interval of the regression line because it includes both the variance of the regression line plus the squared standard deviation of the data set.

While the equations given in table 9–8 may be used for preliminary design purposes, they are subject to several limitations. In the absence of stage-discharge relationships at each site, the bankfull discharge was calculated using Manning's equation and is subject to assumptions related to choice of a resistance coefficient. As cross-sectional geometry was used to calculate discharge, discharge is not truly independent of width in this analysis. Furthermore, only one cross section was measured at each site. Identification of the bankfull reference level, although based on field experience and geomorphic criteria, is always subject to a degree of uncertainty. These factors contribute to the observed variability in the width relationships. Finally, small rivers are not well represented in the data set; therefore, the generalized width predictors should not be applied when channel-forming discharge is less than 600 cubic feet per second in type T1 channels and less than 1,300 cubic feet per second in type T2 channels.

Table 9–8 Hydraulic geometry width predictors for meandering sand-bed rivers

$W = aQ^b$

SI units m and m^3/s (English units ft and ft^3/s)

Data source	Sample size	a	90% single response limit for a	95% mean response limit for a	b	r^2
All sand-bed rivers	58	4.24 (2.34)	2.34–7.68 (1.29–4.24)	3.90–4.60 (2.15–2.54)	0.5	0.76
Type T1: <50% tree cover	32	5.19 (2.86)	3.30–8.14 (1.82–4.49)	4.78–5.63 (2.64–3.11)	0.5	0.87
Type T2: >50% tree cover	26	3.31 (1.83)	2.15–5.08 (1.19–2.80)	3.04–3.60 (1.68–1.99)	0.5	0.85

(d) Hydraulic geometry for gravel-bed rivers

A review of the published gravel-bed river data and hydraulic geometry width predictors for North American and British rivers (Copeland et al. 2001) revealed that North American gravel-bed rivers are generally wider than those found in the United Kingdom, assuming discharge and other conditions are equal. North American data used to develop the hydraulic geometry relationship included data from Brandywine Creek in Pennsylvania (Wolman 1955), Alaskan streams (Emmett 1972), Upper Salmon River in Idaho (Emmett 1975), Colorado, New Mexico, Oregon, Pennsylvania, Tennessee, Utah, West Virginia, and Wyoming (Williams 1978), Alberta, Canada (Annable 1996), and the Rocky Mountain region of Colorado (Andrews 1984). United Kingdom data included data from Nixon (1959), Charlton, Brown, and Benson (1978) and Hey and Thorne (1986). The gravel-bed river data excluded data from braided, anastomosed, and split channel rivers. The hydraulic geometry relationships are shown in fig. 9–8. The difference in these regression curves cannot satisfactorily be explained using the site descriptions given in original publications. A possible explanation is that the United Kingdom sites have on the average more resistant banks than the North American sites. Another plausible explanation is that the North American sites on the average may be flashier. Still, another possibility is that the North American sites may be more active; that is, they may have a higher sediment load. Further research is required to validate these hypotheses.

The hydraulic geometry width predictors for North American and United Kingdom gravel-bed rivers are presented with confidence bands in figures 9–9 and 9–10, respectively. Exponents and coefficients for the hydraulic geometry equation are given in table 9–9. The gravel-bed river data comprise a wide range of bank material types (cohesive, sand, gravel, and composite banks of various strata). However, different width-discharge relationships based on different types of bank material could not be derived for the North American river data from the limited information available.

There were sufficient data available from the United Kingdom gravel-bed rivers to develop distinct width predictors based on erodible banks, low density of trees, and resistant banks, high density of trees (figs. 9–11 and 9–12). These hydraulic geometry relations may be used for preliminary design purposes, recognizing that considerable variability may occur for areas different from the streams used in the development of the equations.

(e) Uncertainty in hydraulic geometry relations

A sufficient number of data points must be measured to ensure that the results from hydraulic geometry analysis are statistically valid. For example, if any three or four random data points were used, a different relation could easily be derived. The fewer and more widely scattered the data points, the less confidence one has in any derived trend. Even with quite a few data points in a relatively homogeneous watershed, there is a great deal of scatter in the data due to natural variability.

Stable natural rivers have morphologies that broadly conform to regime or hydraulic geometry relationships. Therefore, dependent parameters of channel form can be linked to independent controls of flow regime, boundary materials, and riparian vegetation. However, rivers do not follow regime laws precisely. Every river displays local departures from the expected channel form described by morphological equations and possesses inherent variability in space and time. While it is true that natural channel forms are in general predictable, it is also true that each river is in detail unique. Regime dimensions in the natural domain should be interpreted only as representative reach-average, ideal, or target conditions, about which channel morphology fluctuates in time and space.

The coefficient of determination, r^2, in hydraulic geometry analysis numerically represents the amount of variation that can be explained by the selected independent variable. If r^2 is 1.0, there is no variation. The closer the r^2 value is to zero, the less useful the relation, and the wider the scatter in the data. The natural variability of data in a relatively homogeneous watershed such as the upper Salmon River watershed (Emmett 1975) underlines the importance of viewing the data used to develop the curve, not just the curve itself, along with statistical parameters such as r^2 values and confidence limits. If the r^2 value exceeds 95 percent for data collected in natural stream systems, it may indicate autocorrelation or too few data points. Equations given without plotted data points or statistical parameters should be verified for applicability.

Figure 9–8 Downstream width hydraulic geometry for North American gravel-bed rivers, $W = 3.68Q_b^{0.5}$ and U.K. gravel-bed rivers, $W = 2.99Q_b^{0.5}$

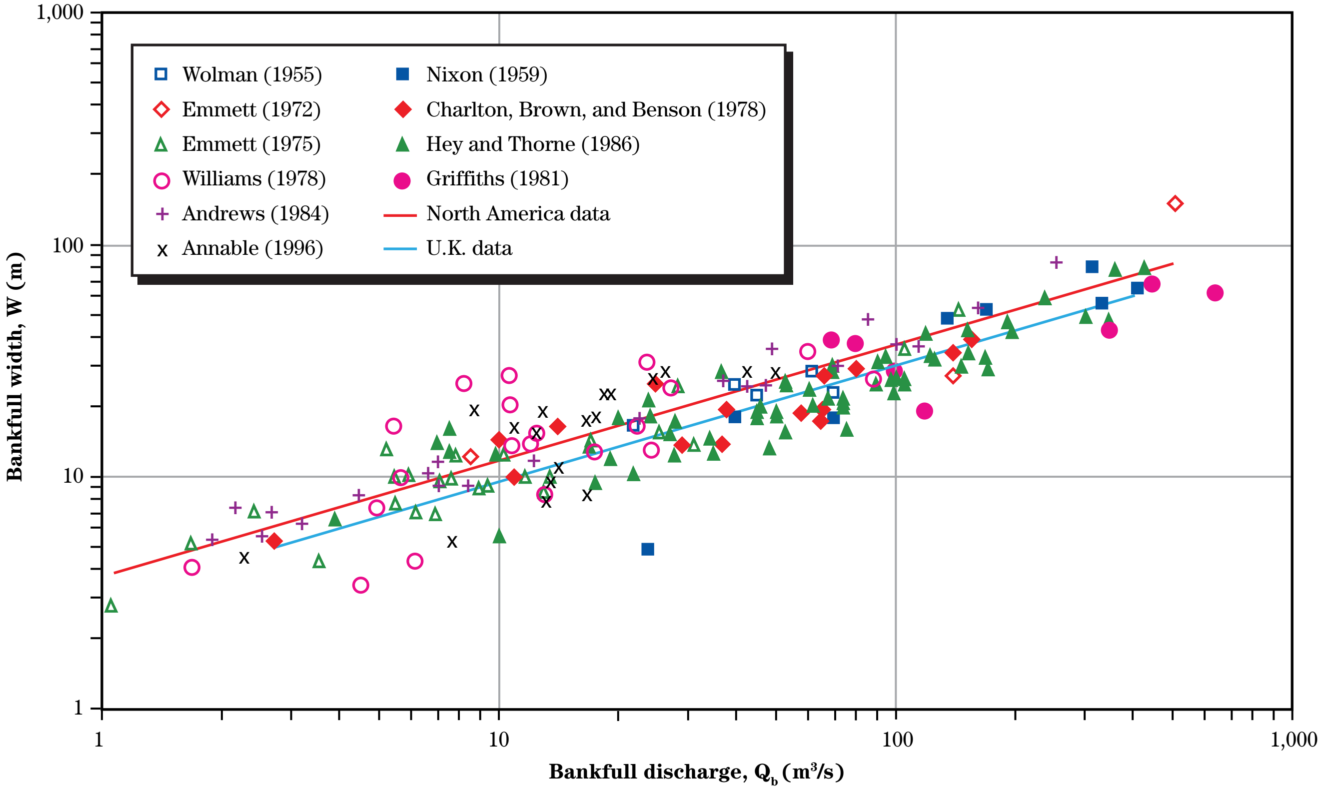


Table 9–9 Hydraulic geometry width predictors for gravel-bed rivers

$W = aQ^b$

SI units m and m³/s (English units ft and ft³/s)

Data source	**Sample size**	**a**	**90% single response limit for a**	**95% mean response limit for a**	**b**	**r^2**
All North American gravel-bed rivers	94	3.68 (2.03)	2.03–6.68 (1.12–3.69)	3.45–3.94 (1.90–2.18)	0.5	0.80
All U.K. gravel-bed rivers	86	2.99 (1.65)	1.86–4.79 (1.02–2.64)	2.83–3.16 (1.56–1.74)	0.5	0.80
<5% tree or shrub cover, or grass-lined banks (U.K. rivers)	36	3.70 (2.04)	2.64–5.20 (1.46–2.87)	3.49–3.92 (1.93–2.16)	0.5	0.92
≥5% tree or shrub cover (UK rivers)	43	2.46 (1.36)	1.87–3.24 (1.03–1.79)	2.36–2.57 (1.30–1.42)	0.5	0.92

Figure 9–9 Downstream width hydraulic geometry for North American gravel-bed rivers, $W = aQ_b^{0.5}$ with confidence bands. Based on 94 sites in North America. SI units – m and m^3/s (English units ft and ft^3/s)

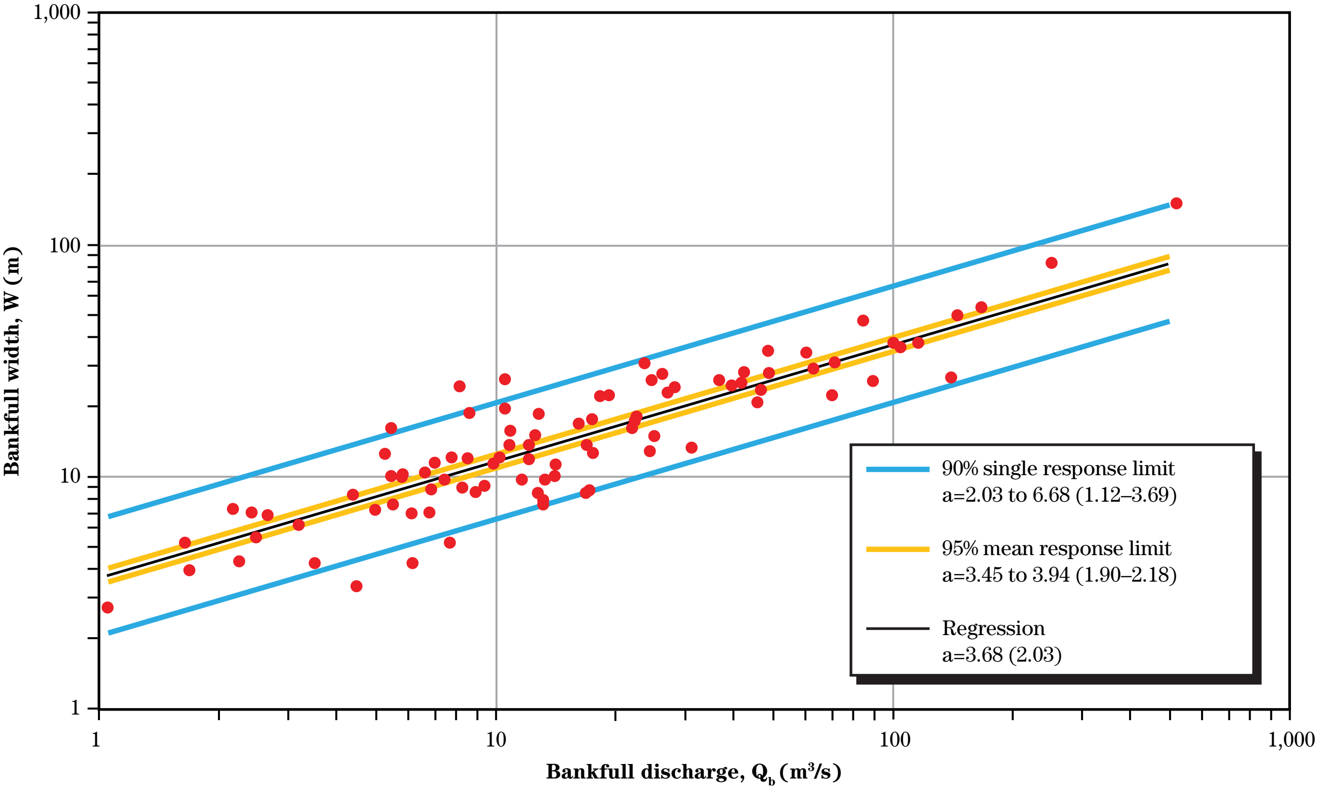


Figure 9–10 Downstream width hydraulic geometry for U.K. gravel-bed rivers, $W = aQ_b^{0.5}$ with confidence bands. Based on 86 sites in the U.K. SI units m and m^3/s (English units ft and ft^3/s)

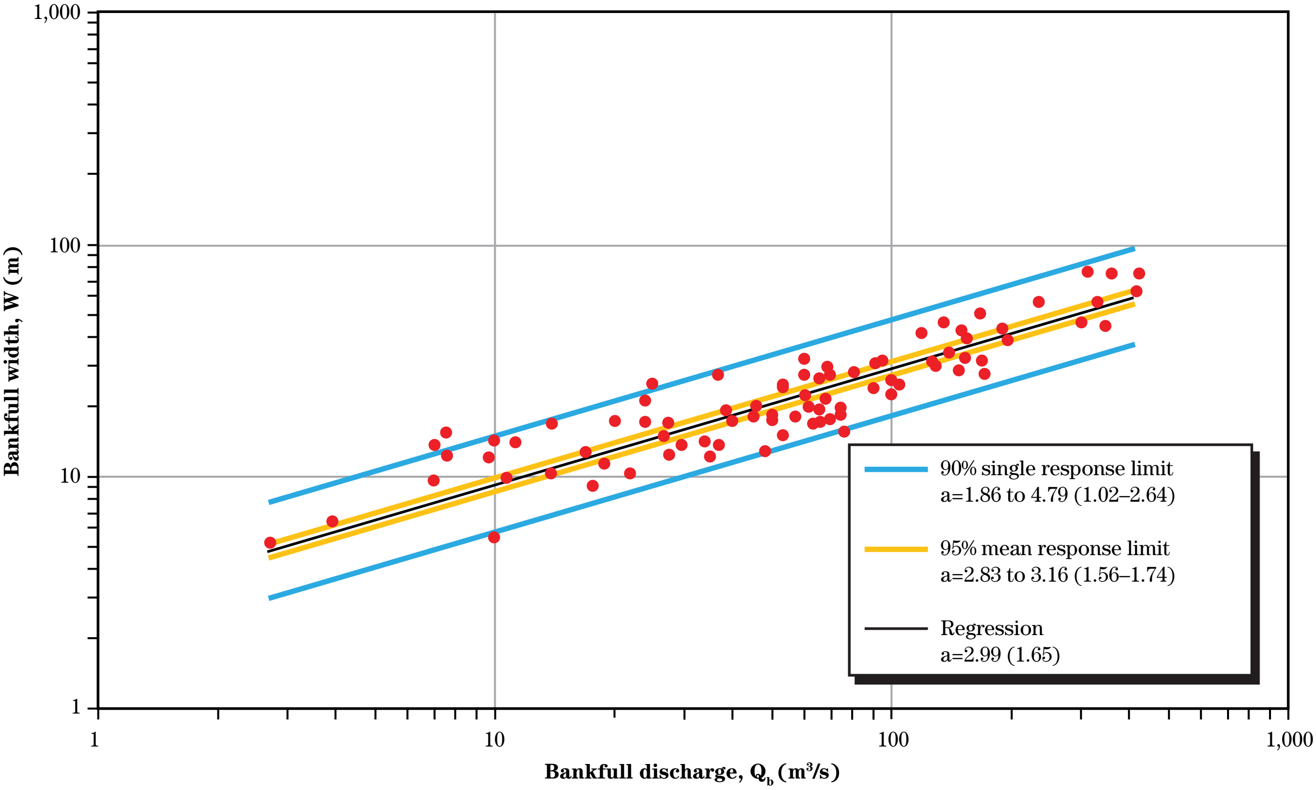


Figure 9–11 Downstream width hydraulic geometry for U.K. gravel-bed rivers, $W = aQ_b^{0.5}$ with confidence bands. Based on 36 sites in the U.K. with erodible banks. SI units m and m^3/s (English units ft and ft^3/s)

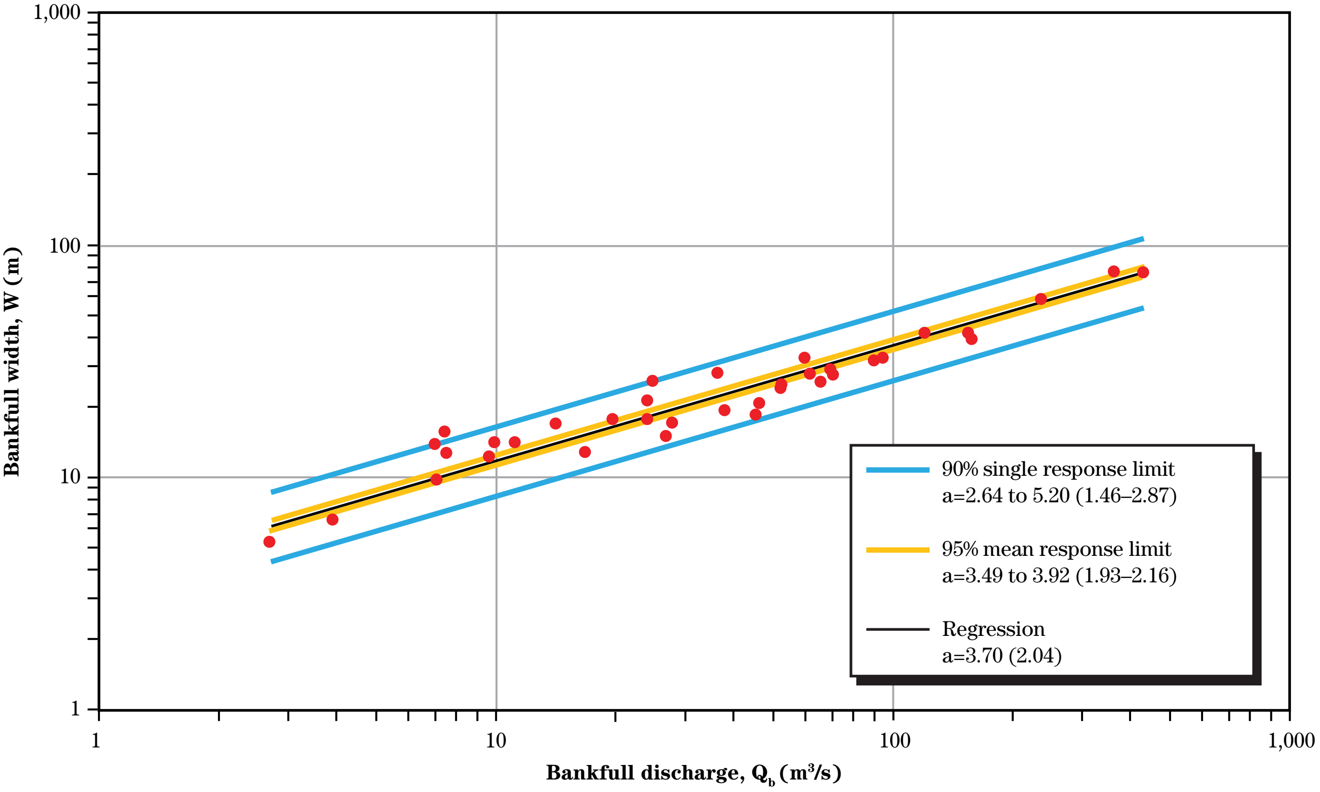
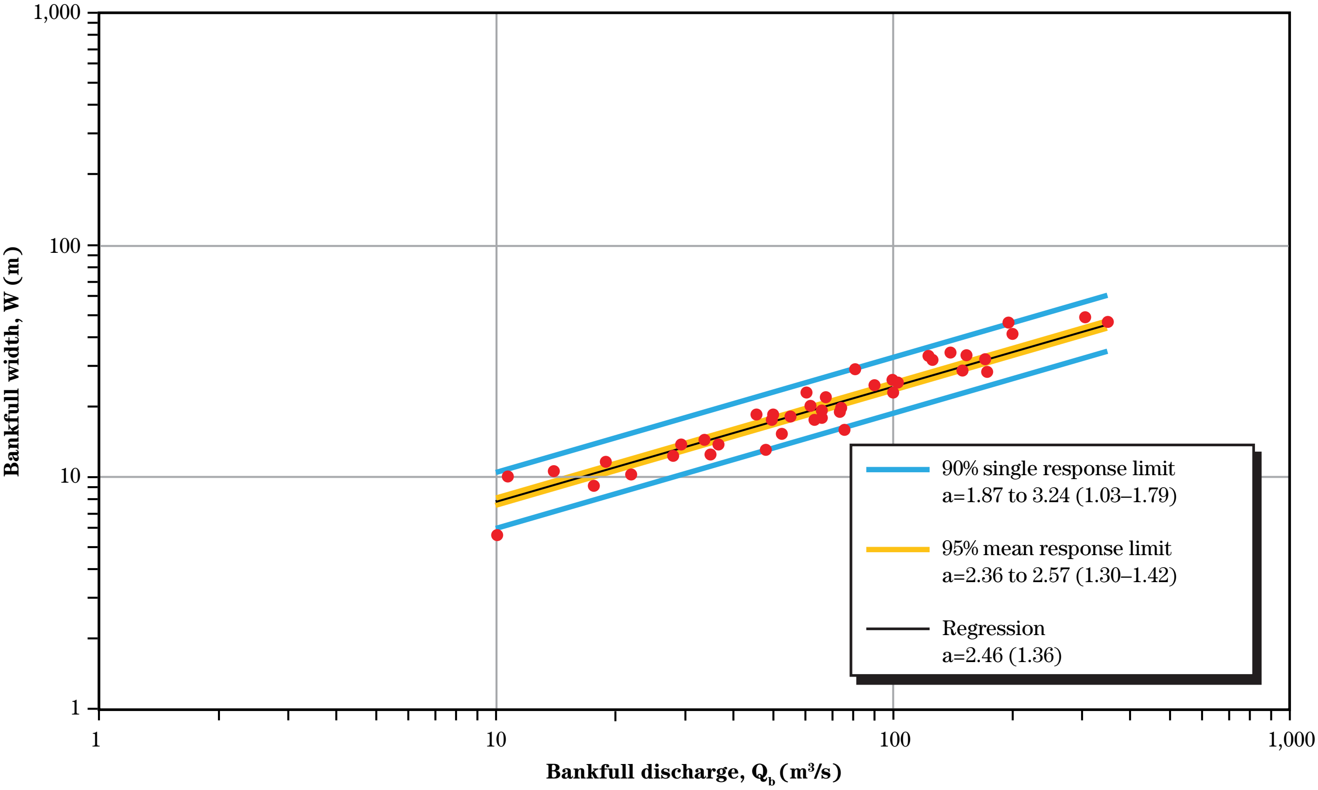


Figure 9–12 Downstream width hydraulic geometry for U.K. gravel-bed rivers, $W = aQ_b^{0.5}$ with confidence bands. Based on 43 sites in the U.K. with resistant banks. SI units m and m^3/s (English units ft and ft^3/s)



(f) Limitations of hydraulic geometry methods

- The formulas provide design variables only for the channel-forming discharge. These design variables may provide the most stable channel, but modifications may be necessary in final design to account for larger flood discharges.
- When developing a hydraulic geometry relationship from field measurements, it is difficult to determine the water surface elevation at channel-forming discharge. This is especially true in unstable channels.
- The hydraulic geometry equation must be developed from physiographically similar streams; that is, streams with depths, slopes, bed and bank material, and sediment inflow concentrations similar to the design channel.
- The assumption that channel dimensions are related only to one or two independent variables is simplistic. The data scatter associated with hydraulic geometry plots demonstrates that stability can occur at more than one combination of width and discharge. The channel-forming discharge may be the most significant factor affecting channel geometry, but other factors can also affect channel dimensions. These include the shape of the annual hydrograph, the shape and magnitude of the annual hydrograph from previous years, upstream or downstream channel control points, and localized variability in alluvial stratum.
- Hydraulic geometry relationships are assumed to be power functions. This assumption provides for visually comforting plots on log-log graph paper, but the actual data scatter may be too great for reliable final engineering design.
- Hydraulic geometry relationships are regression equations and should not be extended beyond the range of the data used to develop them, even in physiographically similar watersheds.

In summary, hydraulic geometry methods suffer the same limitation as the analogy methods. They both depend on a comparison to a channel that is adjusted in some sense. This is true whether it is a reference reach or a channel whose dimensions are used in a hydraulic geometry relationship. If the channel that is to be designed is disturbed or is likely to change due to changes in water or sediment supply, there is really no exact template that is appropriate. Hydraulic geometry relationships are useful for preliminary or trial selection of channel width. Hydraulic and sediment transport analyses are recommended for final channel design.

654.0906 Extremal hypotheses

If a reliable hydraulic geometry relationship cannot be determined from field data or when sediment transport is significant, analytical methods may be employed to obtain a range of feasible solutions. Analytical methods employ an extremal hypothesis as a third equation. One extremal hypothesis assumes that a channel will adjust its geometry so that the time rate of energy expenditure is minimized (Chang 1980; Copeland 1994). Another extremal hypothesis assumes that sediment transport is maximized within the constraints on the system (White, Bettess, and Paris 1982; Millar and Quick 1993). These are equivalent assumptions. Computer programs or look-up charts are required to solve the resistance, sediment transport, and extremal equations simultaneously. The U.S. Army Corps of Engineers Hydraulic Design Package, SAM (Thomas, Copeland, and McComas 2003), as well as HEC–RAS, contains a program to solve these equations. The program uses the Brownlie (1981) resistance and sediment transport equations for sand-bed streams, the Limerinos resistance equation, and the Meyer-Peter and Müller sediment transport equation for gravel-bed streams.

The advantage of using an extremal hypothesis is that a unique solution can be obtained for the dependent variables of width, depth, and slope. However, extensive field experience demonstrates that channels can be stable with widths, depths, and slopes different from those found at the extremal condition. Also, the sensitivity of energy minima or sediment transport maxima to changes in driving variables may be low, so that the channel dimensions corresponding to the extremal value are poorly defined.

654.0907 Constrained dependent variables

In many cases, project constraints limit the theoretical variability in channel geometry. These constraints can be anthropogenic or geologic. For example, the channel slope cannot be greater than the valley slope for a long reach. The channel width may be limited by available rights-of-way. Flood risks and damages may limit allowable depth. For these and many other reasons, the selection of one of the dependent design variables may be based on established project constraints.

654.0908 Analytical methods

After selecting one of the dependent design variables using geomorphic principles, the other two design variables can be computed using a resistance equation and a sediment transport equation. Appropriate equations can be chosen from those described in the American Society of Civil Engineers (ASCE 2006), USACE (1995a), USACE (1991b), Thomas, Copeland, and McComas (2003), or one of many sediment transport textbooks. The data ranges used in the development of sediment transport functions used in Thomas, Copeland, and McComas are given in tables 9–10 through 9–21. These summaries are based on the authors' stated ranges, as presented in their original papers. Otherwise, the summaries were determined based on the author's description of their database in combination with the data listings of Brownlie (1981) or Toffaleti (1968). A review of this information may serve as guidance in selecting the appropriate function.

The stable channel analytical method in the USACE SAM (Thomas, Copeland, and McComas 2003), provides a computer program that simultaneously solves resistance and sediment transport equations. The program provides a family of solutions from which the unique solution for depth and slope can be determined using the width determined from geomorphic principles or from project constraints. This method is described in detail in the following paragraphs.

(a) Stable channel dimensions using analytical techniques

Stable channel dimensions can be calculated analytically using computer programs or spreadsheets. The USACE SAM (Thomas, Copeland, and McComas 2003) calculates stable channel dimensions that will pass a prescribed sediment load without deposition or erosion. This routine is also available in HEC–RAS. The analytical approach (Copeland 1994) determines dependent design variables of width, slope, and depth from the independent variables of discharge, sediment inflow, and bed-material composition. It solves flow resistance and sediment transport equations simultaneously, leaving one dependent variable optional. The extremal hypothesis (minimum stream power) can be used as a third equation for a unique solution. Be aware of the cautions associated with using the extremal hypothesis as described in the previous section of this chapter. This method is based on a typical trapezoidal cross section and assumes steady, uniform flow. The method is especially applicable to small streams because it accounts for transporting the bed-material sediment discharge in the water above the bed, not the banks, and because it separates total hydraulic roughness into bed and bank components.

(b) Basic equations for sand-bed streams

For sand-bed streams, the sediment transport and resistance equations developed by Brownlie are recommended because they account for bed-form roughness. There are separate resistance equations for upper and lower regime flow. Upper regime flow is characterized by relatively high velocities and high sediment transport. The bedforms are plane bed, antidunes or chutes, and pools, which do not provide significant form resistance. Lower regime flow is characterized by relatively low velocity and low sediment transport. The bedforms are dunes or ripples, which provide significant form resistance. The equations are dimensionless and can be used with any consistent set of units.

Upper regime

$$R_b = 0.2836 D_{50} q_*^{0.6248} S^{-0.2877} \sigma^{0.0813} \quad \text{(eq. 9–16)}$$

Relatively high velocities and high sediment transport

Lower regime

$$R_b = 0.3742 D_{50} q_*^{0.6539} S^{-0.2542} \sigma^{0.1050} \quad \text{(eq. 9–17)}$$

$$q_* = \frac{Vd}{\sqrt{gD_{50}^3}} \quad \text{(eq. 9–18)}$$

Relatively low velocities and low sediment transport

where:
R_b = hydraulic radius associated with the bed (ft or m)
D_{50} = median grain size (ft or m)
S = slope

σ = geometric bed-material gradation coefficient
V = average velocity (ft/s or m/s)
d = water depth (ft or m)
g = acceleration of gravity (ft/s^2 or m/s^2)

To determine if upper or lower regime flow exists for a given set of hydraulic conditions, a grain Froude number F_g and a variable F_g' were defined by Brownlie. According to Brownlie, upper regime occurs if $S>0.006$ or if $F_g>1.25F_g'$, and lower regime occurs if $F_g<0.8F_g'$. Between these limits is the transition zone. In the SAM, $F_g = F_g'$ is used to distinguish between upper and lower regime flow. If a spreadsheet analysis is used, the user may choose a different criterion for determining the break between upper and lower regime flow in the transition zone.

$$F_g = \frac{V}{\sqrt{gd_{50}\left(\frac{\gamma_s-\gamma}{\gamma}\right)}} \qquad \text{(eq. 9–19)}$$

$$F_g' = \frac{1.74}{S^{0.3333}} \qquad \text{(eq. 9–20)}$$

where:
γ_s = specific weight of sediment (lb/ft^3 or N/m^3)
γ = specific weight of water (lb/ft^3 or N/m^3)

The hydraulic radius of the side slope is calculated using Manning's equation:

$$R_s = \left(\frac{(V)(n_s)}{(CME)(S^{0.5})}\right)^{1.5} \qquad \text{(eq. 9–21)}$$

where:
R_s = hydraulic radius associated with the side slopes (ft or m)
V = average velocity (ft/s or m/s)
n_s = Manning's roughness coefficient for the bank
CME = 1.486 (English units) = 1.0 (SI units)

If the roughness height k_s of the bank is known, then it can be used instead of Manning's roughness coefficient to define bank roughness. Strickler's equation can be used to calculate the bank roughness coefficient:

$$n_s = 0.039k_s^{\frac{1}{6}} \qquad \text{(eq. 9–22)}$$

where:
k_s = roughness height (ft)

$$n_s = 0.048k_s^{\frac{1}{6}} \qquad \text{(eq. 9–23)}$$

where:
k_s = roughness height (m)

For riprap, k_s should be set equal to the minimum design d_{90}.

Composite hydraulic parameters are partitioned in the manner proposed by Einstein (1950):

$$A = R_bP_b + R_sP_s \qquad \text{(eq. 9–24)}$$

where:
A = total cross-sectional area (ft^2 or m^2)
P_b = perimeter of the bed (ft or m)
P_s = perimeter of the side slopes (ft or m)

This method assumes that the average velocity for the total cross section is representative of the average velocity in each subsection.

Concentration, C, in parts per million, is calculated using the Brownlie sediment transport equation, which is also a regression equation. The equation is based on the same extensive set of flume and field data used to develop the Brownlie resistance equations. This equation is recommended because of its compatibility with the resistance equations, which are coupled with the sediment transport equation in the numerical solution. The equation is dimensionless and can be used with any consistent set of units.

$$C = 9{,}022\left(F_g - F_{go}\right)^{1.978} S^{0.6601}\left(\frac{R_b}{D_{50}}\right)^{-0.3301}$$

$$F_{go} = \frac{4.596\tau_{*0}^{\;0.5293}}{S^{0.1405}\sigma^{0.1606}}$$

$$\tau_{*0} = 0.22Y + 0.06(10)^{-7.7Y}$$

$$Y = \left(\sqrt{\frac{\gamma_s-\gamma}{\gamma}}R_g\right)^{-0.6}$$

$$R_g = \frac{\sqrt{gD_{50}^3}}{\upsilon} \qquad \text{(eq. 9–25)}$$

where:
C = concentration (ppm)
R_b = bed hydraulic radius (ft or m)
D_{50} = median grain size (ft or m)
σ = bed-material gradation coefficient
γ_s = specific weight of sediment (lb/ft^3 or N/m^3)
γ = specific weight of water (lb/ft^3 or N/m^3)
g = acceleration of gravity (ft/s^2 or m/s^2)
ν = kinematic viscosity (ft^2/s or m^2/s)
The other variables are dimensionless.

Table 9–10 Ackers-White transport function

Parameter	Flume data
Particle size range (mm)	0.04–7.0
Specific gravity	1.0–2.7
Multiple size classes	No
Velocity (ft/s)	0.07–7.1
Depth (ft)	0.01–1.4
Slope (ft/ft)	0.00006–0.037
Width (ft)	0.23–4
Water temperature (˚F)	46–89

Table 9–11 Brownlie transport function

Parameter	River data	Flume data
Particle size range (mm)	0.086–1.4	0.088–1.4
Multiple size classes	No	No
Velocity (ft/s) [calculated]	1.2–7.9	0.7–6.6
Depth (ft)	0.35–57	0.11–1.9
Slope (ft/ft)	0.00001–0.0018	0.00027–0.017
Width (ft)	6.6–3640	0.83–8.0
Water temperature (˚F)	32–95	35–102

Table 9–12 Colby transport function

Parameter	Data range
Particle size range (mm)	0.18–0.70
Multiple size classes	No
Velocity (ft/s)	0.70–8.0
Depth (ft)	0.20–57
Slope (ft/ft)	0.000031–0.010
Width (ft)	0.88–3000
Water temperature (˚F)	32–89
Correction for fines (ppm)	Yes

Table 9–13 Einstein transport function

Parameter	Flume data
Particle size range (mm)	0.78–29
Multiple size classes	Yes
Velocity (ft/s)	0.9–9.4
Depth (ft)	0.03–3.6
Slope (ft/ft)	0.00037–0.018
Width (ft)	0.66–6.6
Water temperature (˚F)	Not reported

Table 9–14 Laursen (Copeland 1994) transport function

Parameter	River data	Flume data
Median particle size range (mm)	0.08–0.70	0.011–29
Multiple size classes	Yes	Yes
Velocity (ft/s)	0.068–7.8	0.70–9.4
Depth (ft)	0.67–54	0.03–3.6
Slope (ft/ft)	0.0000021–0.0018	0.00025–0.025
Width (ft)	63–3640	0.25–6.6
Water temperature (˚F)	32–93	46–83

Table 9–15 Laursen (Madden 1985) transport function

Parameter	Data range
Particle size range (mm)	0.04–4.8
Multiple size classes	Yes
Velocity, (ft/s)	0.85–7.7
Depth (ft)	0.25–54
Slope (ft/ft)	0.00001–0.1
Width (ft)	3–3640
Water temperature (˚F)	36–90

Table 9–16 Meyer-Peter and Müller (1948) transport function

Parameter	Data range
Particle size range (mm)	0.4–29
Particle specific gravity	1.25–4
Multiple size classes	Yes
Velocity (ft/s)	1.2–9.4
Depth (ft)	0.03–3.9
Slope (ft/ft)	0.0004–0.02
Width (ft)	0.5–6.6
Water temperature (˚F)	Not published

Table 9–17 Parker transport function

Parameter	River data
Median particle size range (mm)	18–28
Total particle size range (mm)	2–102
Multiple size classes	Yes
Velocity (ft/s)	2.6–3.7
Depth (ft)	1.0–1.5
Slope (ft/ft)	0.0097–0.011
Width (ft)	16–20
Water temperature (˚F)	41–44

Table 9–18 Profitt (Profitt and Sutherland 1983) transport function

Parameter	River data
Particle size range (mm)	2.90–12
Multiple size classes	Yes
Velocity (ft/s)	2.00–3.4
Depth (ft)	0.35–0.84
Slope (ft/ft)	0.003
Width (ft)	2.00
Water temperature (˚F)	59–63

Table 9–19 Schoklitsch transport function

Parameter	Data range
Particle size range (mm)	0.3–4.9
Multiple size classes	No
Velocity (ft/s)	0.8–4.5
Depth (ft)	0.037–0.74
Slope (ft/ft)	0.00012–0.055
Width (ft)	0.23–2.0
Water temperature (˚F)	Not published

Table 9–20 Toffaleti transport function

Parameter	River data	Flume data
Median particle size range (mm)	0.095–0.76	0.91–0.45
Total particle size range (mm)	0.062–4	0.062–4
Multiple size classes	Yes	Yes
Velocity (ft/s)	0.7–7.8	0.7–6.3
Hydraulic radius (ft)	0.7–56.7	0.07–1.1
Slope (ft/ft)	0.000002–0.0011	0.00014–0.019
Width (ft)	63–3640	0.8–8
Water temperature (˚F)	32–93	40–93

Table 9–21 Yang transport function

Parameter	Sand data	Gravel data
Particle size range (mm)	0.15–1.7	2.5–7.0
Multiple size classes	No	No
Velocity, (ft/s)	0.8–6.4	1.4–5.1
Depth (ft)	0.04–50	0.08–0.72
Slope (ft/ft)	0.000043–0.028	0.0012–0.029
Width (ft)	0.44–1750	0.7–1.3
Water temperature (˚F)	32–94	Not reported

(c) Basic equations for gravel-bed streams

For gravel-bed streams, equations more appropriate for coarse bed streams should be used in the analytical solution. The Limerinos equation is recommended to calculate grain roughness on the bed. The Meyer-Peter and Müller equation is recommended to calculate sediment transport. The advantage of the Limerinos equation is that it accounts for the decrease in roughness with increasing water depth in cases where the bed roughness is primarily due to the dimensions of the sediment grains (sand, gravel, or cobbles) on the bed. The Manning equation can be used to calculate the roughness on the channel side slope. The Manning equation is appropriate for this case because bank roughness is best estimated using experience and engineering judgment. Additional roughness may be added in the manner suggested by Cowan (1956).

The Limerinos equation accounts for the grain roughness in a uniform reach of a gravel-bed stream that is relatively free of bedforms. The Limerinos equation may be presented in dimensionless units as:

$$\frac{V}{U'_*} = 5.66\log\left(3.80\frac{R'_b}{D_{84}}\right) \qquad \text{(eq. 9–26)}$$

where:
V = average velocity (ft/s or m/s)
U'_* = shear velocity associated with grain roughness (ft/s or m/s)
R'_b = hydraulic radius associated with grain roughness (ft or m)
D_{84} = grain size for which 84 percent of the bed is finer (ft or m)

Manning's roughness coefficient associated with grain roughness can be determined from the Limerinos equation:

$$n'_b = \frac{(CME)\left(R_b'^{\frac{1}{6}}\right)}{g5.66\log\left(3.80\frac{R'_b}{D_{84}}\right)} \qquad \text{(eq. 9–27)}$$

where:
n'_b = roughness coefficient associated with bed
CME = 1.486 English units (1.0 SI units)
R'_b = bed hydraulic radius associated with grain roughness (ft or m)
g = acceleration of gravity (ft/s or m/s)
D_{84} = grain size for which 84 percent of the bed is finer (ft or m)

Additional bed roughness may be added to the grain bed roughness using the Cowan (1956) method. Roughness may be added to account for factors such as surface irregularities, variability in channel shape, obstructions, vegetation, and meandering. Meandering can be accounted for with a meandering coefficient, m. In a straight channel, the meandering coefficient is 1.0. Appropriate values for the meandering coefficient and additions to the grain roughness *n* value can be found in Cowan (1956) and Chow (1959). Using the Cowan equation the total bed roughness coefficient is:

$$n_b = m\left(n''_b + n'_b\right) \qquad \text{(eq. 9–28)}$$

where:
n_b = total bed roughness coefficient
m = Cowan meander coefficient
n''_b = bed roughness other than grain roughness

Using the Manning equation the hydraulic radius associated with the bed is calculated

$$R_b = \left(\frac{(V)(n_b)}{\left(S^{\frac{1}{2}}\right)(CME)}\right)^{\frac{3}{2}} \qquad \text{(eq. 9–29)}$$

where:
S = channel slope, dimensionless

The hydraulic radius associated with the bank or side slope is

$$R_s = \left(\frac{(V)(n_s)}{\left(S^{\frac{1}{2}}\right)(CME)}\right)^{\frac{3}{2}} \qquad \text{(eq. 9–30)}$$

where:
n_s = the roughness coefficient associated with the side slope

Values for m, n''_b and n_s must be selected by the designer. Using the Cowan method provides water surface elevations that account for the total channel roughness and not just the grain roughness.

Sediment transport can be calculated using the Meyer-Peter and Müller equation:

$$\left(\frac{k_r}{k_r'}\right)^{\frac{3}{2}} \gamma_w R_b S = 0.047\left(\gamma_s - \gamma_w\right) D_m + 0.25\left(\frac{\gamma_w}{g}\right)^{\frac{1}{3}} \left(\frac{\gamma_s - \gamma_w}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}} \qquad \text{(eq. 9–31)}$$

where:

k_r = total bed roughness = $\frac{1}{n_b}$

k_r' = particle roughness = $\frac{1}{n_b'}$

γ_w = specific weight of water (lb/ft^3 or N/m^3)

γ_s = specific weight of sediment (lb/ft^3 or N/m^3)

D_m = median sediment size (ft or m)

g_s = sediment transport (lb/s-ft or N/s-m)

R_b = bed hydraulic radius (ft or m)

and

$$\left(\frac{k_r}{k_r'}\right)^{\frac{3}{2}} R_b = R_b' \qquad \text{(eq. 9–32)}$$

and

$$D_m = \sum_{i=1}^{n} f_i D_i \qquad \text{(eq. 9–33)}$$

where:

f_i = fraction of size class “i” in bed

D_i = geometric mean diameter of size class “i” in bed (ft or m)

(d) Calculating sediment discharge and concentration

A typical cross section, with the critical hydraulic parameters labeled, is shown in figure 9–13. The concentration calculated from the sediment transport equation applies only vertically above the bed. Total sediment transport in weight per unit time is calculated by the following equation:

$$Q_s = \gamma CBDV \qquad \text{(eq. 9–34)}$$

where:

Q_s = sediment transport (weight/time)

B = base width, length

An average concentration for the total discharge is then calculated:

$$\bar{C} = \frac{Q_s}{0.027Q} \qquad \text{(eq. 9–35)}$$

where:

$\bar{C}$ = concentration using the total discharge (ppm)

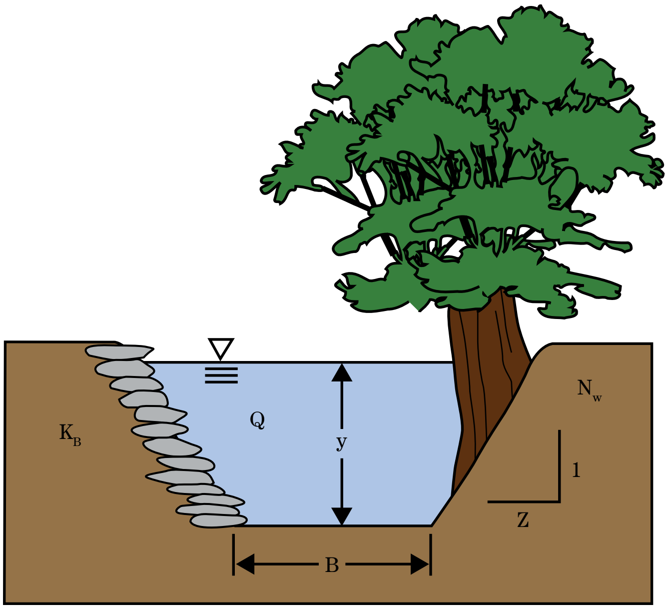
Q_s = sediment transport (tons/d)

Q = discharge (ft^3/s)

(e) Input requirements

Required input data for the analytical method are sediment inflow concentration, side slope, bank roughness coefficient, additional channel roughness and meandering coefficients for the Cowan method, bed material D_{50}, bed-material gradation coefficient, and water discharge. If sediment inflow is to be calculated, which is the recommended procedure, additional data are required for the supply reach. These are base width, side slope, bank roughness coefficient, bed material

Figure 9–13 Typical cross section used in analytical method



median grain size, geometric gradation coefficient, average slope, and discharge. It is important that the base width be representative of the total movable bed width of the channel. Additional channel roughness due to surface irregularities, variability in channel shape, obstructions, instream structures, vegetation, and meandering are added using the Cowan method. If either the USACE SAM or HEC–RAS program is used, adding additional roughness with the Cowan method is only available with the gravel-bed option. If the sand-bed option is used, only grain and form roughness is included in the Brownlie equations, so additional roughness can only be added by increasing the roughness coefficient assigned to the bank. In this case, the bank roughness should serve as a composite of all additional roughness factors. This can be accomplished using one of the hydraulic compositing methods described in NEH654.06. Only flow over the bed is considered capable of transporting the bed-material sediment load.

Water discharge

The design discharge is critical in determining appropriate dimensions for the channel. The channel-forming discharge will provide the most stable channel, but it is also important to evaluate how the design channel will respond during flood events. The channel-forming discharge is typically used to set channel dimensions, and flood discharges are used to evaluate channel performance at design conditions.

Investigators have proposed different methods for estimating the channel-forming discharge. The 2-year frequency peak discharge is sometimes used for perennial streams. Some have suggested that the 10-year frequency peak discharge is more appropriate for ephemeral and intermittent streams. The bankfull discharge is sometimes suggested. Others prefer using the effective discharge, which is the discharge that transports the most bed-material sediment. Currently, there is no generally accepted method for determining the channel-forming discharge. It is recommended that a range of discharges be used in the analysis to test sensitivity of the solution.

Inflowing sediment discharge

This is the concentration of the inflowing bed-material load. The bed-material load should be calculated using the same sediment transport equation and same hydraulic equations that are used in the analysis of the design channel. This is automatically done in USACE SAM or HEC–RAS, if the dimensions and bed-material composition of the upstream supply reach are supplied as input data. Measured data may be used to evaluate the applicability of the Brownlie or Meyer-Peter and Müller equations, but measured data should not be used as input to the analytical method.

Valley slope

Valley slope is the maximum possible slope for the channel invert. The valley slope is determined by the local topography, and a channel with a slope equal to the valley slope would be straight. The valley slope is used to test for sediment deposition. If the minimum slope that will transport the incoming bed-material load is greater than the valley slope, it is not possible to design a stable channel, and deposition is inevitable.

Bank slopes and roughness

The analytical method assumes that all bed-material transport occurs over the bed of the cross section and that none occurs above the side slopes. Therefore, the portion of water conveyed above the side slopes expends energy, but does not transport sediment. This makes the selection of base width in the supply reach important. The base width should reflect the entire alluvial boundary of the channel. In the design reach, the designer must select the channel side slope and side slope roughness. As in the supply reach, sediment transport is calculated only above the base width in the design reach. Therefore, sediment discharge will increase with the selection of steeper design bank angles.

(f) Range of solutions

For each specified combination of water discharge, sediment transport rate, and transport grain size, unique values of slope and depth are calculated. This can be used to evaluate stability in an existing channel or to evaluate stability in a proposed channel. Considering river morphology is important when interpreting these calculated values. Consistent is also important in the selection of channel dimensions; that is, once a width is selected, the depth and slope are fixed. This allows the designer to consider specific project constraints, such as right-of-way, bank height, sinuosity, bend radius, and minimum bed slope. A consistent set of channel dimensions can then be computed.

If the calculations indicate that the slope of the project channel needs to be less than the natural terrain, the calculated slopes can be used to aid in spacing drop structures or in introducing sinuosity into the project alignment.

An example of a family of slope-width solutions that satisfy the resistance and sediment transport equations for the design discharge is illustrated in figure 9–14. Designers typically use these to focus on a range of appropriate width slope combinations, rather than on a single value set. Any combination of slope and base width from this curve will be stable for the prescribed channel design discharge. Combinations of width and slope that plot above the stability curve will result in degradation, and combinations below the curve will result in aggradation. The greater the distance from the curve, the more severe the instability.

Constraints on this wide range of solutions may result from a maximum possible slope or a width constraint due to right-of-way. Maximum allowable depth could also be a constraint. With constraints, the range of solutions is reduced.

Different water and sediment discharges will produce different stability curves. A channel designed for the channel-forming discharge may not be stable at a different discharge. To evaluate the significance of this difference, a stable channel solution is first obtained for the channel-forming discharge. Then, stability curves are calculated for a range of discharges to determine how sensitive the channel dimensions are to variations in water and sediment inflow events. Figure 9–15 shows two stability curves for the same supply reach, but different discharges. The stability curve in this figure is for a channel-forming discharge of 5,000 cubic feet per second. Any width-slope solution along this line will theoretically provide a channel with long-term sediment continuity and stability. If the design channel has a depth constraint for flood control, a width-slope solution is selected from the right end of the stability curve where widths are greater and depths lower.

Conversely, if the design channel has a width constraint due to limited right-of-way, the width-slope solution is selected from the left end of the stability curve. To evaluate channel response for another discharge, a new stability curve is calculated and the design dimensions and compared to the new stability curve. For example, in figure 9–15, a stability curve for a flood discharge of 30,000 cubic feet per second is shown. Width-slope solutions that plot above the flood stability curve indicate that the design channel will degrade during the flood, and width-slope solutions that plot below the flood stability curve will aggrade during the flood. Figure 9–15 shows that degradation will occur during the flood in the channel designed with a depth constraint, and that aggradation will occur during the flood in the channel designed with a width constraint. Note that there is only one combination of width-slope solutions that satisfy sediment continuity for both discharges.

Long-term aggradation and degradation are associated with the channel-forming discharge, but short-term aggradation or degradation can occur during a flood event depending on which channel dimensions are selected from the stable channel stability curve.

Using a spreadsheet or USACE SAM or HEC–RAS, stable channel dimensions can be calculated for a range of widths on either side of a prescribed median value. It is recommended that calculations be made for at least 20 base widths, each with an increment of 0.1 times the median base width. Stability curves can then be plotted from these data. Typically there will be two solutions for each slope.

A solution for minimum stream power can also be calculated. This solution represents the minimum slope that will transport the incoming sediment load. Opinions are divided regarding the use of minimum stream power to uniquely define channel stability.

Figure 9–14 Stability curve from stable channel analytical method

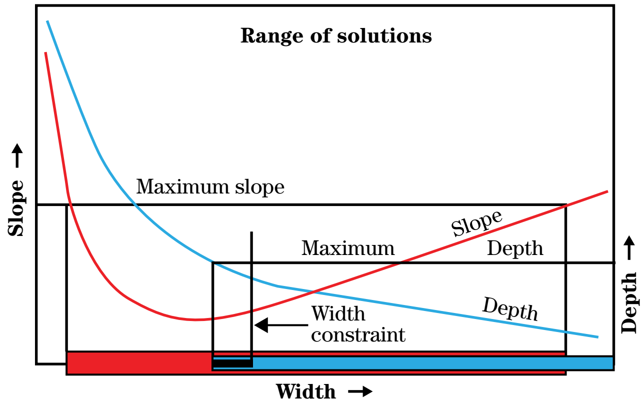
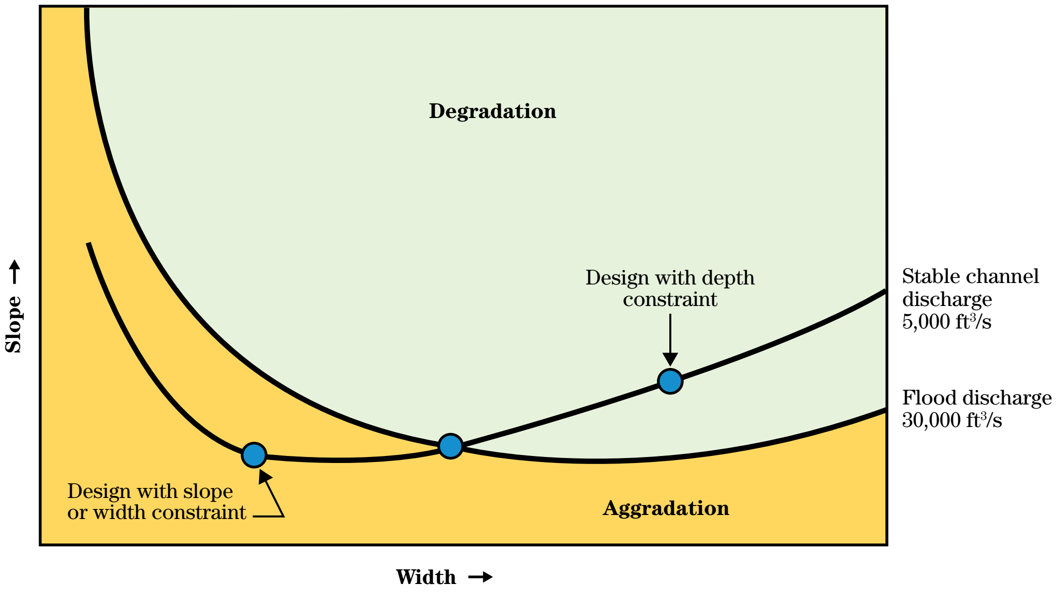


Figure 9–15 Stability curves for channel-forming (stable channel) discharge and a flood discharge



654.0909 Sediment impact analysis

Stream restoration projects should not be designed using only a single flow event and the sediment load transported by that event. This approach does not account for potential instability driven by the range of natural flow events. A determination of the potential for aggradation or degradation in a channel reach requires an assessment of the reach-scale sediment budget. The sediment impact assessment is a closure loop at the end of the design procedure to:

- validate the efficacy of the restored channel geometry
- identify flows which may cause aggradation or degradation over the short term (these changes are inevitable and acceptable in a dynamic channel)
- recommend minor adjustments to the channel design to ensure dynamic stability over the medium to long term

This can be accomplished using a sediment budget approach for relatively simple projects or by using a numerical model that incorporates a solution of the sediment continuity equation for more complex projects. More information on this subject is provided in NEH654.13.

654.0910 Basic steps in alluvial channel design

Step 1 Determine the channel-forming discharge—The initial design step is to determine the stable geometry for a single discharge. Use bankfull discharge, effective discharge, or a specific peak frequency as described in NEH654.05.

Step 2 Determine sediment inflow for the project reach—Calculate a sediment transport rating curve for the upstream supply reach. The sediment discharge may be computed based on a typical upstream cross section using a normal depth equation and an appropriate sediment transport equation.

Step 3 Develop a stability curve—Calculate a family of slope-width-depth solutions that satisfy resistance and sediment transport equations for the channel-forming discharge. This step provides a channel geometry that is capable of transporting the inflowing sediment load through the project reach. The equations are used to calculate the design variables of width, slope, and depth from the independent variables of discharge and sediment inflow.

Step 4 Determine channel width—A channel top width for the channel-forming discharge is selected from the stability curve using geomorphic principles or project constraints. Analogy methods, hydraulic geometry curves, or the extremal hypothesis are geomorphic relations that can be used to select width. Depth and slope for the selected width are determined from the stability curve.

Step 5 Conduct an analytical sediment budget analysis—Using the design channel dimensions, calculate a sediment-transport rating curve in the project reach. Using a flow-duration curve that includes some high flood discharges, calculate sediment yield into and out of the project reach. More information is provided in NEH654.13.

Step 6 Determine channel planform—Sinuosity is determined from the calculated channel slope and valley slope. Remaining planform design parameters include the meander wavelength, an appropriate channel length for one meander wavelength, and the trace of the channel. These can be determined from analogy methods, hydraulic geometry relations, or analytical techniques that assume minimum expenditure of energy. These techniques are described in NEH654.12.

Step 7 Natural variability in cross-sectional shape—Variability in channel width and depth can either be allowed to develop naturally or can be part of the project design. Sand-bed streams have the ability to create natural variability in channel form rather quickly because they are characterized by significant bed-material sediment transport. Gravel-bed streams typically adjust much more slowly. Streams with very little bed-material movement may not adjust at all. If variability is to be included in the project design, dimensions for cross sections in riffles and pools can be obtained from stable reaches of the existing stream or from reference reaches. Thorne (1988) has provided morphologic relationships for channel width for a meandering sand-bed river. Other researchers have correlated variability to riparian and bank conditions. Analogy methods have also been used in the design of variability. Techniques for design of variability in cross-sectional shape are described in NEH654.12.

Step 8 Instream structures—Successful stream restoration often includes the use of bank protection, grade control, and habitat features. To restore a stream with physical habitat features resembling a natural stream, a combined technology approach is required. Sound physical principles and well established engineering formulas are used in the analysis and design of both soft and hard features. Systems composed of living plant materials are often used in association with inert materials, such as wood or rock, and manufactured products. A significant flood event (normally no smaller than the 10-year frequency discharge) is used to size structures and compute scour depths. In addition, the quantity of water and its related hydroperiod largely determines what type of vegetation will grow in an area. The flexibility of these features depends on the project goals, tolerance for project change, and consequences of failure. Consideration is given to the effects that proposed features could have on flooding. For example, vegetation often increases boundary roughness, decreasing velocities, and increasing flood profiles. Additional design considerations include the level of risk that is acceptable, natural system dynamics, anthropogenic activities in the watershed, the construction time frame, existing infrastructure, and desired speed of improvement, cost, and maintenance. Guidelines for design of instream structures are described in NEH654.14.

Example 2: Stable channel analytical method

Objective: Determine stable channel dimensions for a diversion channel. Upstream natural stream is coming out of a hillside watershed.

Given: Dimensions of the upstream natural channel reach are:

Base width = 22 ft

Side slopes

Left bank = 2.2H:1V

Right bank = 1.1H:1V

Side slope roughness coefficient = 0.07

Channel slope = 0.0025

Bed material — sandy gravel

D_{84} = 22 mm D_{50} = 3.7 mm

D_{16} = 0.43 mm

Channel-forming discharge = 2,500 ft^3/s

Design values for the bypass channel:

Side slopes = 3H:1V

Side slope roughness coefficient = 0.045

Valley slope = 0.0020 (maximum design slope)

Solution: Solve the Brownlie resistance and sediment transport equations using the USACE SAM (Thomas, Copeland, and McComas 2003) or another program or spreadsheet. Example output is shown in figure 9–16. The sand-bed equations are chosen because bedforms may occur at the channel-forming discharge. However, the bed gradation is borderline between sand and gravel, and it would be prudent to make computations using both sand and gravel equations. From this table, stability curves for slope and depth as a function of depth can be platted (figs. 9–17 and 9–18).

The stability curves provide a family of solutions for width, depth, and slope that satisfy the resistance and sediment transport equations. Any combination of solutions on these curves will theoretically be stable in terms of aggradation and degradation. If the extremal hypothesis is adopted, a unique solution is provided. In this case:

Base width = 67 ft
Depth = 6.7 ft
Slope = 0.001879

If a straight channel is desired, then the channel slope would be set equal to the valley slope, 0.0020 (from the stability curves, base width = 38 ft, depth = 8.4 ft).

If a sinuous meandering channel is desired, then the maximum sinuosity for a stable channel can be calculated by dividing the valley slope by the calculated slope at minimum stream power.

$$\frac{0.0020}{0.001879} = 1.06$$

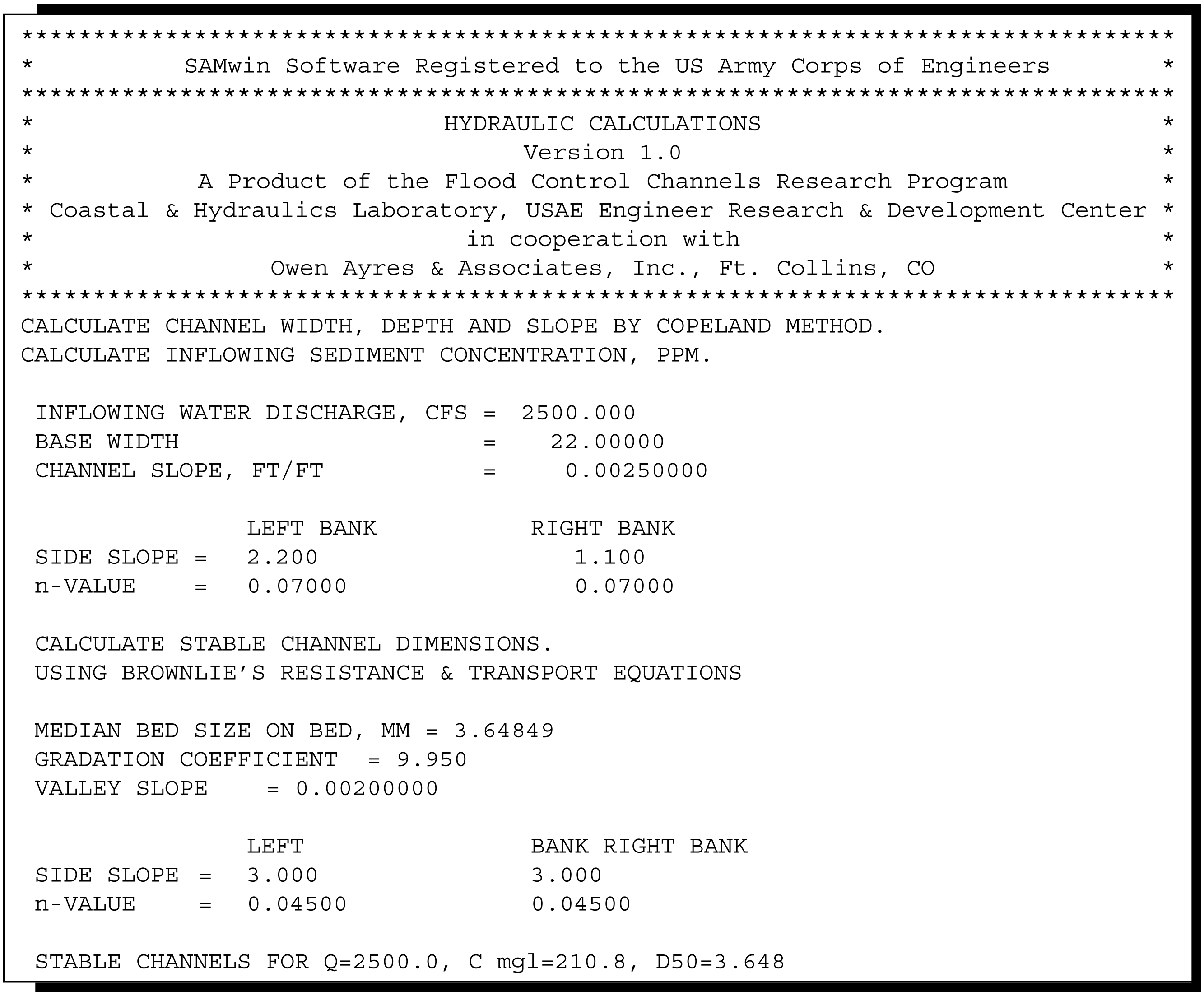
The stable channel dimensions for base width and depth are values calculated at minimum stream power. Any additional sinuosity would result in an aggrading stream. Thus, the only stable solutions occur with sinuosities between 1.0 and 1.06.

If one objective of this channel is flood control then it is best to design a compound channel to achieve both maximum channel stability and flood control benefits. The low-flow channel would be designed based on stability concepts for the channel-forming discharge, while the width and depth of the overflow channels would be based on normal depth or backwater calculations in a compound channel for the design flood (NEH654.06).

The design channel should be checked for the full range of expected natural flow conditions. A sediment budget analysis should be conducted to determine if there will be long-term aggradation or degradation in the channel. A hydraulic analysis should also be conducted at a design flood flow to obtain critical velocities for design on in channel structures and bank protection. It may be necessary to revise the initial design and iterate on a final solution that meets additional project constraints.

Example 2: Stable channel analytical method—Continued

Figure 9–16 Sample output from USACE SAM



```
********************************************************************************
*          SAMwin Software Registered to the US Army Corps of Engineers        *
********************************************************************************
*                            HYDRAULIC CALCULATIONS                            *
*                                 Version 1.0                                  *
*           A Product of the Flood Control Channels Research Program           *
* Coastal & Hydraulics Laboratory, USAE Engineer Research & Development Center *
*                              in cooperation with                             *
*                Owen Ayres & Associates, Inc., Ft. Collins, CO                *
********************************************************************************
CALCULATE CHANNEL WIDTH, DEPTH AND SLOPE BY COPELAND METHOD.
CALCULATE INFLOWING SEDIMENT CONCENTRATION, PPM.

 INFLOWING WATER DISCHARGE, CFS =  2500.000
 BASE WIDTH                     =    22.00000
 CHANNEL SLOPE, FT/FT           =     0.00250000

               LEFT BANK           RIGHT BANK
 SIDE SLOPE =   2.200                 1.100
 n-VALUE    =   0.07000               0.07000

 CALCULATE STABLE CHANNEL DIMENSIONS.
 USING BROWNLIE'S RESISTANCE & TRANSPORT EQUATIONS

 MEDIAN BED SIZE ON BED, MM = 3.64849
 GRADATION COEFFICIENT  = 9.950
 VALLEY SLOPE    = 0.00200000

               LEFT                BANK RIGHT BANK
 SIDE SLOPE =   3.000              3.000
 n-VALUE    =   0.04500            0.04500

 STABLE CHANNELS FOR Q=2500.0, C mgl=210.8, D50=3.648
```

Example 2: Stable channel analytical method—Continued

Figure 9–16 Sample output from USACE SAM—Continued

	BOTTOM WIDTH	DEPTH	ENERGY SLOPE	CMPOSIT n-Value	HYD RADIUS	VEL	FROUDE NUMBER	SHEAR STRESS	BED REGIME*
	FT	FT	FT/FT		FT	FPS		#/SF	
1	5.	10.4	0.004550	0.0456	5.30	6.69	0.37	2.94	LO
2	10.	10.4	0.003240	0.0458	5.64	5.86	0.32	2.10	LO
3	15.	10.1	0.002711	0.0459	5.81	5.45	0.30	1.71	LO
4	20.	9.8	0.002422	0.0460	5.89	5.19	0.29	1.48	LO
5	25.	9.4	0.002241	0.0460	5.92	5.00	0.29	1.31	LO
6	30.	9.0	0.002121	0.0461	5.91	4.86	0.29	1.19	LO
7	35.	8.6	0.002039	0.0461	5.88	4.74	0.28	1.10	LO
8	40.	8.3	0.001981	0.0461	5.82	4.65	0.28	1.03	LO
9	45.	8.0	0.001940	0.0461	5.75	4.56	0.29	0.96	LO
10	50.	7.6	0.001913	0.0460	5.67	4.49	0.29	0.91	LO
11	55.	7.3	0.001895	0.0460	5.57	4.42	0.29	0.87	LO
12	60.	7.1	0.001884	0.0460	5.48	4.36	0.29	0.83	LO
13	65.	6.8	0.001880	0.0459	5.38	4.31	0.29	0.80	LO
14	70.	6.6	0.001880	0.0459	5.27	4.26	0.29	0.77	LO
15	75.	6.3	0.001883	0.0458	5.17	4.21	0.30	0.74	LO
16	80.	6.1	0.001890	0.0457	5.06	4.16	0.30	0.72	LO
17	85.	5.9	0.001899	0.0457	4.96	4.12	0.30	0.70	LO
18	90.	5.7	0.001911	0.0456	4.85	4.08	0.30	0.68	LO
19	95.	5.5	0.001924	0.0456	4.75	4.04	0.30	0.66	LO
20	100.	5.4	0.001939	0.0455	4.65	4.01	0.30	0.65	LO
	RESULTS AT MINIMUM STREAM POWER								
21	67.	6.7	0.001879	0.0459	5.32	4.28	0.29	0.78	LO

* REGIMES: LO=LOWER, TL=TRANSITIONAL-LOWER, TU=TRANSITIONAL-UPPER, UP=UPPER

Example 2: Stable channel analytical method—Continued

Figure 9–17 Stability curve slope versus base width, Q = 2,500 ft^3/s, bed-material sediment concentration = 211 mg/L. Brownlie resistance and sediment transport equations

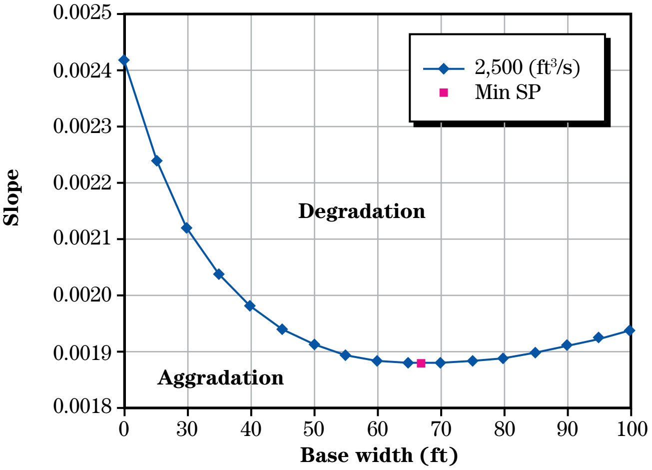
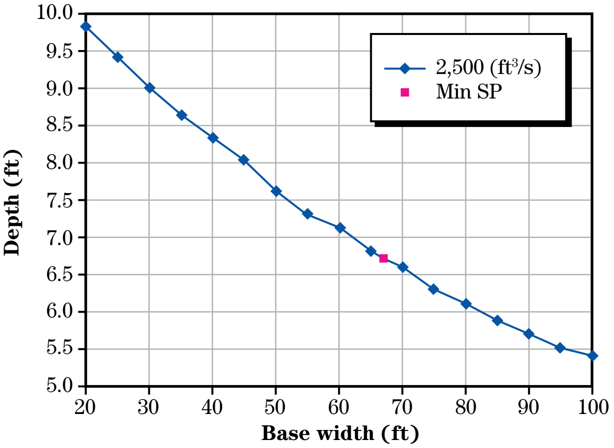


Figure 9–18 Stability curve depth versus base width, Q = 2,500 ft^3/s, bed-material sediment concentration = 211 mg/L. Brownlie resistance and sediment transport equations



Example 3: Hydraulic design with hydraulic geometry and the stable channel analytical method

Objective: Determine stable channel dimensions for single thread meandering channel that maximizes habitat benefits on an existing braided alluvial fan. The upstream natural stream comes out of a hillside watershed. The project reach is an alluvial fan with a braided channel that flows into a larger river downstream from the project reach. Note that the braided alluvial fan may be a naturally stable channel, but due to the wide shallow flow, water temperature is too high for certain fish species. Cross-sectional variability is negligible due to the lack of pools and riffles.

Given: Dimensions of the upstream natural channel reach are:

Base width = 55 ft
Side slopes
  Left bank = 1.5H:1V
  Right bank = 1.5H:1V
Side slope roughness coefficient = 0.08

Use Cowan method and add 0.01 to upstream channel roughness to account for channel irregularity.

Channel slope = 0.0065
Bed material—gravel
  D_{84} = 19.7 mm
  D_{50} = 6.9 mm
  D_{16} = 0.76 mm
Channel-forming discharge = 1,500 ft^3/s

Design values for the single-thread channel:

Side slopes = 1V:2.5H
Side slope roughness coefficient = 0.05
Use Cowan method and add 0.005 to account for channel irregularity
Valley slope = 0.0055 (maximum design slope)

Solution: Solve the Limerinos resistance and Meyer-Peter and Müller sediment transport equations using the USACE SAM (Thomas, Copeland, and McComas 2003), HEC–RAS, or another program or spreadsheet. Example output is shown in figure 9–19. The gravel-bed equations are chosen because bedforms are not expected to be a factor. From this table, stability curves for slope and depth as a function of depth can be plotted (figs. 9–20 and 9–21).

The stability curves provide a family of solutions for width, depth, and slope that satisfy the resistance and sediment transport equations. Any combination of solutions on these curves will theoretically be stable in terms of aggradation and degradation. Note that a wide range of width solutions will satisfy sediment continuity requirements with a slope of about 0.0045. Selecting a design slope in this range will provide for a stable channel. If the extremal hypothesis is adopted, a unique solution is provided. In this case:

Base width = 150 ft
Depth = 1.9 ft
Slope = 0.004488

These channel dimensions also provide the maximum sinuosity with a stable channel. The sinuosity is calculated by dividing the valley slope by the calculated slope at minimum stream power. In this case:

$$\text{Sinuosity} = \frac{0.0055}{0.004488} = 1.23$$

Any additional sinuosity would result in an aggrading stream. Thus, the only stable solutions occur with sinuosities between 1.0 and 1.23.

If a straight channel is desired, then the channel slope would be set equal to the valley slope, 0.0055. Base width and depth, at a slope of 0.0055, can be read from the stability curves:

Base width = 60 ft
Depth = 3.4 ft

Hydraulic geometry relationships may be used to select an appropriate width. Ideally, a hydraulic geometry relationship could be developed from the study watershed or a regional hydraulic geometry relationship from physiographically similar watersheds might be available. Lacking one of these, figure 9–9, developed from North American gravel-bed rivers, can be used. Converting 1,500 cubic feet per second to 42.5 cubic meters per second, a bankfull width of 24 meters (79 ft) is obtained from the mean regression line. The hydraulic geometry relationship refers to top width, while the stable channel analytical method in the USACE SAM calculates base width. Figure 9–22 is a top width versus base width curve developed from

Example 3: Hydraulic design with hydraulic geometry and the stable channel analytical method—Continued

the SAM output for the design channel which has side slopes of 1V:2.5H. A top width of 79 feet corresponds to a base width of 62 feet. Going back to the stability curve, this width would require a channel slope of about 0.0055. This is equal to the valley slope and, therefore, would be a straight channel. Using the maximum 90 percent single response limit from figure 9–9, a bankfull width of 43.5 meters or 142 feet is calculated. This corresponds to a base width of 132 feet and a stable channel slope of 0.0045. The design base width should be between 62 feet and 132 feet to satisfy both hydraulic geometry relationships and sediment continuity requirements. Decreasing the width provides for greater depths and more shade from trees on the banks, but it also decreases the sinuosity and channel variability that accompanies meandering. The following mean channel dimensions would be appropriate:

Base width = 80 ft
Slope = 0.005
Depth = 2.9 ft
Sinuosity = 1.1

The analogy method is another means of selecting an appropriate channel width. The reference reach used for the analogy method must be from a physiographically similar watershed. In this case, the upstream channel is not appropriate because the channel slope is significantly different from the slope in the design reach. The reference reach would need to be from a watershed with a similar sized drainage area that originates in the hills and flows onto an alluvial plain similar to the project reach. The key stability factor here is the abrupt change in slope between the upland stream and the alluvial fan stream. The reference reach would need to be stable and should have the favorable habitat characteristics desired in the project reach.

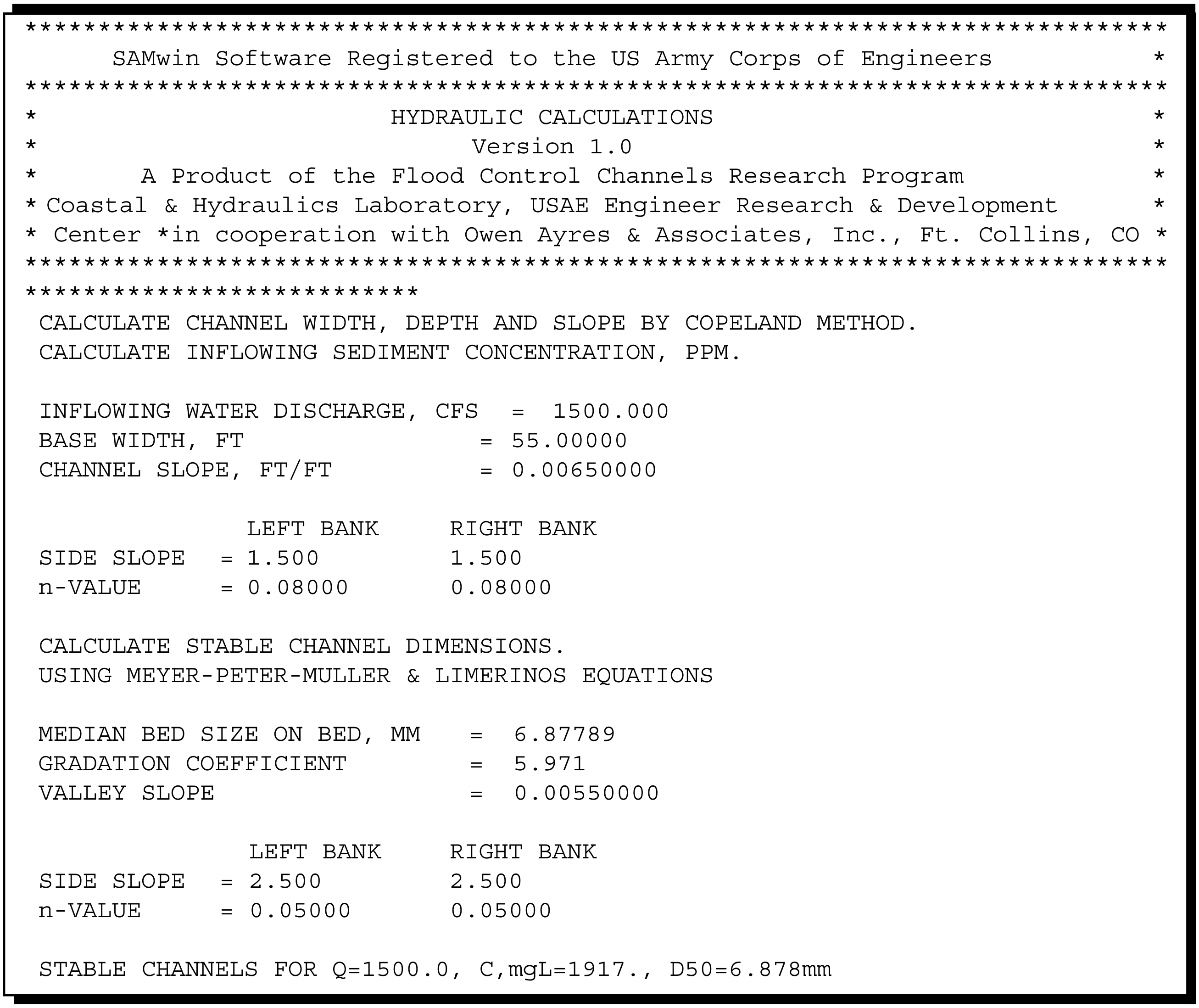
Other possible criteria for selecting the channel width could be constrained rights-of-way or minimum flow depths for habitat preservation. Minimum flow depths for a specified percent exceedance discharge can be determined by calculating normal depth for the proposed width.

The design channel should be checked for the full range of expected natural flow conditions. A sediment budget analysis should be conducted to determine if there will be long-term aggradation or degradation in the channel. A hydraulic analysis at a design flood flow should also be conducted to obtain critical velocities for design on inchannel structures and bank protection if necessary. It may be necessary to revise the initial design and iterate on a final solution that meets additional project constraints.

This example provides average channel dimensions of width, depth, and slope for the project channel. The planform layout is the next design parameter and is described in NEH654.12. Channel variability (riffles and pools) is also addressed in this chapter.

Example 3: Hydraulic design with hydraulic geometry and the stable channel analytical method—Continued

Figure 9–19 Sample output from USACE SAM



```
******************************************************************************
      SAMwin Software Registered to the US Army Corps of Engineers           *
******************************************************************************
*                        HYDRAULIC CALCULATIONS                              *
*                              Version 1.0                                   *
*       A Product of the Flood Control Channels Research Program             *
* Coastal & Hydraulics Laboratory, USAE Engineer Research & Development      *
* Center *in cooperation with Owen Ayres & Associates, Inc., Ft. Collins, CO *
******************************************************************************
***************************
 CALCULATE CHANNEL WIDTH, DEPTH AND SLOPE BY COPELAND METHOD.
 CALCULATE INFLOWING SEDIMENT CONCENTRATION, PPM.

 INFLOWING WATER DISCHARGE, CFS   =  1500.000
 BASE WIDTH, FT                 = 55.00000
 CHANNEL SLOPE, FT/FT           = 0.00650000

               LEFT BANK     RIGHT BANK
 SIDE SLOPE   = 1.500         1.500
 n-VALUE      = 0.08000       0.08000

 CALCULATE STABLE CHANNEL DIMENSIONS.
 USING MEYER-PETER-MULLER & LIMERINOS EQUATIONS

 MEDIAN BED SIZE ON BED, MM    =  6.87789
 GRADATION COEFFICIENT         =  5.971
 VALLEY SLOPE                  =  0.00550000

               LEFT BANK     RIGHT BANK
 SIDE SLOPE   = 2.500         2.500
 n-VALUE      = 0.05000       0.05000

 STABLE CHANNELS FOR Q=1500.0, C,mgL=1917., D50=6.878mm
```

Example 3: Hydraulic design with hydraulic geometry and the stable channel analytical method—Continued

Figure 9–19 Sample output from USACE SAM—Continued

	BOTTOM WIDTH	DEPTH	ENERGY SLOPE	CMPOSIT n-Value	HYD RADIUS	VEL	FROUDE NUMBER	SHEAR STRESS
1	10.	6.0	0.020654	0.0494	3.54	10.03	0.72	7.71
2	20.	5.3	0.011705	0.0450	3.64	8.45	0.65	3.89
3	30.	4.7	0.008537	0.0416	3.54	7.67	0.62	2.49
4	40.	4.2	0.006974	0.0389	3.36	7.16	0.62	1.81
5	50.	3.7	0.006084	0.0368	3.16	6.77	0.62	1.42
6	60.	3.4	0.005534	0.0353	2.97	6.46	0.62	1.17
7	70.	3.1	0.005177	0.0341	2.79	6.20	0.62	1.00
8	80.	2.9	0.004938	0.0332	2.63	5.98	0.62	0.89
9	90.	2.7	0.004775	0.0325	2.48	5.79	0.62	0.80
10	100.	2.5	0.004664	0.0320	2.35	5.61	0.62	0.73
11	110.	2.4	0.004588	0.0316	2.24	5.46	0.63	0.68
12	120.	2.2	0.004539	0.0312	2.13	5.32	0.63	0.64
13	130.	2.1	0.004509	0.0309	2.04	5.19	0.63	0.60
14	140.	2.0	0.004493	0.0307	1.96	5.08	0.63	0.57
15	150.	1.9	0.004488	0.0305	1.88	4.97	0.63	0.55
16	160.	1.9	0.004492	0.0304	1.81	4.87	0.63	0.52
17	170.	1.8	0.004503	0.0302	1.75	4.78	0.63	0.50
18	180.	1.7	0.004519	0.0301	1.69	4.70	0.63	0.49
19	190.	1.7	0.004539	0.0300	1.63	4.62	0.63	0.47
20	200.	1.6	0.004563	0.0300	1.58	4.55	0.63	0.46
	RESULTS AT MINIMUM STREAM POWER							
21	150.	1.9	0.004488	0.0305	1.88	4.97	0.63	0.54

Example 3: Hydraulic design with hydraulic geometry and the stable channel analytical method—Continued

Figure 9–20 Stability curve slope versus base width, Q = 1,500 ft^3/s, bed-material sediment concentration = 1,917 mg/L. Limerinos resistance and Meyer-Peter and Müller sediment transport equations

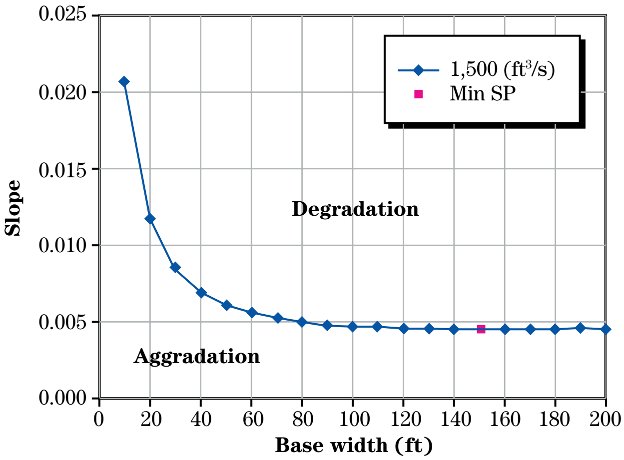


Figure 9–21 Stability curve depth versus base width, Q = 1,500 ft^3/s, bed-material sediment concentration = 1,917 mg/L. Limerinos resistance and Meyer-Peter and Müller sediment transport equations

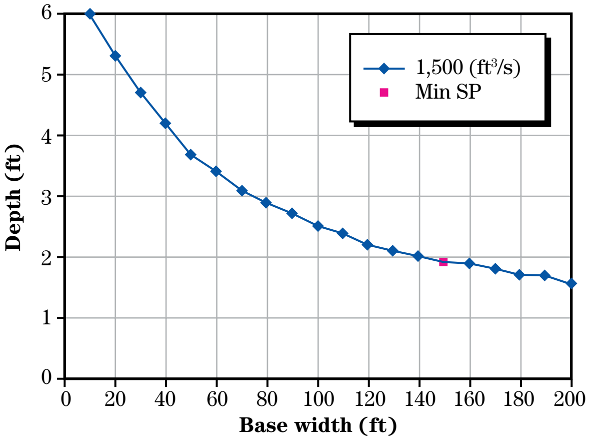
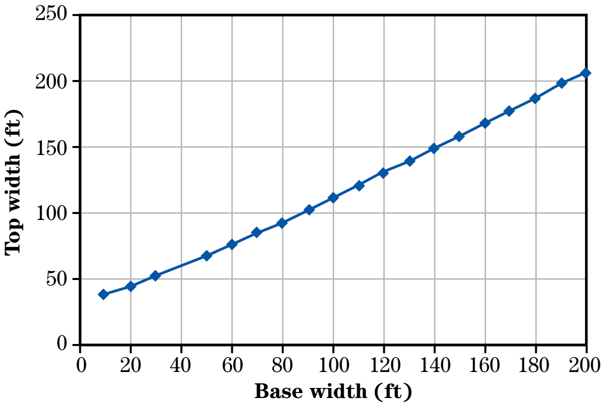


Figure 9–22 Top width verses base width for example problem which has 1V:2.5H side slopes



654.0911 Conclusion

Channels in which there is expected to be an exchange of the inflowing sediment load with the channel boundary should be designed using alluvial design methods. The design goal in an alluvial channel is to pass the inflowing sediment load without significant aggradation, degradation or planform change. Several techniques are available for the design of channels in an alluvial environment. They are the regime method, the analogy method, hydraulic geometry method, and the analytical method. All of these techniques have both advantages and disadvantages.

The analogy method is used to select design elements that are based on the premise that conditions in a reference reach with similar characteristics can be copied to the project reach. The hydraulic geometry method is similar to the analogy method insofar as that it is based on the premise that a river system tends to develop in a predictable way. The theory typically relates a dependent variable, such as width or slope, to an independent or driving variable, such as channel-forming discharge or drainage area. The regime method is similar to the hydraulic geometry, but is more appropriate for canal or drainage ditch type systems. The analytical method uses bed resistance and sediment transport equations to approximate a family of curves for width, slope, and depth for a range of potential stable configurations. These can be used indirectly with project constraints or in conjunction with the analogy or hydraulic geometry methods to estimate critical design elements.

All of the methods presented have advantages and disadvantages. Due to the high degree of uncertainty which is inherent to the nature of alluvial channels, many designers opt to use several methods. For example, during the assessment and design of proposed realignment, the family of curves calculated with the aforementioned analytical techniques can be used to provide another line of evidence which may give the designers more confidence in the chosen section, profile and planform.

All alluvial channel designs require analysis of channel stability. A stream is defined as stable when it has the ability to pass the incoming sediment load without significant degradation or aggradation and when its width, depth, and slope are fairly consistent over time. For design in an alluvial channel, it is suggested that an analytical sediment budget/assessment be conducted to compare the supply capabilities of the upstream reach to the sediment transport capacity of the design reach. Since bed-material sediment transport is significant under flows below, at, and above design flow in an alluvial channel, a sediment assessment should be done for a range of flows in any proposed realignment. Preparing sediment budgets is presented in NEH654.13.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 10 Two-Stage Channel Design

Issued August 2007

Cover photo: Low gradient, nonincising channels and ditches may be modified by creating a narrow flood plain, thereby creating some ecological benefits, while minimizing the need for maintenance (clean-outs).

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 10 Two-Stage Channel Design

Contents

Tables

Figures

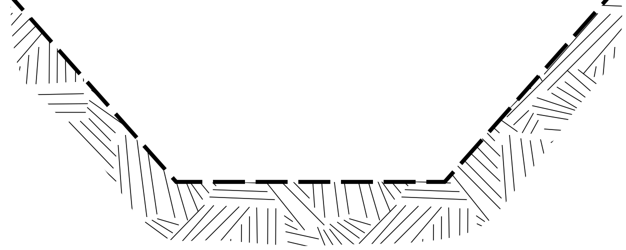
Chapter 10 Two-Stage Channel Design

654.1000 Purpose

Constructed channels are part of extensive portions of productive agricultural land in the United States. These channels provide important drainage and flood control functions. However, these agricultural channels are often constructed as traditional trapezoidal ditches using threshold design techniques. While this approach is suitable in some areas, channels of this design can require frequent and expensive maintenance in other parts of the country. In addition, natural ecological functions are normally not a consideration in the design of these channels. This chapter presents an alternative design to the conventional trapezoidal drainage channel. This two-stage channel system incorporates benches that function as flood plains and attempts to restore or create some natural alluvial channel processes. However, these two-stage channels are not an exact copy of natural streams, as the width of the benches is often small due to the confining geometry of the constructed channel. This chapter outlines measurement and analysis procedures that can be used to size two-stage channel systems that are more self-sustaining than conventional one-stage constructed channels. Although this chapter focuses primarily on an alternative design for constructed ditches, the technique may also have application in natural streams that have undergone incision or in streams where boundary constraints restrict restoration designs such as in urban or developed areas. A case study is also presented for a constructed two-stage ditch in Michigan.

This two-stage channel design approach is applicable to low gradient ditches and channels that are not undergoing incision.

Figure 10–1 Trapezoidal cross section of a constructed drainage ditch



654.1001 Introduction

Agricultural ditches and channels have long been used to provide important drainage and flood control. Historically, many of these drainageways are designed following threshold design techniques and result in a large, trapezoidal cross section. The primary purpose of the constructed channel is to convey water from agricultural fields.

Figure 10–1 illustrates the basic design configuration for a trapezoidal channel, and figure 10–2 is an example of one in Iowa. In many situations, the waterway does behave as a threshold channel, so this is an appropriate approach. However, when the waterway behaves as an alluvial channel, the ditch can be too entrenched and have overwidened bed widths. While the large section of a traditional agricultural drainage channel may provide sufficient flood conveyance, the more frequent discharges may not flow at a depth and velocity sufficient to move sediment through the reach. Deposition results, requiring maintenance to maintain the design flow capacity. As deposition occurs, bank stability may also become an issue as sediment deposits may force flows into one bank or the other. In addition, baseflows in this wide channel may have a depth which does not provide adequate aquatic habitat.

Figure 10–2 Drainage ditch constructed in north-central IA

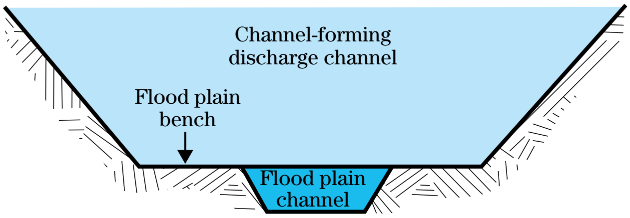
Fluvial processes at work in agricultural ditches functioning as alluvial channel systems often try to develop a flood plain that consists of low benches. While this deposition reduces flood capacity, these ditches show improved stability and improved habitat quality. This chapter presents a two-stage approach to design stable agricultural drainage channels (fig. 10–3). Specifically, the two stages are the:

- dominant discharge or channel-forming discharge channel
- flood plain bench or flood plain channel

This two-stage approach provides improved physical, as well as ecological performance. The channel-forming discharge channel provides the necessary sediment conveyance, while the flood plain channel provides for the design flood conveyance. By nesting the channel-forming discharge channel within the larger channel, the entire waterway is more stable.

The technique described herein uses bankfull discharge as representative of the channel-forming discharge. Therefore, the channel-forming discharge channel is referred to as the bankfull channel. The bankfull channel has also been referred to as the effective discharge channel. However, this is not necessarily accurate. There are no calculations made to define the effective discharge. Rather, this lower stage is assumed to be the bankfull discharge of a low-flow channel formed in a typical constructed ditch. The distinctions between bankfull, channel-forming, and effective discharge are addressed in more detail in NEH654.05. The differences between alluvial and threshold channels are addressed in NEH654.07.

Figure 10–3 Conceptual design for two-stage channel system



654.1002 Background

Highly modified channels drain extensive portions of productive agricultural land in the United States. Headwaters are typically the most modified. In some areas, virtually all of the natural channels have been deepened and straightened to facilitate the flow of water from agricultural subsurface drainage outlets and to maximize water conveyance. Work is done periodically to maintain the drainage function, which typically includes removal of woody vegetation, weeds, and deposited sediment. Ancillary work includes stabilizing bank slope failures and toe scour. Ditch form is a result of not only construction and maintenance, but also to verifying degrees, due to fluvial (flowing water) processes.

Ditch maintenance typically restores the ditch to a trapezoidal shape designed to transport large storm events (fig. 10–4). To facilitate drainage and reduce the frequency of over bank flows, trapezoidal ditches are designed to accommodate large flows (5- to 100+- year recurrence interval) within the ditch. Also the width of the ditch bottom is constructed wider than the channel bottom that would form by fluvial processes, thus, making the channel relatively wide and shallow. Therefore, the constructed ditch channel is often oversized for small flows and provides no flood plain for large flows.

In contrast to trapezoidal agricultural drainage ditches, integral parts of many natural stream channels are the flood plains. The flood plains of natural streams (except for those with steep bed slopes) are characterized by frequent, extensive over-bank flow. In dynamic equilibrium, a stream system depends on both the ability of the flood plain to dissipate the energy of high flows and to concentrate the energy of low flows to effectively create a balance in sediment transport, storage, and supply. In natural alluvial streams, fluvial processes work to size and maintain the dimensions of the bankfull channel based on the effective discharge (Ward and Trimble 2004).

In response to the construction of an oversized trapezoidal channel, alluvial channel processes often work to create a small bankfull channel by building a flood plain or bench within the confines of the ditch (fig. 10–4). If conditions allow, these benches can reach a stable size, thickly vegetated with mostly grasses. This results in a two-stage channel. The small bankfull channel will often meander slightly within the ditch. The bankfull channel will usually have steep (1H:1V) sides and a bed consisting of material coarser than that of adjacent reaches where benches have not formed. Further details on fluvial processes in ditches are available form Landwehr and Rhoads (2003) and Ward, Mecklenburg, and Brown (2002). It is important to note that these deposits within a constructed trapezoidal ditch reduce the overall flood conveyance. As a result, the channel may no longer provide the designed flood protection.

(a) Advantages of a two-stage channel

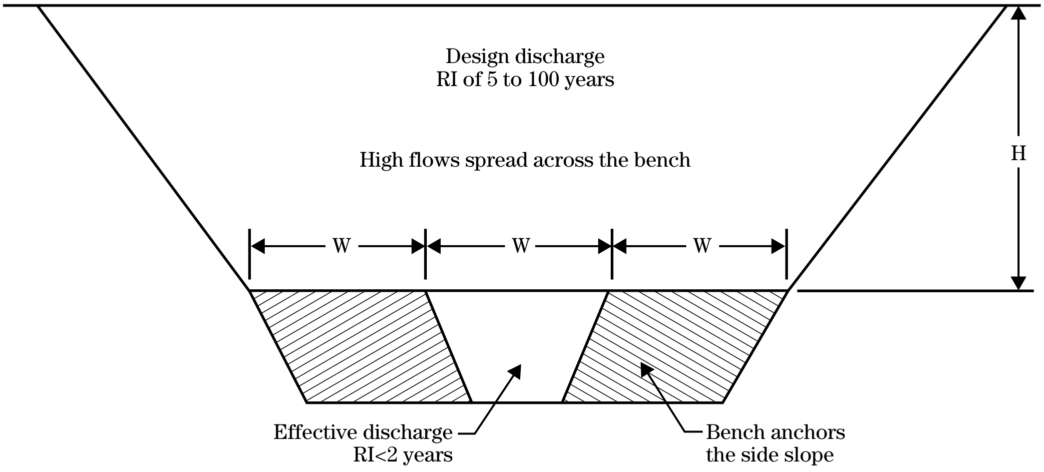
Benefits of a two-stage ditch over a conventional trapezoidal ditch are potentially both improved drainage function and ecological function. Drainage benefits may include increased ditch stability and reduced maintenance. Evidence and theory both suggest that ditches prone to filling with accumulated sediment may require less frequent dipping out if constructed in a two-stage form. Second, channel stability may be improved by a reduction in the erosive potential of larger flows as they are shallower and spread out across the bench (fig. 10–5).

Figure 10–4 Ditch before maintenance and after maintenance (MN)

(a) Before

(b) After

Figure 10–5 Two-stage ditch geometry with minimum sized benches



Stability of the ditch bank should be improved where the toe of the ditch bank meets the bench, rather than the ditch bottom. Here the water depth is effectively reduced, and the shear stress (erosive force) on the toe of the bank is less. Also, not being in contact with low flow, this bank material will be dryer and can be stabilized with vegetation using threshold design techniques as described in NEH654.08. Since a two-stage channel in an alluvial system will be more likely to retain its design shape, it is easier to predict its flood protection performance.

The biggest advantage of these two-stage channels is the ability to transport sediment more effectively. However, the two-stage ditch also has the potential to create and maintain better habitat than a conventional trapezoidal ditch. The narrow, deep bankfull channel provides better water depth during periods of low flow. Grass on the benches can provide some instream cover and shade. The substrate in the bankfull channel is improved as the two-stage form increases sediment conveyance and sorting, with fines deposited on the benches and coarser material forming the bed.

(b) Design of a two-stage channel

Design and construction of two-stage channels is different than that of traditional trapezoidal channels. The design of a two-stage agricultural ditch in an alluvial channel system involves correctly sizing the bankfull channel and minimum bench widths for the flood plain bench. The dimensions of the bankfull discharge or fluvial channel dictate the two-stage channel design. If properly sized, the bankfull channel will be maintained by fluvial processes and will reduce or possibly even eliminate large-scale channel maintenance. The flood plain bench serves as a flood plain for the smaller bankfull channel, but it acts more as a threshold channel. The upper stage must convey the channel-forming discharge and must have an adequate size to prevent design flood flows from overtopping the ditch banks and flooding surrounding land.

654.1003 Field measurements

Initial reconnaissance of the site area is recommended to establish a base knowledge of the project characteristics, surrounding area, and regional environment. The unique characteristics of the project site will generate the criteria for regional measurements. If searching for a reference reach, the watershed area, vegetation, soil, land use, and slope should correspond to the site in question.

Where a modification will be made to an existing channel, detailed measurements should be made of the channel profile and the dimensions of the bankfull channel and benches that have formed within the channel system. Often, the bankfull channel will be overwidened, and the benches will be intermittent and sloping. Guidance on performing such investigations is provided in NEH654.03. Conducting an onsite geomorphology study is a simple and reliable method, but is only adequate if:

- a bankfull channel and benches have formed
- the project length is short; the drainage area is relatively constant

A detailed survey along the reach of interest, or a reference reach, consists of measuring the profile, pattern, and dimension of the channel. The profile is the slope of the bed surface including all pools, riffles, and runs. The undulating elevations of the channel bed leads to questions of the true channel profile. To compensate for the bed slope variability, the water surface is also measured to represent the slope of the channel. The pattern of a reach measures the sinuosity of the bankfull channel. This is obtained using a compass and measuring the azimuth from magnetic north. The dimensions of the channel are obtained by surveying cross sections, either at increments along the reach or at representative cross sections. A laser level and survey tape, or a total station instrument, are often used. The distance from the left channel bank and the change in elevation are measured for each grade break across the channel cross section. A pebble count should be performed to estimate the mean bed particle size. Guidance for performing pebble counts is provided in NEH654 TS13A.

654.1004 Bankfull channel design

The first step in developing a two-stage design is determining the probable dimensions of the bankfull channel. This channel will carry most of the sediment in the channel. The width of the bankfull channel is a key design characteristic. It will determine the success in achieving the intended drainage effects, as well as ecological benefits. Channel design dimensions are determined by measuring the bankfull discharge features or calculating the effective discharge at the project site and then by creating a watershed specific regional curve for the project.

(a) Regional curve development

The probable dimensions of the bankfull channel can be empirically determined based on regional studies similar to those that are conducted for natural streams. Typically, for natural streams this knowledge is acquired by developing regional curves that relate the bankfull channel dimensions to drainage area. Traditional regional curves are created by performing numerous profile and cross-sectional surveys at locations with different drainage areas, which often include U.S. Geological Survey (USGS) stream gage sites as described in NEH654.05 and NEH654.09. The regional sites should be selected to provide fluvial information over a range of drainage areas that can be plotted to show channel dimension relationships to drainage area.

Measurements can be taken at the water surface and the bankfull fluvial features. Each gage station has a unique rating curve, which is a relationship between the gage reading and the streamflow rate. The bankfull height at each gage can be obtained by the measurements at bankfull and the waters surface along with the USGS real-time gage value. However, it is important to note that while each gage station may have a unique rating curve, the relationship between gage height and discharge is not necessarily unique. The rating curve may shift over the long term as the cross-sectional shape and/or elevation changes, and it may shift over the course of a hydrograph due to the unsteady loop effect or changing bedforms. If the rating curve is applicable, these values, combined with the width, will provide an additional point when creating a regional curve. An applicable and complete regional curve can be a valuable tool for two-stage channel design, as well as many other stream design activities.

Care must be taken with the use and development of the regional curves. The data used to develop a curve needs to be from physiographically similar basins. Drainage network patterns and the relative location of the channel site with respect to uplands are significant characteristics. The bed and bank characteristics used in the regional curve development should be the same as those at the project site. Issues related to the development and use of regional hydraulic geometry curves are described in more detail in NEH654.09.

Small watersheds that are drained by agricultural ditches can present particular challenges in the development of traditional regional curve data. In most parts of the Nation, there are a limited number of small-gaged watersheds, and these typically have short records or have been discontinued. Some additional difficulties associated with developing regional curves are that gages are often located at road crossings or the reach within the vicinity of the gage is highly modified.

(b) Rapid regional curve development

For two-stage channel design in many agricultural watersheds, an abbreviated rapid regional curve may be adequate. The method consists of finding ditches or streams with well-developed benches/flood plains and measuring at least the width and depth of the naturally formed bankfull channel. The selected channels must have reached a state of equilibrium and must be stable. Sites for any regional curve should also have similar characteristics to the project site and should come from physiographically similar watersheds. Several measurements should be taken for each range of drainage areas to verify that the measured feature is consistent with those across the watershed. Whenever possible, precision surveying instruments should be used to make the elevation and distance measurements.

Traditional regional curves are created by performing numerous detailed surveys at locations with different drainage areas. In contrast, a rapid regional curve channel dimension measurement consists of quickly measuring visual fluvial features with a 100-foot tape and a telescoping leveling rod. The channel dimensions taken at a complementary range of several drainage areas should provide a sufficient spread for each log cycle. The bankfull dimensions of width and depth are measured where visible fluvial features are noticed. The drainage area for each measurement is acquired from a variety of methods such as calculating the area by hand using a planimeter or computer GIS software. The measured dimensions can be the plotted area versus drainage area, and a power regression equation can be fitted to the data. This equation can be used to estimate the bankfull channel design dimensions for a ditch, given the drainage area.

This rapid regional curve approach has been used on several watersheds in Ohio. Reportedly, this approach typically provides relationships between the bankfull channel and drainage areas with r^2 values of 0.8 or greater (Ward 2005; Ward et al. 2003).

(c) Reference reach

Measurements from a reference reach can provide valuable design guidance for the design of the bankfull channel. Typically, for natural streams this knowledge is acquired by conducting detailed surveys along a reach of interest and by conducting a detailed survey of a reference reach along the same stream or a similar nearby stream system. However, finding reference reaches can be a time consuming, costly, and frustrating activity. The attributes of the local subwatershed, such as the topography, soil and bedrock properties, vegetation on the banks and adjacent riparian zone, and size and characteristics of the active flood plain, can result in a variety of different stable channel dimensions for similar-sized drainage areas within a watershed or region. For a reference reach to be directly applicable, it must have similar climate, history, drainage area, and watershed conditions. More information on the identification and use of reference reaches is provided in NEH654.09 and 654.12.

654.1005 Flood plain channel design

The formation of benches in constructed ditches is the natural result of fluvial processes in most alluvial systems. The bench acts as a flood plain within the ditch to dissipate energy, reduce the erosive potential of high-flow volumes, and reduce the shear stress on the bank toe. In establishing two-stage geometry, it is often not cost effective or practical to form a flood plain as wide as fluvial processes would form under natural conditions. Large, deep agricultural ditches have often already been constructed to handle discharges from subsurface drainage systems. Making these large ditches even wider would result in extensive earth moving, high cost, and substantial losses in productive agricultural land. Therefore, the ability of these small flood plains (benches) to aid in developing a self-sustaining system is dependent on the establishment of dense grass cover on the benches and banks of the ditch. Also, the side slopes and depths of the ditch above the benches must satisfy geotechnical engineering requirements to provide bank stability.

In a designed two-stage channel, the elevations of the flood plain channel benches are dependent on correctly determining the size of the bankfull channel. The flooded width is defined as the total width across the ditch at the stage elevation where benches have formed and/or are anticipated to form. The two-stage width ratio is defined as the flooded width divided by the top width of the bankfull channel. Based on visual observations and modeling bed-load transport, two rules of thumb have been established:

- If the total width, when out-of-channel flow is initiated, is less than three times the top width of the bankfull channel, the benches might not fully develop, the benches are more likely to be unstable, and shear stresses on the bed and banks of the ditch will be high during large events.
- If the total width, when out-of-channel flow is initiated, is more than five times the top width of the bankfull channel, the channel will begin to exhibit a natural meander pattern that, at places in the ditch, is likely to cut into the banks of the ditch.

Therefore, when out-of-channel flow is initiated, the designed target total width should be between three to five channel widths (total bench sizes that are two to four times the channel width), if the objective is to provide adequate conveyance capacity and a more self-sustaining system, while maintaining a relatively straight ditch geometry. If the project goals or the stability requirements of the channel design require the development of a sinuous channel, a wider bench may be required. However, channel alignment design elements, such as are described in NEH654.12, will need to be addressed so that a stable planform is chosen.

654.1006 Flood conveyance

The overall conveyance capacities of the two-stage systems can be sized based on the probability of out-of-ditch flooding into adjacent areas. This probability is based on the recurrence interval storm event that the entire ditch can transport. Where possible, stream gage data should be used to determine the discharges associated with a prescribed recurrence interval. However, in most parts of the Nation, there are limited numbers of small watershed gages. Typically, these gages have short records or have been discontinued. Therefore, measured streamflows at locations without gages are determined from hydrologic models or from regional discharge curves. One source of regional discharge information is the National Flood Frequency (NFF) Program. The NFF Program includes 2,065 regression equations for 289 flood regions nationwide. These equations are contained in a Windows® program for estimating the magnitude and frequency of peak discharges for unregulated rural and urban watersheds. This program can be obtained at the following Web site:

http://water.usgs.gov/software/

Since most two-stage channels are of fairly uniform section and constant slope, a resistance equation, such as Manning's equation, can be used to calculate the depth corresponding to the design flow recurrence intervals.

654.1007 Spreadsheet tools for data analysis and design

Many of the calculations for two-stage channel assessment and design can be performed with the help of computer spreadsheets. One set has been developed by the Ohio Department of Natural Resources (ODNR). This suite of spreadsheet tools can be obtained from the following Web site:

> *http://www.ohiodnr.com/soilandwater/streammorphology.htm*

These spreadsheets aid in designing a new bankfull channel together with various size benches, based on the following:

- a regional curve for the area
- cross-sectional data for a ditch or channel reach
- profile data for the reach that can include bed, water elevation, bench, and top of ditch data
- the D_{50} fraction of the bed material
- user-defined adjustments to the channel, bench, and ditch geometry

The channel width, depth, and cross-sectional area associated with the bankfull discharge at each location surveyed are entered into the spreadsheet to develop a regional curve. The calculated drainage area and bankfull discharge at each location are also entered into the same spreadsheet. A log-log plot is then made of each bankfull discharge dimension versus drainage area. A least-squares analysis is then used to fit a power regression line (a trend line) through each set of data and calculate the coefficients of the regional curve.

In the spreadsheet, stage-discharge relationships for each site are obtained based on Manning's equation. A separate Manning's n value is used for the bankfull channel and the vegetated benches and banks of the ditch. The roughness of the bed, banks, and benches vary seasonally based on winter conditions, vegetation growth, maintenance, and scour or deposition on these features. Therefore, the approach used only provides a general representation of roughness conditions. User-defined discharge versus recurrence interval data, or estimates based on the USGS Urban Method for Ohio, are used together with Manning's equation to calculate the flow stage associated with each recurrence interval. The ODNR channel design spreadsheet is programmed to obtain coefficients for recurrence intervals of 0.25, 0.5, 1.0, and 1.5 years.

In the spreadsheet, bed-load transport in the bankfull channel is calculated based on the probable discharges that will occur during a 100-year time period, the D_{50} of the bed material, and based on estimates obtained from the Meyer-Peter and Müller bed-load transport equation (Ward and Trimble 2004). Estimates are obtained for the bed load, recurrence interval of the bankfull discharge, and probable stage of the bankfull discharge.

While these spreadsheet tools have been developed to aid in the analysis of stream form and processes, they are best applied to alluvial stream systems that are a function of the bankfull discharge.

(a) Site selection and reconnaissance

Potential sites for regional curve measurements were marked on Michigan, Indiana, and Ohio State Gazetteers published by DeLorme. Sites were selected to provide data for several sized drainage areas within each log cycle. Due to the remoteness of the area from Columbus, Ohio, no preliminary reconnaissance was conducted. At each site, the widths and depths associated with grade breaks were measured using a 100-foot tape and a telescoping surveying rod. A more detailed and accurate survey was conducted at the Hillsdale ditch using a laser level, 100-foot tape, and a telescoping rod with a laser receiver. At that site, cross-sectional information was obtained every 100 feet, and the location of the thalweg was noted. On November 16, just prior to construction of the two-stage geometry, a pebble count was conducted for reaches 600 to 800 feet, 800 to 1,000 feet, and 1,000 to 1,200 feet.

(b) Regional curve

Data were obtained at 14 locations within a 600-square-mile drainage area. A regression analysis of the data (fig. 10–7) indicates that the bankfull discharge dimensions are highly correlated with drainage area.

The poorest correlation is with channel depth, perhaps because some of the channels were associated with streams that were highly connected to the flood plain, while others were associated with grade breaks and small bench formation in ditches. The Hillsdale ditch has a 4.5-square-mile drainage area, and its measured channel dimensions are located almost exactly on the regression lines.

(c) Discharge data

The regional curve analysis was extended to the USGS gage on the St. Joseph River near Newville, Indiana. Streamflow data for this gage was obtained from the following Web site:

http://water.usgs.gov/oh/nwis/rt

At this site, a laser level was used to determine the bankfull discharge and water surface elevation. Real-time gage data were available at the time the survey was performed and downloaded from the Internet. Due to deep flow conditions, it was only possible to estimate the width of the river by making a measurement on the road across the bridge.

(d) Discharge versus recurrence interval

An annual series of peak flow data for the period 1947 through 2002 were available for the gage on the St. Joseph River near Newville, Indiana. The Weibull method (Ward and Trimble 2004) was used to develop a plot of discharge versus recurrence interval data resulting in a high correlation (r^2=0.96) between peak discharge and recurrence interval.

Example 10–1: Hillsdale County case study

The Hillsdale County, Michigan, case study was conducted as part of a demonstration project for The Nature Conservancy, Upper St. Joseph River Project Office, and is funded with a grant from the Great Lakes Commission. The survey was conducted in July 2003, and an existing ditch was modified to a two-stage geometry in November 2003 (fig. 10–6). The project site is located in Hillsdale County, within the St. Joseph Watershed (MI). In 1997, the ditch was cleaned out as part of a maintenance action and in July 2003, had 0.5 to 2.0 feet of sediment deposits on the bed and had formed small intermittent benches.

Figure 10–6 Ditch before construction at location 1,000–1,200 ft, and after widening of small benches at location 1,600–2,100 ft (Hillsdale County, MI)

(a) Before

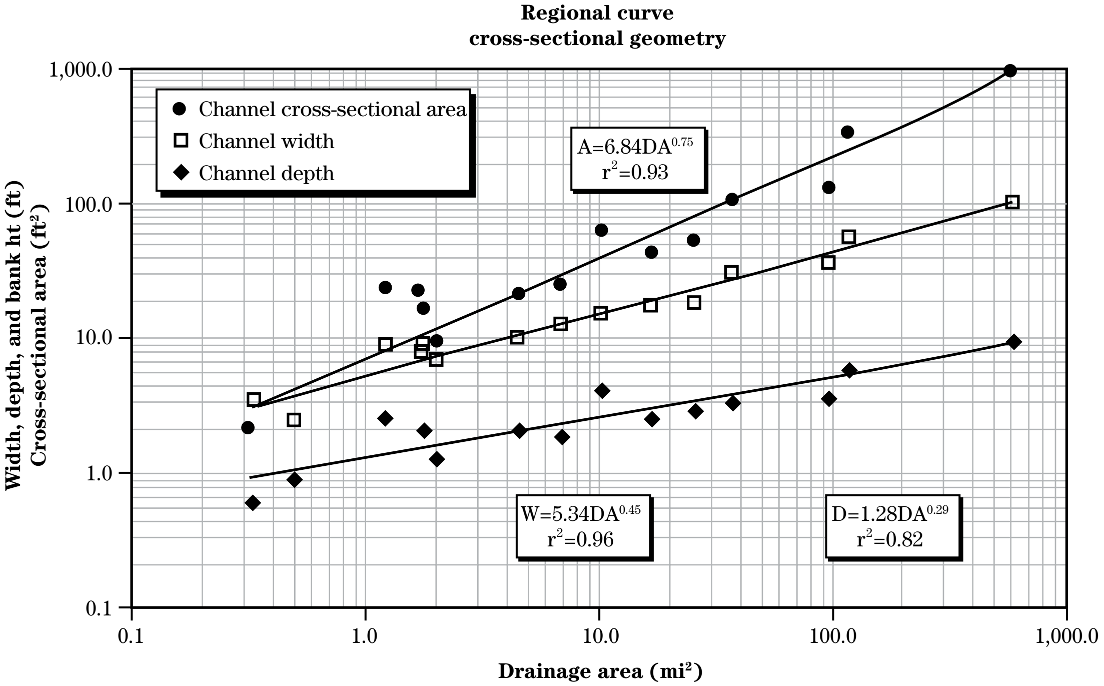
(b) After

On the day of the survey, the water depth at the gage was about 3.7 feet (based on the real-time measurement from the USGS NWIS Web site), and the bankfull discharge dimensions were measured on both banks at about 3.7 to 5.4 feet above the water elevation. The most dominant feature was a continuous approximately 20-foot high bench that was located on the left bank. A shorter bench at a similar elevation was located on the right bank. Therefore, it was estimated that the bankfull stage was 7.4 to 9.1 feet.

An approximate rating curve for the gage was created using data from the USGS Web site. The bankfull discharge was estimated from the survey data, and the rating curve to be between 740 and 1,330 cubic feet per second. While this is a wide range, an analysis of the recurrence interval curve indicates that this corresponds to a recurrence interval that is much more frequent than 1 year. This frequent occurrence is not surprising. In flat, poorly drained areas in the Midwest, where subsurface drainage is widely used, the bankfull discharge occurs frequently and primarily due to subsurface drainage discharges. Since this bankfull discharge is associated with high subsurface flows, it is usually associated with a recurrence interval that is much more frequent that one year (Ward 2005; Ward et al. 2003).

An analysis of the daily flow records shows that discharges within this range or larger occur on average 40 to 80 days annually. This range of flow seems to be too frequent to correspond to the bankfull or channel-forming discharge. However, an analysis of the daily flows exceeding 1,330 cubic feet per second revealed that, on average, they are associated with 1 to 13 discharge events annually, and the duration of these flows ranged from 1 to 49 days. High flows lasting many days typically occurred between November and April. On

Figure 10–7 Bankfull discharge channel dimensions for the St. Joseph River (OH) upstream of the gage near Newville, IN



average, annually, there are slightly more than five events, with an average duration of 8 days that exceeded 1,330 cubic feet per second.

A bankfull channel associated with very frequent flows is consistent with observation by Ward, Mecklenburg, and Brown (2002) in Wood County, Ohio. However, in a recent study, they noted that typically, only about 10 percent of the sediment is transported by flows that are less than double the mean discharge. For most of the gages, less than 25 percent of the sediment load is transported by flows that are 3 to 5 times the mean discharge. (Ward et al. 2003). For example: the mean annual discharge for the St. Joseph gage is about 540 cubic feet per second, so it is probable that a discharge of 1,330 cubic feet per second or higher corresponds to the bankfull discharge at the gage.

At the gage, the river was very entrenched the top of the bank corresponded to a stage of at least 16 to 18 feet (not measured). From further analysis, it was estimated that the out-of-bank discharge is 6,000 to 9,000+ cubic feet per second and corresponds to a 4- to 20-year recurrence interval flow. Therefore, at this location, the behavior of the river is similar to that of a ditch.

The results of discharge versus recurrence interval estimation analysis are presented in table 10–1 for this example. The gage data results were obtained from the regression equation. At the gage, the USGS Rural method gave similar results to the gage data. However, the USGS Urban method greatly overestimated the discharges, even though an annual precipitation of only 32 inches was used, rather than the 34 to 35 inches suggested by the annual precipitation map for Ohio (Ward and Trimble 2004). For the rural equation, a slope of 0.1 percent (5.2 ft/mi) and a storage value of 3 were used. At the Hillsdale ditch, the urban method also gave much higher estimates than the rural equation. However, if the urban method were calibrated based on the ratio of the urban to gage data results, the urban and rural methods gave similar results, except for a recurrence interval of 2 years. It was decided to base the analysis on the rural equation results. For this ditch, knowledge of the actual discharge versus recurrence interval has little influence on the design. The ditch is extremely large, and regardless of what estimates are used, the out-of-bank discharge is associated with a recurrence interval greater than 100 years.

Table 10–1 Discharge vs. recurrence interval results at the gage and the Hillsdale ditch

	St. Joseph gage			Hillsdale ditch		
Recurrence interval (years)	Gage data	USGS Urban method	USGS Rural method	USGS Urban method	Urban calibrated	USGS Rural method
2	4160	4902	5261	176	149	110
5	6337	9735	7365	302	197	171
10	7984	13920	8635	373	214	205
25	10162	22495	10148	546	247	246
50	11809	30121	11141	663	260	274
100	13456	37488	12148	786	282	301

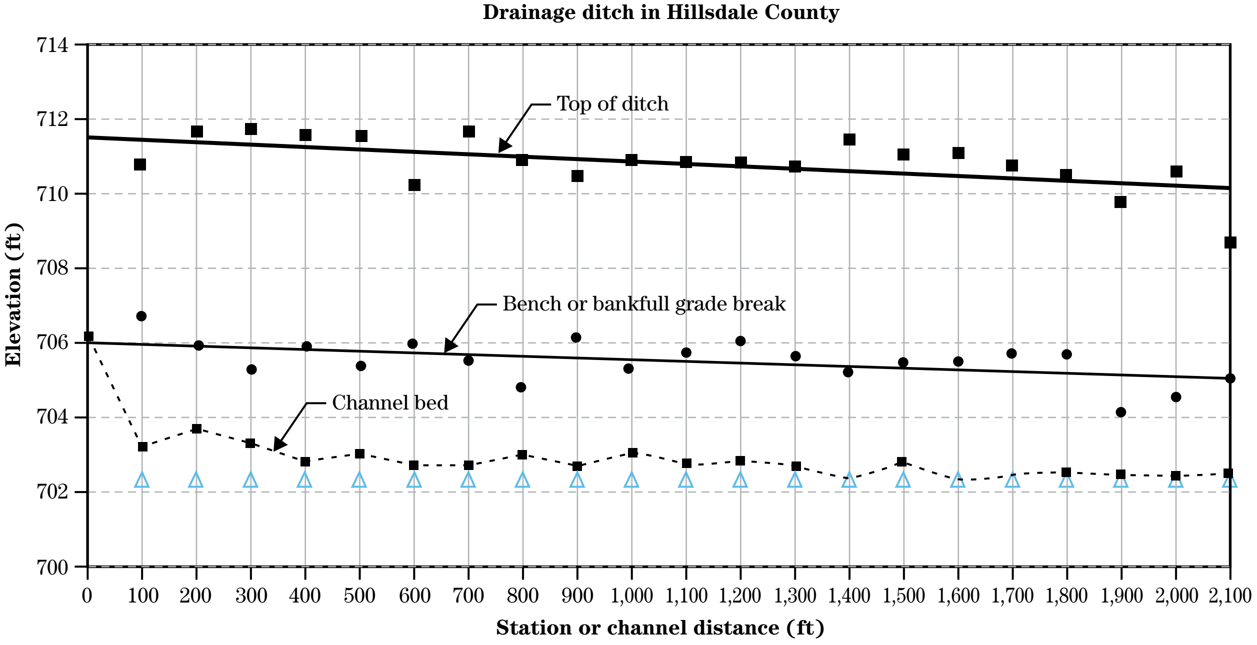
(e) Ditch geometry

A survey of a 2,100-foot length of ditch was performed on July 17, 2003. Station 1+00 is located 100 feet south of the upstream bridge, and station 21+00 is located near the southeast corner of the field on the right bank. This location is close to the Michigan-Ohio state line and the point where the ditch enters a wooded area.

Working conditions in the ditch were difficult because of steep slopes, dense vegetation, and deep deposits of fine sediment in the bottom of the ditch. Therefore, cross-sectional data were obtained by locating a person with a rod and receiver on each side of the ditch and stretching a tape between the two people. Each person took elevation and position data on their side of the ditch and part of the bankfull channel. Notes were made indicating the location of the thalweg in the bankfull channel, and the water depth. Thalweg data were then used in place of conducting a separate profile survey. Also, grade-break data and top-of-bank data were extracted from the cross-sectional data to obtain profiles of these features. Profiles of the various features are shown in figure 10–8. All elevation data are relative to an arbitrary datum. For most of the ditch, the bed slope varied from 0.05 to 0.2 percent.

A typical cross section is shown in figure 10–9, with a possible new design with a 4:1 overtopped width to channel-width ratio. For a 4:1 ratio, the total width of the benches is three times the width of the bankfull channel. The top width of the bankfull channel is 10 feet, the mean depth is 1.8 feet, and the maximum depth is 2.3 feet. Based on an analysis of the data, the maximum stable size of this channel might be 12.3 feet wide, with a mean depth of 2.2 feet, and a maximum depth of 2.8 feet. The channel has a 0.1 percent slope, the channel dimensions estimated from the regional curve (top width of 10 ft and maximum depth of 2.3 ft), and an over bench flow width to channel width ratio of 4:1. The 0.2-year recurrence interval discharge almost fills the small channel, the 1.6-year recurrence interval discharge fills the channel to a depth of about 4.5 feet, and the stage for the 100-year discharge is just over 5.5 feet. For these conditions, fine sediment will be flushed from the bankfull channel, and substrate with a mean size of about 3 to 4 millimeters will be established.

Figure 10–8 Profiles of the bed, bench, and top of ditch



This ditch was cleaned out about 6 years prior to this survey and only exhibited intermittent small bench formations along much of its length. There was up to 2 feet of sediment deposited on the bed in the first few hundred feet, perhaps because of the culvert configuration and a rapid change in bed elevation. Further downstream from the bridge, the bench formations improved, the depth of the sediment deposits decreased, and in places (1,000 to 1,400 ft), clean, coarse substrate was observed in the bottom of the bankfull channel.

(f) Bed material and bed-load transport

The measured D_{50} and D_{84} for reaches 600 to 800 feet, 800 to 1,000 feet, and 1,000 to 1,200 feet were <1 millimeter, <1 millimeter and 12 millimeters, and 3 millimeters and 10 millimeters, respectively. More than 80 percent of the bed material was clay and silt where there were only small intermittent benches (600–800 ft). In the next two reaches, the bench development was more pronounced, and the main channel was narrower, resulting in the coarse substrate sizes. Pebble counts for the last 200 feet (1,000–1,200 ft, fig 10–6a) had the coarsest substrate, widest benches, and narrowest bankfull channel.

The mean bed-material size is associated with the tractive force (mean shear stress) on the bed and can be estimated as (Ward and Trimble 2004):

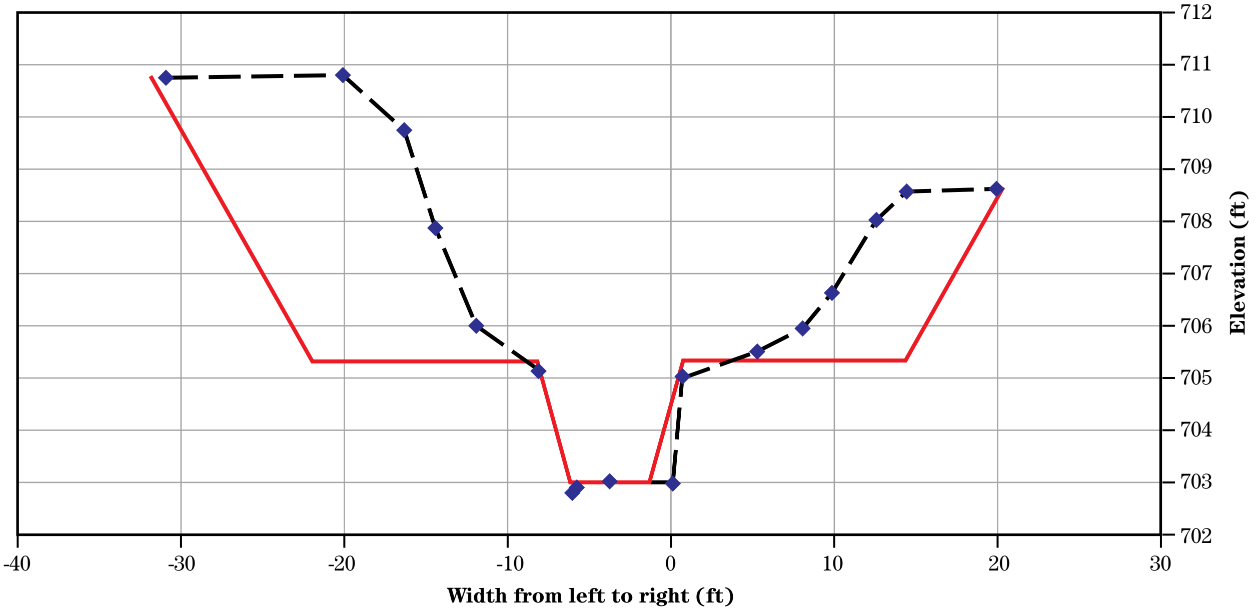
$$D_{50} = 1000ds$$

where:

D_{50} = particle size (mm)
d = flow depth (m)
s = bed slope (ft/ft)

Therefore, a 0.6-meter (2.0 ft) bankfull discharge depth in a channel with a bed slope of 0.1 percent might result in a D_{50} of 6 millimeters. The bed slope varies from 0.05 to 0.2 percent, and the bankfull discharge depth is 1.8 to 2.5 feet, so the probable D_{50} is about 3 to 13 millimeters. This is in good agreement with the measured D_{50} and D_{84} of 3 millimeters and 10 millimeters in the channel at reach 1,000 to 1,200 feet, where fluvial benches have formed.

Figure 10–9 Pre- (dashed line) and post- (solid line) maintenance geometries at a location with a grade break, but weak bench formation at the elevation where it was determined that a bench would naturally form. The existing main channel has a similar geometry to the projected geometry.



While this equation is readily applied, it should be noted that it contains some inherent assumptions. Its use assumes that sufficient coarse material is available to form the armor layer. If sufficient coarse material is not available, then this approach may not be advisable.

Actual bed-load transport is difficult to quantify because of the complexity of the system and the lack of any sediment transport data. Relative bed-load estimates were obtained by relating bed-load transport to the current channel conditions: a bed slope of 0.1 percent and a D_{50} of 2 millimeters. The geometry for current conditions was approximated as a cross-sectional area that is three times the area predicted by the regional curve and an over-bench flow width to channel width ratio of 1.5. The results of the bed-load transport analysis results are summarized in table 10–2. It is anticipated that fluvial processes will establish a coarse substrate with a mean particle size of 4 to 8 millimeters, and bed-load transport will be less than half current rates. Following the flushing of deposited fines, and bench building by fluvial processes, the total sediment export will primarily be a function of conservation practices on the landscape and ditch instability problems upstream of this reach.

(g) Discussion

In establishing two-stage geometry, the ditch is widened at the elevation that corresponds to existing bench features or the elevation at which these benches are predicted to form from fluvial processes. Vegetation is left along the fringe of the existing channel, and no work is done to reshape or narrow the current channel. The benches will vegetate quickly, and it is anticipated that the channel will adjust its shape as a function of fluvial processes.

A much debated and often controversial issue is the type of vegetation that should be established on the benches and at the top of the ditches. Trees provide many benefits in natural stream systems and are particularly important for the aquatic biota. However, in straightened, channelized systems, grass might provide better overall benefits. Often trees will affect the ability of nature to establish stable benches, as much of the stability of these systems depends on the dense grass cover that quickly establishes, in the absence of trees. A way of viewing these systems is to think of the small bankfull channels as meadow streams (Rosgen type E channels) that lack the sinuosity that occurs in natural systems. Therefore, trees will often provide the most benefit if they are set back from a grass buffer at the top of the two-stage system or at locations where there is a wide, well-attached flood plain—something that is rarely found in watersheds with extensive networks of agricultural ditches. Constructing wide benches with a 10:1 or larger flood-width ratio might be considered, but that approach will be very expensive in locations where the main function of the ditches is primarily to convey discharges from subsurface drainage systems. In those situations, the ditches must be more than 5 feet deep and sometimes are more than 10 feet deep.

Table 10–2 Relative bed-load transport for various channel conditions

Geometry	Bed slope 0.05%		Bed slope 0.1%		Bed slope 0.2%	
	Relative bed load	D_{50} (mm)	Relative bed load	D_{50} (mm)	Relative bed load	D_{50} (mm)
Current	0.36	2	1	2	2.45	2
3:1 bench ratio	0.06–0.18	4–6	0.28–0.49	6–8	1.03–1.38	8–10
4:1 bench ratio	0.04–0.16	4–6	0.25–0.45	6–8	0.96–1.30	8–10

The primary costs of two-stage ditches are associated with the increased ditch width required. This increased width requires additional initial earthwork. Costs for construction increase with both watershed size and ditch depth and might range from $5 to $20 per linear foot.

Creating a low bench typically requires the top width of the ditch to be greater than what would be required for a traditional trapezoidal channel. It is important to note that the wider ditch top width results in the surrendering of surrounding agricultural production land. To offset landowner costs, the potential for including the bench width in buffer conservation programs should be considered. Buffers have typically been measured from the top of the ditch. Alternatively measuring from the top of the small channel to include the bench and the main side slope of the ditch is preferable from a water-quality perspective and profitability perspective.

In many locations, a do nothing approach might be considered. Removing benches will only provide an increase in the conveyance capacity of the ditch. However, this improvement might only be temporary. If subsurface drains are free flowing and not blocked by bench formations, constructing wider benches may provide limited benefit and could disrupt a functional system that currently provides aquatic and terrestrial habitat and water quality benefits.

654.1008 Conclusion

In channelized ditches and streams that are entrenched and have overwidened bed widths, alluvial channel processes try to develop a flood plain that consists of low benches. Often, these ditches show improved stability. The techniques presented in this chapter are based on observations and analysis of the behavior and evolution of traditional trapezoidal earth channels.

The elevation of the benches and size of the bankfull channel can be determined from regional curves that relate channel dimensions to drainage area. The design approach considers the magnitude and design frequency of discharges for both stages of the channel. It is anticipated that total bench widths that are two to four times the bankfull channel width will result in a stable geometry and a channel with low sinuosity. The overall conveyance capacities of these two-stage systems can be sized based on the probability of out-of-ditch flooding into adjacent areas.

Construction of a two-stage channel system requires a significant capital investment to create a wider design top width. However, it is anticipated that two-stage systems will have improved conveyance capacity, be more self-sustaining, and create and maintain improved aquatic habitat.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 11

Rosgen Geomorphic Channel Design

Issued August 2007

Cover photo: Stream restoration project, South Fork of the Mitchell River, NC, three months after project completion. The Rosgen natural stream design process uses a detailed 40-step approach.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 11 Rosgen Geomorphic Channel Design

Contents

Tables

Figures

Chapter 11 Rosgen Geomorphic Channel Design

654.1100 Purpose

This chapter outlines a channel design technique based on the morphological and morphometric qualities of the Rosgen classification system. While this approach is written in a series of steps, it is not a cookbook. This approach is often referred to as the Rosgen design approach. The essence for this design approach is based on measured morphological relations associated with bankfull flow, geomorphic valley type, and geomorphic stream type. This channel design technique involves a combination of hydraulic geometry, analytical calculation, regionalized validated relationships, and analogy in a precise series of steps. While this technique may appear to be straightforward in its application, it actually requires a series of precise measurements and assessments. It is important for the reader to recognize that the successful application of this design approach requires extensive training and experience.

The contents of this chapter were submitted to the technical editors of this handbook as a manuscript titled Natural Channel Design Using a Geomorphic Approach, by Dave Rosgen, Wildland Hydrology, Fort Collins, Colorado. This material was edited to fit the style and format of this handbook. The approaches and techniques presented herein are not universally applicable, just as other approaches and techniques presented in this handbook are not necessarily appropriate in all circumstances. However, the Rosgen Geomorphic Approach for Natural Channel Design has been implemented in many locations and is cited as the methodology of choice for stream restoration by several state and local governments.

654.1101 Introduction

River restoration based on the principles of the Rosgen geomorphic channel design approach is most commonly accomplished by restoring the dimension, pattern, and profile of a disturbed river system by emulating the natural, stable river. Restoring rivers involves securing their physical stability and biological function, rather than the unlikely ability to return the river to a pristine state. Restoration, as used in this chapter, will be used synonymously with the term rehabilitation. Any river restoration design must first identify the multiple specific objectives, desires, and benefits of the proposed restoration. The causes and consequences of stream channel problems must then be assessed.

Natural channel design using the Rosgen geomorphic channel design approach incorporates a combination of analog, empirical, and analytical methods for assessment and design. Because all rivers within a wide range of valley types do not exhibit similar morphological, sedimentological, hydraulic, or biological characteristics, it is necessary to group rivers of similar characteristics into discreet stream types. Such characteristics are obtained from stable reference reach locations by discreet valley types, and then are converted to dimensionless ratios for extrapolation to disturbed stream reaches of various sizes.

The proper utilization of this approach requires fundamental training and experience using this geomorphic method. Not only is a strong background in geomorphology, hydrology, and engineering required, but the restoration specialist also must have the ability to implement the design in the field. The methodology is divided into eight major sequential phases:

I Define specific restoration objectives associated with physical, biological, and/or chemical process.

II Develop regional and localized specific information on geomorphologic characterization, hydrology, and hydraulics.

III Conduct a watershed/river assessment to determine river potential; current state; and the nature, magnitude, direction, duration, and consequences of change. Review land use history and time trends of river change. Isolate the primary causes of instability and/or loss of physical and biological function. Collect and analyze field data including reference reach data to define sedimentological, hydraulic, and morphological parameters. Obtain concurrent biological data (limiting factor analysis) on a parallel track with the physical data.

IV Initially consider passive restoration recommendations based on land use change in lieu of mechanical restoration. If passive methods are reasonable to meet objectives, skip to the monitoring phase (VIII). If passive efforts and/or recovery potential do not meet stated multiple objectives, proceed with the following phases.

V Initiate natural channel design with subsequent analytical testing of hydraulic and sediment transport relations (competence and capacity).

VI Select and design stabilization/enhancement/vegetative establishment measures and materials to maintain dimension, pattern, and profile to meet stated objectives.

VII Implement the proposed design and stabilization measures involving layout, water quality control, and construction staging.

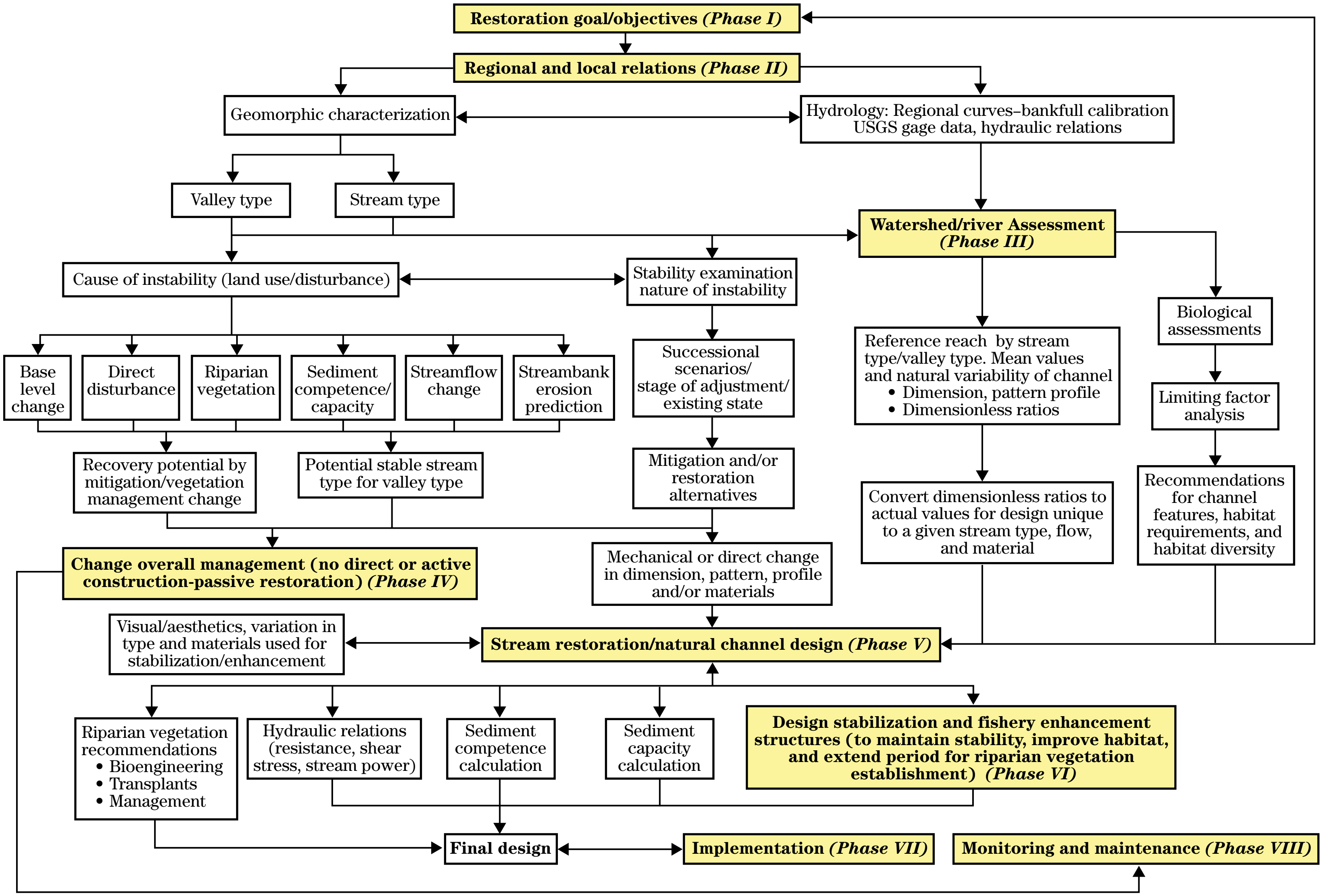
VIII Design a plan for effectiveness, validation, and implementation monitoring to ensure stated objectives are met, prediction methods are appropriate, and the construction is implemented as designed. Design and implement a maintenance plan.

The conceptual layout for the phases of the Rosgen geomorphic channel design approach is shown in figure 11–1. The various phases listed above are indicated on this generalized layout. The flowchart is indicative of the full extent and complexity associated with this method.

Because of the complexity and uncertainty of natural systems, it becomes imperative to monitor each restoration project. The following are three objectives of such monitoring:

- Ensure correct implementation of the design variables and construction details.
- Validate the analog, empirical, and analytical methods used for the assessment and design.
- Determine effectiveness of the restoration methods to the stated physical and biological restoration objectives.

Figure 11–1 River restoration using Rosgen geomorphic channel design approach



654.1102 Restoration phases

(a) Phase I—Restoration objectives

It is very important to obtain clear and concise statements of restoration objectives to appropriately design the solution(s). The potential of a certain stream to meet specific objectives must be assessed early on in the planning phases so that the initial restoration direction is appropriate. The common objectives are:

- flood level reduction
- streambank stability
- reduce sediment supply, land loss, and attached nutrients
- improve visual values
- improve fish habitat and biological diversity
- create a natural stable river
- withstand floods
- be self-maintaining
- be cost-effective
- improve water quality
- improve wetlands

It is essential to fully describe and understand the restoration objectives. The importance of formulating clear, achievable, and measurable objectives is described in detail in NEH654.02. Often the objectives can be competing or be in conflict with one another. Conflict resolution must be initiated and can often be offset by varying the design and/or the nature of stabilization methods or materials planned.

The assessment required must also reflect the restoration objectives to ensure various related processes are thoroughly evaluated. For example, if improved fishery abundance, size, and species are desired, a limiting factor analysis of habitat and fish populations must be linked with the morphological and sedimentological characteristics.

(b) Phase II—Developing local and regional relations in geomorphic characterization, hydrology, and hydraulics

Geomorphic characterization

The relations mapped at this phase are the geomorphic characterization and description levels for stream classification (Rosgen 1994, 1996). Valley types (table 11–1) are mapped prior to stream classification to ensure reference reach data are appropriately applied for the respective valley types being studied. Morphological relations associated with stream types are presented in figures 11–2 (Rosgen 1994) and 11–3 (Rosgen 1996) and summarized in table 11–2. In natural channel design using the Rosgen geomorphic channel design approach, it is often advantageous to have an undisturbed and/or stable river reach immediately upstream of the restoration reach. Reference reach data are obtained and converted to dimensionless ratio relations to extrapolate channel dimension, pattern, profile, and channel material data to rivers and valleys of the same type, but of different size. If an undisturbed/stable river reach is not upstream of the restoration reach, extrapolation of morphological and dimensionless ratio relations by valley and stream type is required for both assessment and design.

An example of the form used to organize reference reach data, including dimensionless ratios for a given stream type, is presented in table 11–3. Specific design variables use reference reach data for extrapolation purposes, assuming the same valley and stream type as represented. These relations are only representative of a similar stable stream type within a valley type of the disturbed stream.

Hydrology

The hydrology of the basin is often determined from regional curves constructed from long-term stream gage records. Relationships of flow-duration curves and flood-frequency data are used for computations in both the assessment and design phases. Stream Hydrology is also addressed in NEH654.05. Relations are converted to dimensionless formats using bankfull discharge as the normalization parameter. Bankfull discharge and dimensions associated with stream gages are plotted as a function of drainage area for extrapolation to ungaged sites in similar hydro-physiographic provinces. A key requirement in the development of

Table 11–1 Valley types used in geomorphic characterization

Valley types	Summary description of valley types
I	Steep, confined, V-notched canyons, rejuvenated side slopes
II	Moderately steep, gentle-sloping side slopes often in colluvial valleys
III	Alluvial fans and debris cones
IV	Gentle gradient canyons, gorges, and confined alluvial and bedrock-controlled valleys
V	Moderately steep, U-shaped glacial-trough valleys
VI	Moderately steep, fault, joint, or bedrock (structural) controlled valleys
VII	Steep, fluvial dissected, high-drainage density alluvial slopes
VIII	Wide, gentle valley slope with well-developed flood plain adjacent to river and/or glacial terraces
IX	Broad, moderate to gentle slopes, associated with glacial outwash and/or eolian sand dunes
X	Very broad and gentle valley slope, associated with glacio- and nonglacio-lacustrine deposits
XI	Deltas

Figure 11–2 Broad-level stream classification delineation showing longitudinal, cross-sectional, and plan views of major stream types

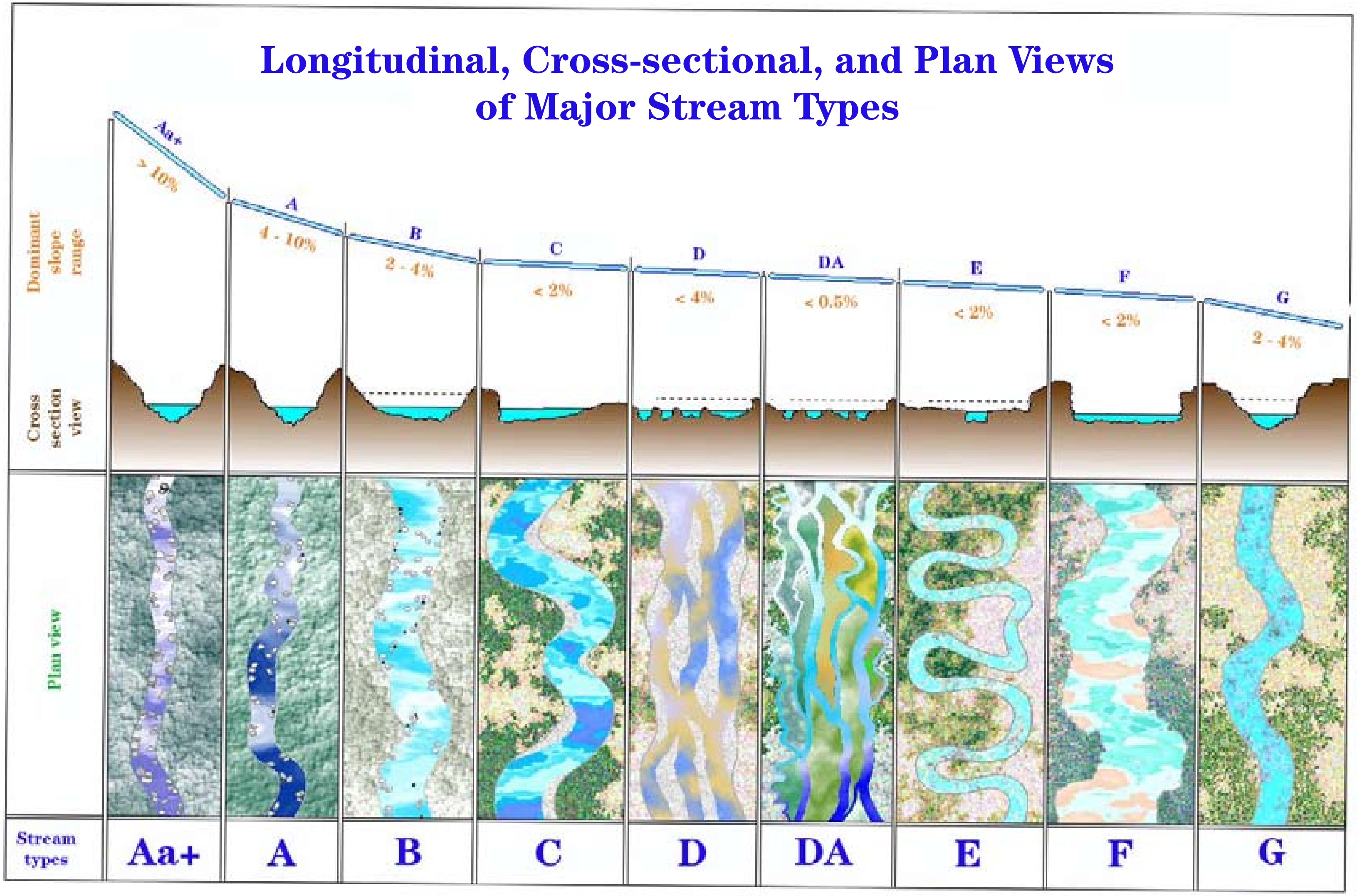
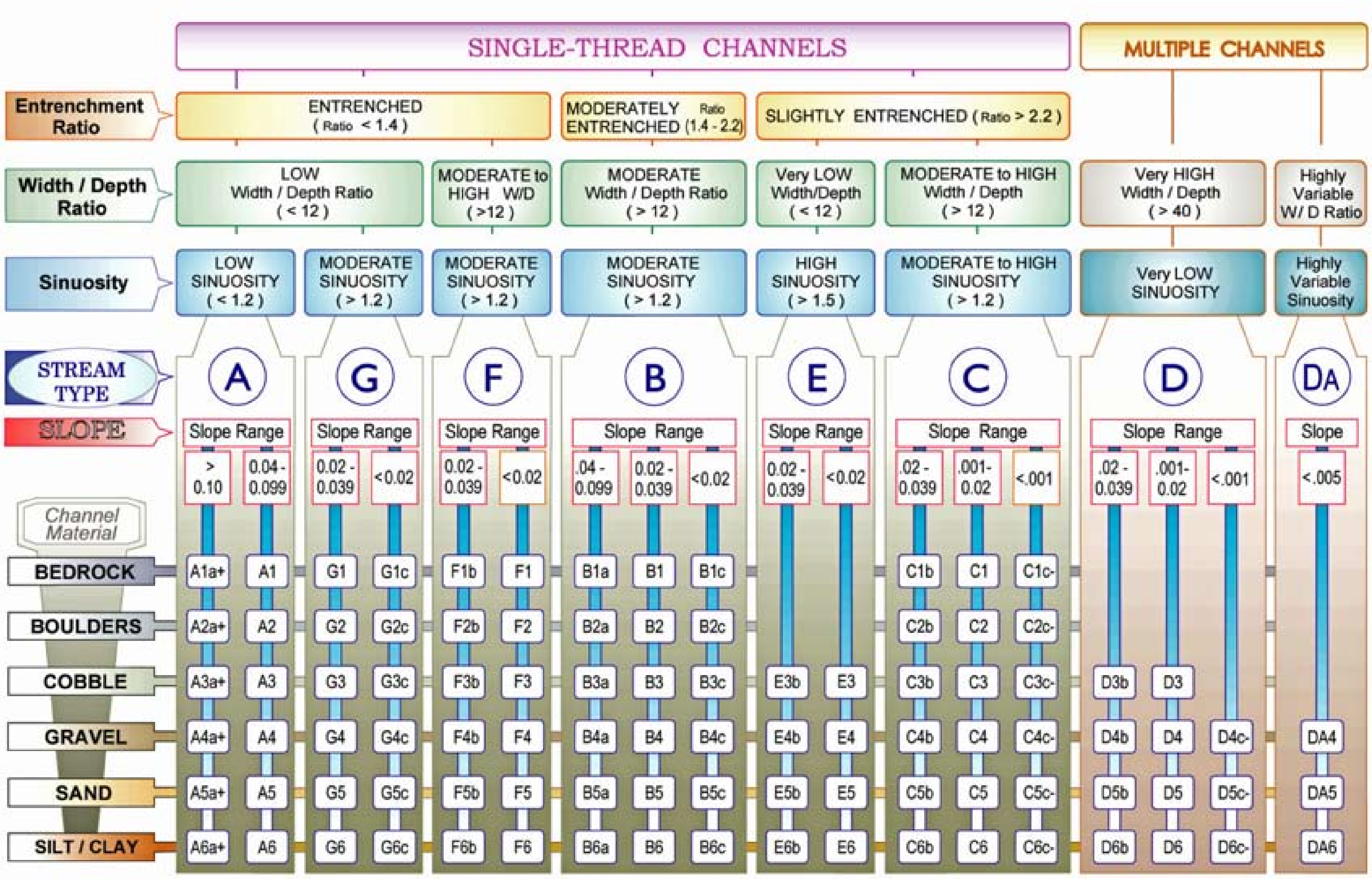


Figure 11–3 Classification key for natural rivers



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Table 11–2 General stream type descriptions and delineative criteria for broad-level classification (level 1)

Stream type	General description	Entrenchment ratio	W/d ratio	Sinuosity	Slope	Landform/ soils/features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams	<1.4	<12	1.0 to 1.1	>.10	Very high relief. Erosional, bedrock, or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls
A	Steep, entrenched, cascading, step-pool streams. High energy/ debris transport associated with depositional soils. Very stable if bedrock or boulder-dominated channel	<1.4	<12	1.0 to 1.2	.04 to .10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology
B	Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools. Very stable plan and profile. Stable banks	1.4 to 2.2	>12	>1.2	.02 to .039	Moderate relief, colluvial deposition and/or structural. Moderate entrenchment and width-to-depth ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools
C	Low gradient, meandering, point bar, riffle/pool, alluvial channels with broad, well-defined flood plains	>2.2	>12	>1.2	<.02	Broad valleys with terraces, in association with flood plains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/ pool bed morphology
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks	n/a	>40	n/a	<.04	Broad valleys with alluvium, steeper fans. Glacial debris and depositional features. Active lateral adjustment with abundance of sediment supply. Convergence/divergence bed features, aggradational processes, high bed load and bank erosion
DA	Anastomizing (multiple channels) narrow and deep with extensive, well-vegetated flood plains and associated wetlands. Very gentle relief with highly variable sinuosities and width-to-depth ratios. Very stable streambanks	>2.2	Highly variable	Highly variable	<.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomized (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland flood plains. Very low bed-load, high wash load sediment
E	Low gradient, meandering riffle/pool stream with low width-to-depth ratio and little deposition. Very efficient and stable. High meander width ratio	>2.2	<12	>1.5	<.02	Broad valley/meadows. Alluvial materials with flood plains. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low width-to-depth ratios
F	Entrenched meandering riffle/pool channel on low gradients with high width-to-depth ratio	<1.4	>12	>1.2	<.02	Entrenched in highly weathered material. Gentle gradients with a high width-to-depth ratio. Meandering, laterally unstable with high bank erosion rates. Riffle/pool morphology
G	Entrenched gully step-pool and low width-to-depth ratio on moderate gradients	<1.4	<12	>1.2	.02 to .039	Gullies, step-pool morphology with moderate slopes and low width-to-depth ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials (fans or deltas). Unstable, with grade control problems and high bank erosion rates

Table 11–3 Reference reach summary data form

River Reach Summary Data

Channel dimension

Mean riffle depth (d_{bkf})		ft	Riffle width (W_{bkf})		ft	Riffle area (A_{bkf})		ft^2
Mean pool depth (d_{bkfp})		ft	Pool width (W_{bkfp})		ft	Pool area (A_{bkfp})		ft^2
Mean pool depth/mean riffle depth		d_{bkfp}/ (d_{bkf})	Pool width/riffle width		W_{bkfp} /W_{bkf}	Pool area/riffle area		A_{bkfp}/ A_{bkf}
Max riffle depth (d_{mbkf})		ft	Max pool depth (d_{mbkfp})		ft	Max riffle depth/mean riffle depth		
Max pool depth/mean riffle depth						Point bar slope		
Streamflow: estimated mean velocity at bankfull stage (u_{bkf})					ft/s	Estimation method		
Streamflow: estimated discharge at bankfull stage (Q_{bkf})					ft^3/s	Drainage area		mi^2

Channel pattern

Geometry	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Meander length (Lm)				ft	Meander length ratio (Lm/W_{bkf})			
Radius of curvature (Rc)				ft	Radius of curvature/riffle width (Rc/W_{bkf})			
Belt width (W_{blt})				ft	Meander width ratio (W_{blt}/W_{bkf})			
Individual pool length				ft	Pool length/riffle width			
Pool to pool spacing				ft	Pool to pool spacing/riffle width			

Channel profile

Valley slope (VS)		ft/ft	Average water surface slope (S)		ft/ft	Sinuosity (VS/S)	
Stream length (SL)		ft	Valley length (VL)		ft	Sinuosity (SL/VL)	

Low bank height (LBH)	start		ft	Max riffle depth	start		ft	Bank height ratio (LBH/max riffle depth)	start	
	end		ft		end		ft		end	

Facet slopes	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle slope (S_{rif})				ft/ft	Riffle slope/average water surface slope (S_{rif}/S)			
Run slope (S_{run})				ft/ft	Run slope/average water surface slope (S_{run}/S)			
Pool slope (S_p)				ft/ft	Pool slope/average water surface slope (S_p/S)			
Glide slope (S_g)				ft/ft	Glide slope/average water surface slope (S_g/S)			

Feature midpoint[a]	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle depth (d_{rif})				ft	Riffle depth/mean riffle depth (d_{rif}/d_{bkf})			
Run depth (d_{run})				ft	Run depth/mean riffle depth (d_{run}/d_{bkf})			
Pool depth (d_p)				ft	Pool depth/mean riffle depth (d_p/d_{bkf})			
Glide depth (d_g)				ft	Glide depth/mean riffle depth (d_g/d_{bkf})			

Channel materials

Geometry		Reach[b]	Riffle[c]	Bar		Reach[b]	Riffle[c]	Bar	
% Silt/clay					D_{16}				mm
% Sand					D_{35}				mm
% Gravel					D_{50}				mm
% Cobble					D_{84}				mm
% Boulder					D_{95}				mm
% Bedrock					D_{100}				mm

a/ Minimum, maximum, mean depths are the average midpoint values except pools which are taken at deepest part of pool
b/ Composite sample of riffles and pools within the designated reach
c/ Active bed of a riffle

such relations is the necessity to field-calibrate the bankfull stage at each gage within a hydro-physiographic province (a drainage basin similar in precipitation/runoff relations due to precipitation/elevation, lithology and land uses).

Regional curves—The field-calibrated bankfull stage is used to obtain the return period associated with the bankfull discharge. Regional curves of bankfull discharge versus drainage area are developed (fig. 11–4) (adapted from Dunne and Leopold 1978)). To plot bankfull dimensions by drainage area, the U.S. Geological Survey (USGS) 9–207 data (summary of stream discharge measurements at the gage) are obtained to plot the at-a-station hydraulic geometry relations (fig. 11–5 (adapted from Rosgen 1996; Rosgen and Silvey 2005)). These data are then converted to dimensionless hydraulic geometry data by dividing each value by their respective bankfull value. These relations are used during assessment and design to indicate the shape of the various cross sections from low flow to high flow. In the development of the dimensionless hydraulic geometry data, current meter measurements must be stratified by stream type (Rosgen 1994, 1996) and for specific bed features such as riffles, glides, runs, or pools.

Figure 11–4 Regional curves from stream gaging stations showing bankfull discharge (ft^3/s) vs. drainage area (mi^2)

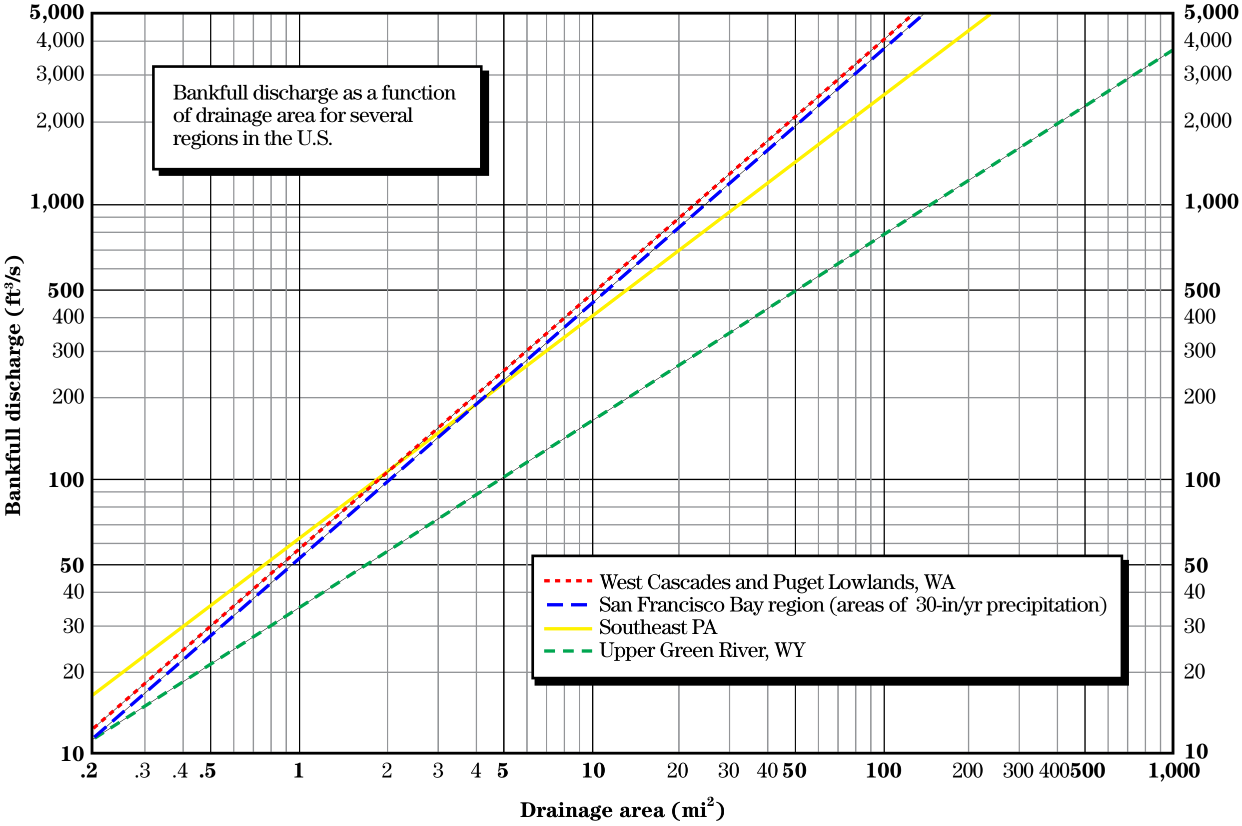
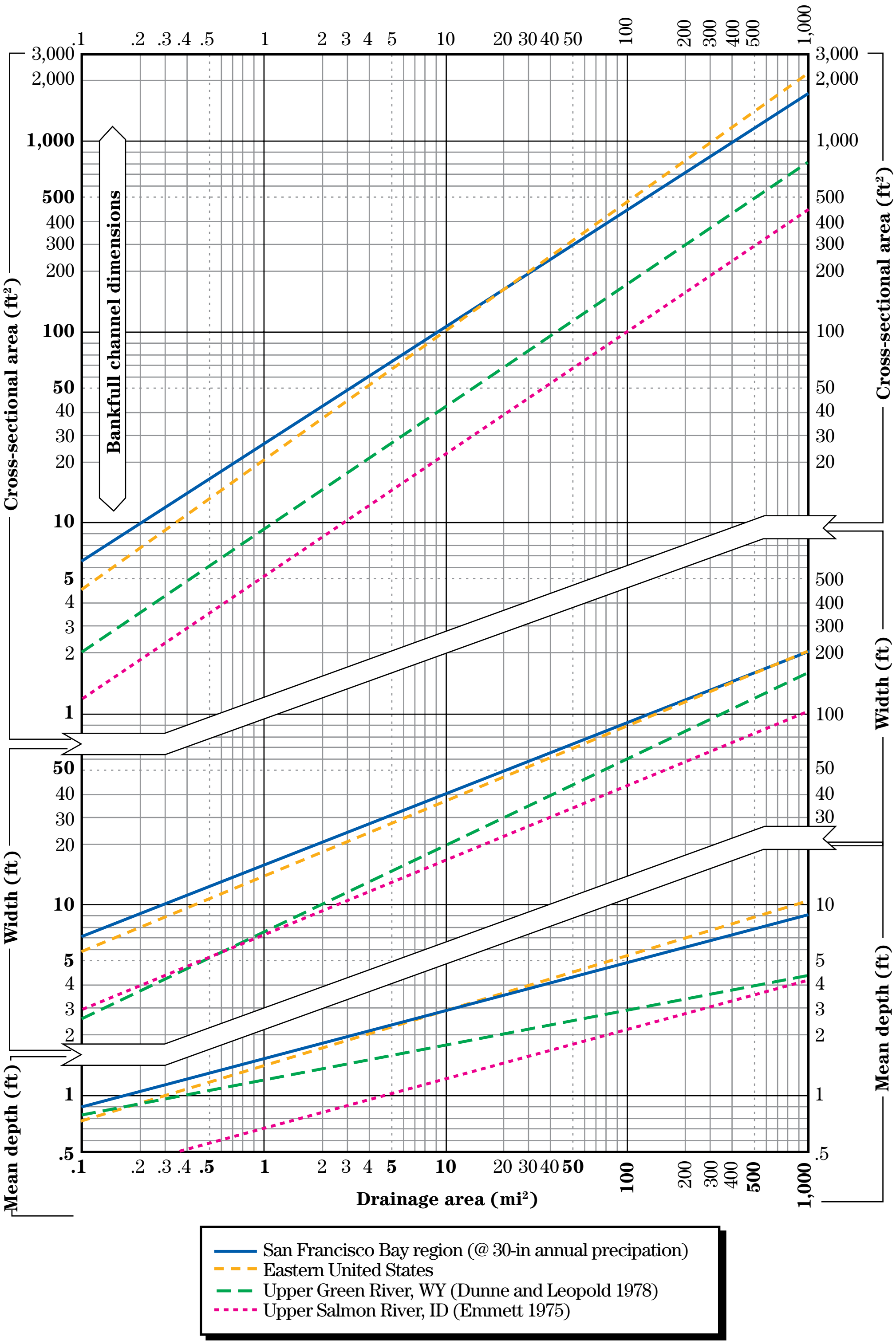


Figure 11–5 Regional curves from stream gage stations showing bankfull dimensions (width, depth, and cross-sectional area) vs. drainage area (mi^2)



Hydraulic relations

Hydraulic relations are validated using resistance equations for velocity prediction at ungaged sites. (Stream Hydraulics is addressed in more detail in NEH654.06) Validation is accomplished by back calculating relative roughness (R/D_{84}) and a friction factor (u/u^*) from actual measured velocity for a range of streamflows including bankfull:

$$u = \left[2.83 + 5.66 \log\left(\frac{R}{D_{84}}\right)\right] u* \qquad \text{(eq. 11–1)}$$

where:
u = mean velocity (ft/s)
R = hydraulic radius
D_{84} = diameter of bed material of the 84th percentile of riffles
u^* = shear velocity $(gRS)^{1/2}$
g = gravitational acceleration
S = slope

Measured velocity, slope, channel material, and hydraulic radius data from various Colorado rivers using this friction factor (u/u^*) and relative roughness (R/D_{84}) relation are shown in figure 11–6 (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005).

Manning's *n* (roughness coefficient) can also be back-calculated from measured velocity, slope, and hydraulic radius. Another approach to predict velocity at ungaged sites is to predict Manning's *n* from a friction factor back-calculated from relative roughness shown in figure 11–7 (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005). Manning's *n* can also be estimated at the bankfull stage by stream type as shown in the relationship from gaged, large streams in figure 11–8. Vegetative influence is also depicted in these data (Rosgen 1994).

Dimensionless flow-duration curves—Flow-duration curves (based on mean daily discharge) are also obtained from gage stations then converted to dimensionless form using bankfull discharge as the normalization parameter (fig. 11–9 (Emmett 1975)). The purpose of this form is to allow the user to extrapolate flow-duration curves to ungaged basins. This relationship is needed for the annual suspended and bed-load sediment yield calculation along with channel hydraulic variables.

(c) Phase III—Watershed and river assessment

Land use history is a critical part of watershed assessment to understand the nature and extent of potential impacts to the water resources. Past erosional/depositional processes related to changes in vegetative cover, direct disturbance, and flow and sediment regime changes provide insight into the direction and detail for assessment procedures required for restoration. Time series of aerial photos are of particular value to understand the nature, direction, magnitude, and rate of change. This is very helpful, as it assists in assessing both short-term, as well as long-term river problems.

Assessment of river stability and sediment supply

River stability (equilibrium or quasi-equilibrium) is defined as the ability of a river, over time, in the present climate to transport the flows and sediment produced by its watershed in such a manner that the stream maintains its dimension, pattern, and profile without either aggrading or degrading (Rosgen 1994, 1996, 2001d). A stream channel stability analysis is conducted along with riparian vegetation inventory, flow and sediment regime changes, limiting factor analysis compared to biological potential, sources/causes of instability, and adverse consequences to physical and biological function. Procedures for this assessment are described in detail by Rosgen (1996, 2001d) and in Watershed Assessment and River Stability for Sediment Supply (WARSSS) (Rosgen 1999, 2005).

It is important to realize the difference between the dynamic nature of streams and natural adjustment processes compared to an acceleration of such adjustments. For example, bank erosion is a natural channel process; however, accelerated streambank erosion must be understood when the rate increases and creates a disequilibrium condition. Many stable rivers naturally adjust laterally, such as the "wandering" river. While it may meet certain local objectives to stabilize high risk banks, it would be inadvisable to try to "control" or "fix in place" such a river.

In many instances, a braided river and/or anastomizing river type is the stable form. Designing all stream systems to be a single-thread meandering stream may not properly represent the natural stable form. Valley types are a key part of river assessment to understand

Figure 11–6 Relation of channel bed particle size to hydraulic resistance with river data from a variety of eastern and western streams

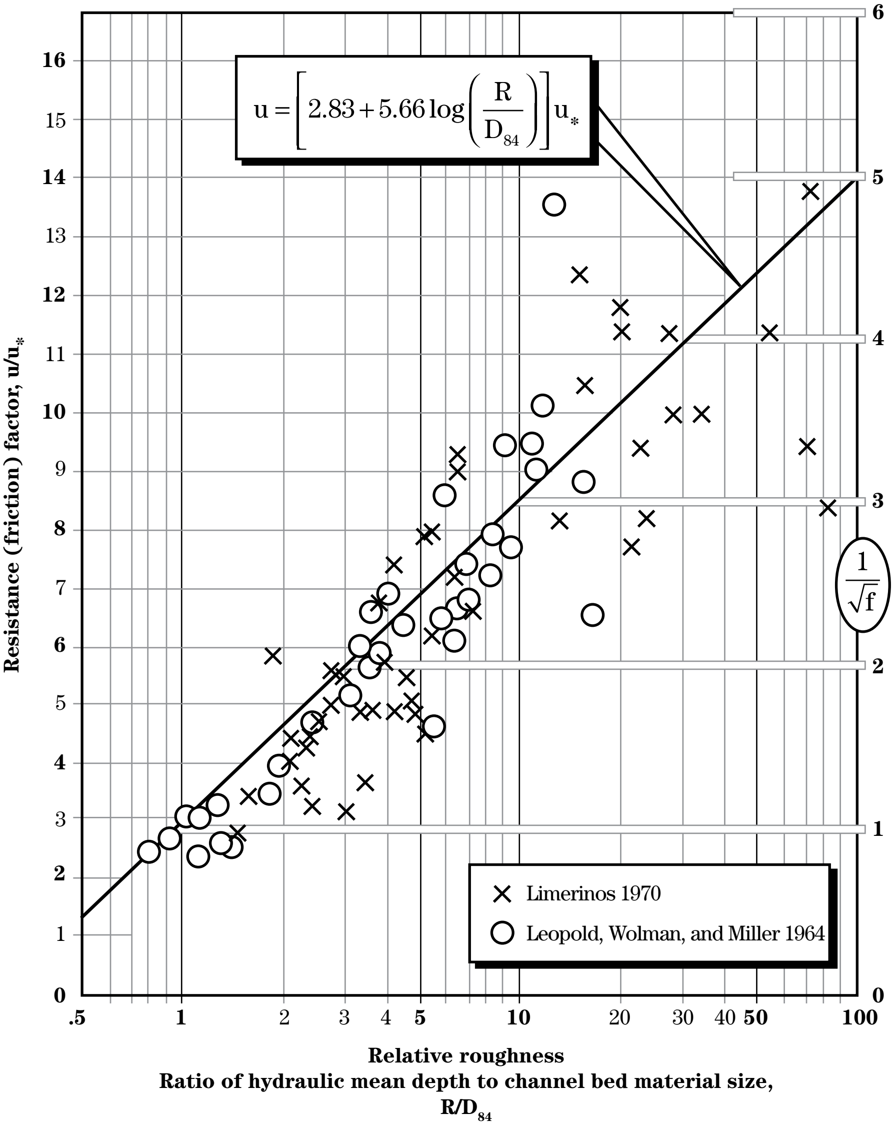
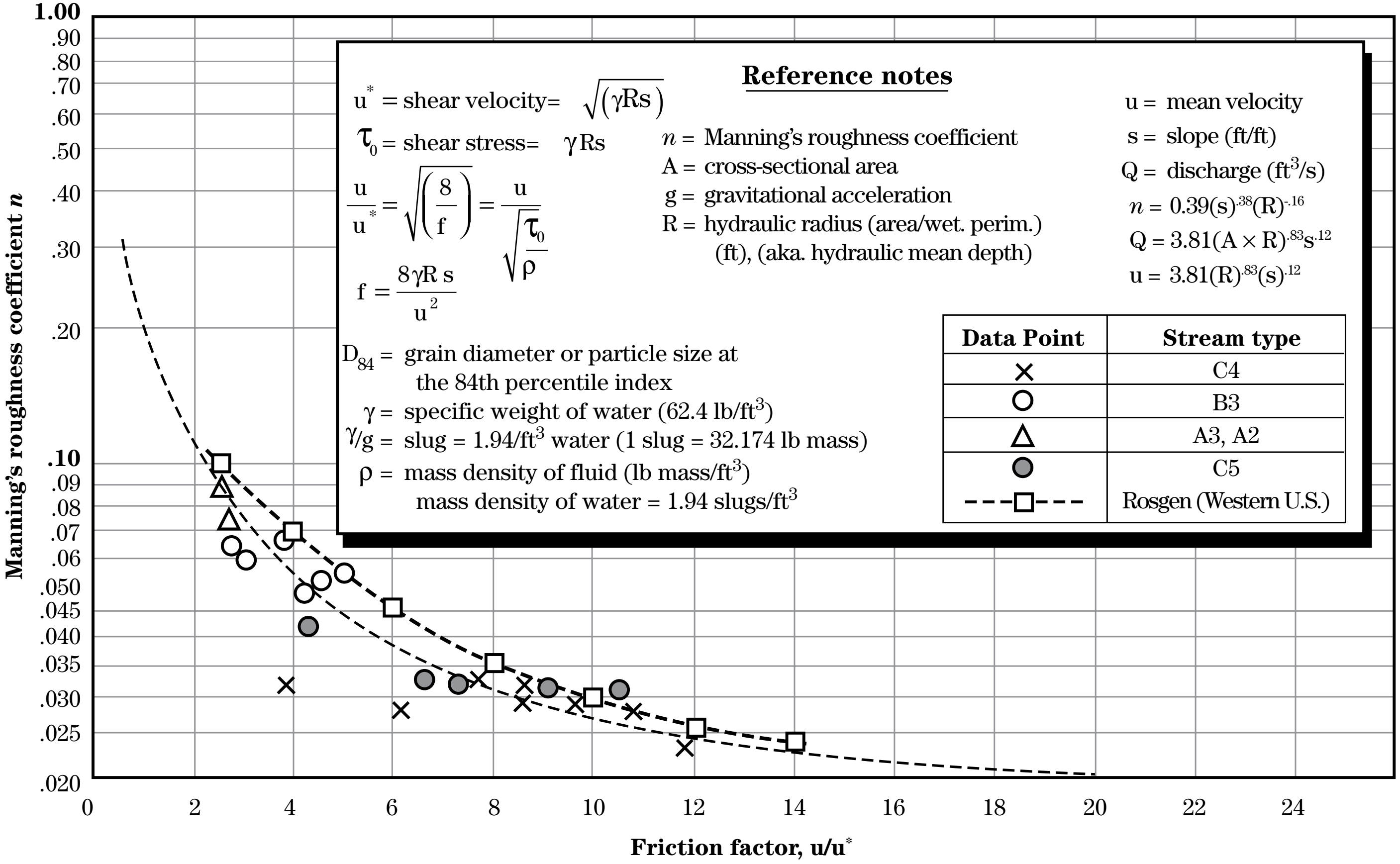


Figure 11–7 Prediction of Manning's *n* roughness coefficient



Reference notes

$u^* =$ shear velocity $= \sqrt{(\gamma R s)}$

$\tau_0 =$ shear stress $= \gamma R s$

$$\frac{u}{u^*} = \sqrt{\left(\frac{8}{f}\right)} = \frac{u}{\sqrt{\frac{\tau_0}{\rho}}}$$

$$f = \frac{8 \gamma R\, s}{u^2}$$

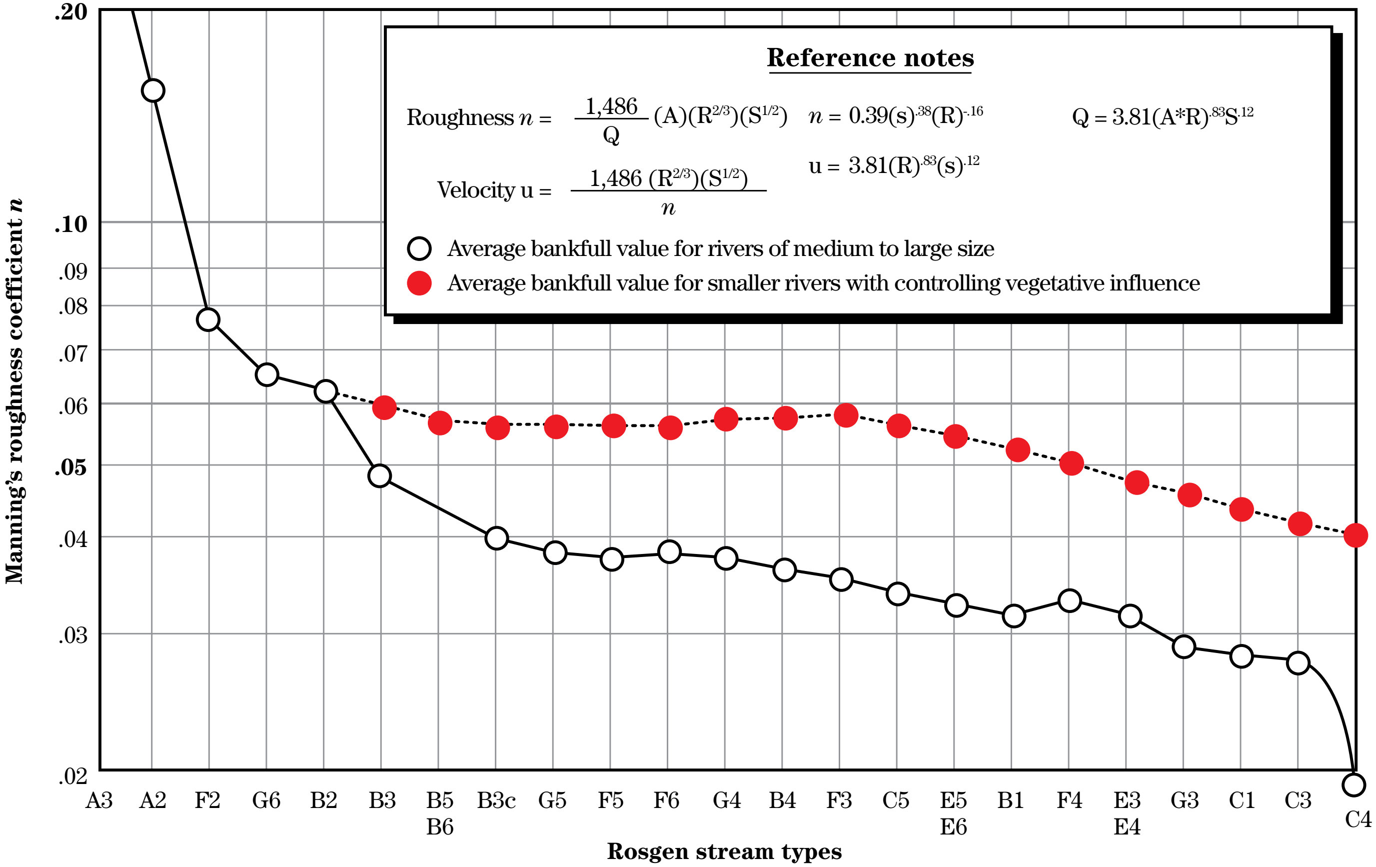
$n =$ Manning's roughness coefficient
A = cross-sectional area
g = gravitational acceleration
R = hydraulic radius (area/wet. perim.) (ft), (aka. hydraulic mean depth)

u = mean velocity
s = slope (ft/ft)
Q = discharge (ft^3/s)
$n = 0.39(s)^{.38}(R)^{-.16}$
$Q = 3.81(A \times R)^{.83} s^{.12}$
$u = 3.81(R)^{.83}(s)^{.12}$

$D_{84} =$ grain diameter or particle size at the 84th percentile index
$\gamma =$ specific weight of water (62.4 lb/ft^3)
$\gamma/g =$ slug = 1.94/ft^3 water (1 slug = 32.174 lb mass)
$\rho =$ mass density of fluid (lb mass/ft^3)
mass density of water = 1.94 slugs/ft^3

Data Point	Stream type
×	C4
○	B3
△	A3, A2
●	C5
- - -□- - -	Rosgen (Western U.S.)

Figure 11–8 Bankfull stage roughness coefficients (*n* values) by stream type for 140 streams in the United States and New Zealand

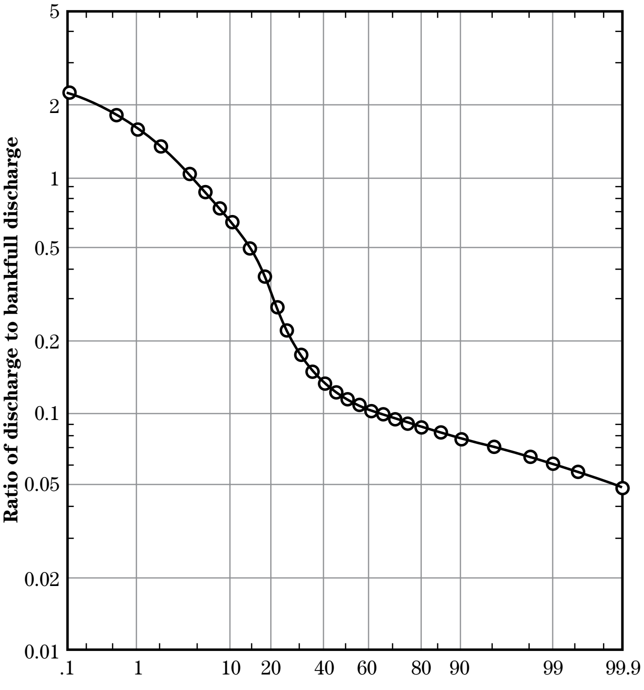


which stream types are stable within a variety of valley types in their geomorphic settings. Reference reaches that represent the stable form have to be measured and characterized only for use in similar valley types. This prevents applying good data to the *wrong* stream type.

Time-trend data using aerial photography is very valuable at documenting channel change. Field evidence using dendrochronology, stratigraphy, carbon dating, paleochannels, or evidence of avulsion and avulsion dates can help the field observer to understand rate, direction, and consequence of channel change.

The field inventory and the number of variables required to conduct a watershed and river stability assessment is substantial. The flowchart in figure 11–10 represents a general summary of the various elements used for assessing channel stability as used in this methodology. The assessment effort is one of the key procedural steps in a sound restoration plan, as it identifies the causes and consequences of the problems leading to loss of physical and biological river function. Some of the major variables are described to provide a *general* overview.

Figure 11–9 Dimensionless flow-duration curve for streamflow in the upper Salmon River area

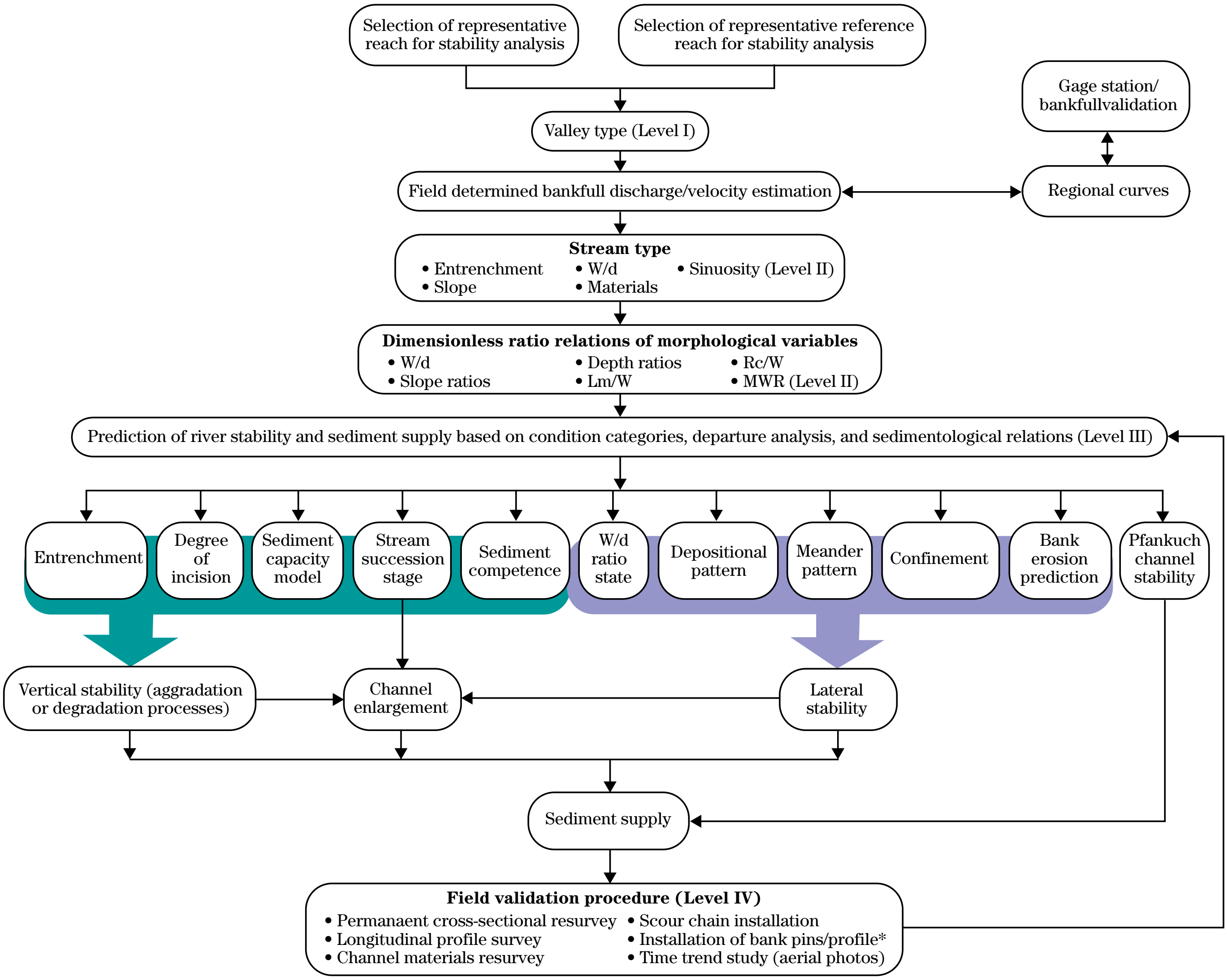


Streamflow change—Streamflow alteration (magnitude, duration, and timing) due to land use changes, such as percent impervious cover, must be determined at this phase. Streamflow models, such as the unit hydrograph approach, must be calibrated by back-calculating what precipitation probability generates bankfull discharge for various antecedent soil moisture and runoff curve numbers. It is critical to separate bankfull discharge from flood flows, as each flow category, including flood flow, has a separate dimension, pattern, and profile. This varies by stream type and the lateral and vertical constraints imposed within the valley (or urban “valley”).

Flow-duration curves by similar hydro-physiographic provinces from gaged stations are converted to bankfull dimensionless flow duration for use in the annual sediment yield calculation. Snowmelt watershed flow prediction output (Troendle, Swanson, and Nankervis 2005) is generally shown in flow-duration changes, rather than an annual hydrograph. Similar model outputs using flow-duration changes are shown in Water Resources Evaluation of Nonpoint Silvicultural Sources (U.S. Environmental Protection Agency (EPA) 1980).

Sediment competence—Sedimentological data are obtained by a field measurement of the size of bar and bed material, bed-load sediment transport, suspended sediment transport, and bankfull discharge measurements at the bankfull stage. Sediment relations are established by collecting energy slope, hydraulic radius, bed material, bar material, and the largest particle produced by the drainage immediately upstream of the assessment reach. Critical dimensionless shear stress is calculated from field data to determine *sediment competence* (ability to move the largest particle made available to the channel). Procedures for this field inventory are presented in Andrews (1984) and Rosgen (2001a, 2001d, 2005). Potential aggradation, degradation, and channel enlargement are predicted for the disturbed reach, comparing the required depth and slope necessary to transport the largest size sediment available. These calculations can be accomplished by hand, spreadsheet, or by commercially available computer programs.

Figure 11–10 Generalized flowchart of application of various assessment levels of channel morphology, stability ratings, and sediment supply



*Optional: sediment measurements (largest size moved at bankfull, D_i)

Changes in channel dimension, pattern, and profile are reflected in changes of velocity, depth, and slope. These changes in the hydraulic variables are reflected in values of shear stress. Shear stress is defined as:

$$\tau = \gamma RS \qquad \text{(eq. 11–2)}$$

where:
τ = bankfull shear stress (lb/ft^2)
γ = specific weight of water = 62.4 lb/ft^3
R = hydraulic radius of riffle cross section (ft)
S = average water surface slope (ft/ft)

Use the calculated value of τ (lb/ft^2) and the Shields diagram as revised with the Colorado data (fig. 11–11 (Rosgen and Silvey 2005)) to predict the moveable particle size (mm) at bankfull shear stress.

Another relationship used in assessment and in design is the use of dimensionless shear stress (τ^*_{ci}) to determine particle entrainment. Dimensionless shear stress is defined as:

$$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872} \qquad \text{(eq. 11–3)}$$

where:
τ^* = dimensionless shear stress
D_{50} = median diameter of the riffle bed (from 100 count in the riffle or pavement sample)
$\hat{D}_{50}$ = median diameter of the bar sample (or subpavement sample)

If the ratio $\frac{D_{50}}{\hat{D}_{50}}$ is between the values of 3.0 and 7.0, calculate the critical dimensionless shear stress using equation 11–3 (modifications adapted from Andrews 1983, 1984; Andrews and Erman 1986).

If the ratio $\frac{D_{50}}{\hat{D}_{50}}$ is **not** between the values of 3.0 and 7.0, calculate the ratio $\frac{D_{max}}{D_{50}}$

where:
D_{max} = largest particle from the bar sample (or the subpavement sample)
D_{50} = median diameter of the riffle bed (from 100 count in the riffle or the pavement sample)

If the ratio $\frac{D_{max}}{D_{50}}$ is between the value of 1.3 and 3.0, calculate the critical dimensionless shear stress:

$$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887} \qquad \text{(eq. 11–4)}$$

Once the dimensionless shear stress is determined, the bankfull mean depth required for entrainment of the largest particle in the bar sample (or subpavement sample) is calculated using equation 11–5:

$$d_{bkf} = 1.65\tau^* \frac{D_{max}}{S} \qquad \text{(eq. 11–5)}$$

where:
d_{bkf} = required bankfull mean depth (ft)
1.65 = submerged specific weight of sediment
τ^* = dimensionless shear stress
D_{max} = largest particle from bar sample (or subpavement sample) (ft)
S = bankfull water surface slope (ft/ft)

The bankfull water surface slope required for entrainment of the largest particle can be calculated using equation 11–6:

$$S = 1.65\tau^* \frac{D_{max}}{d_{bkf}} \qquad \text{(eq. 11–6)}$$

Equations 11–5 and 11–6 are derived from the basic Shields relation.

If the protrusion ratios are out of the usable range as stated, another option is to calculate sediment entrainment using dimensional bankfull shear stress (eq. 11–2 and fig. 11–11).

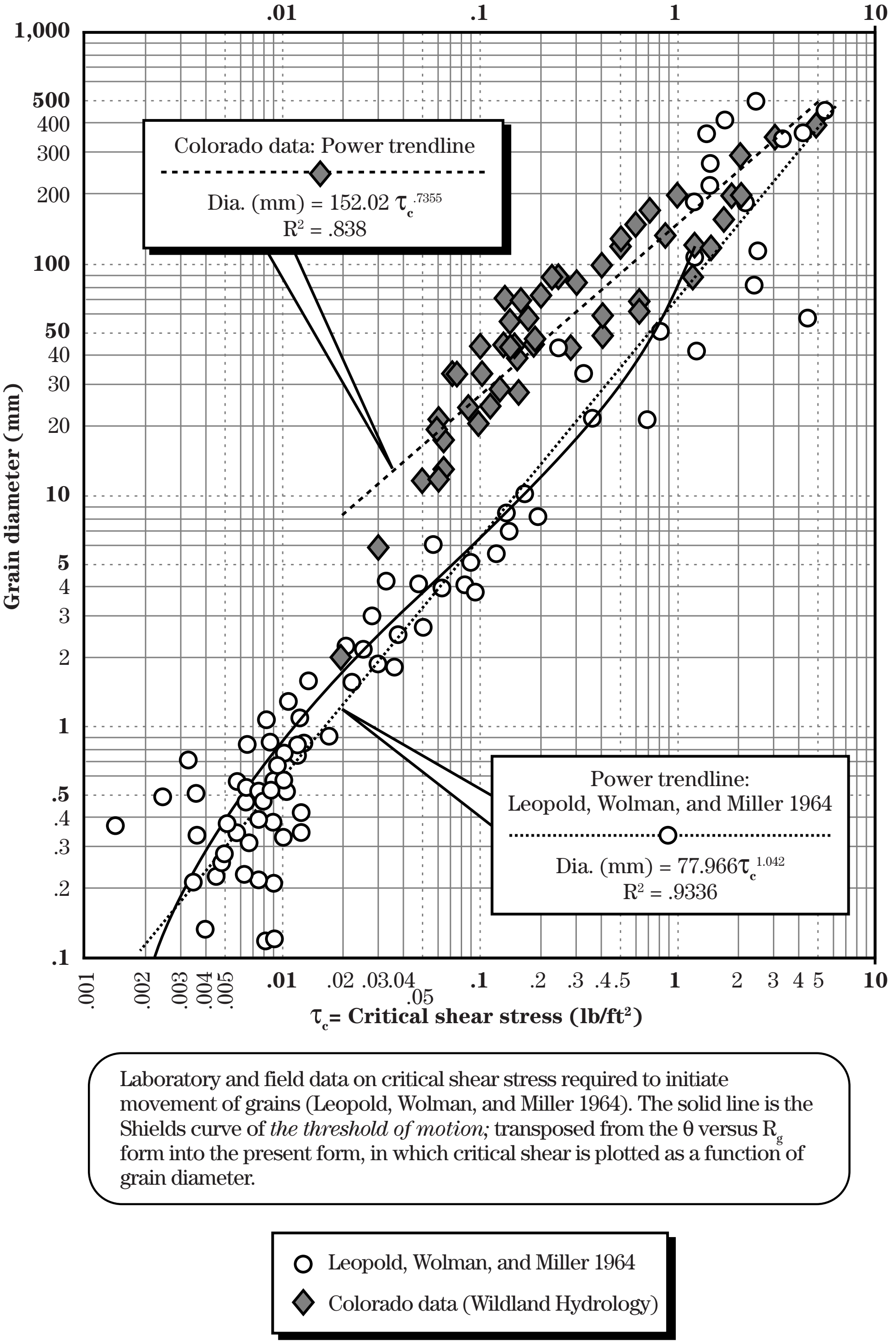
Sediment capacity—In addition to sediment competence, sediment capacity is important to predict river stability. Unit stream power is also utilized to determine the distribution of energy associated with changes in the dimension, pattern, profile, and materials of stream channels. Unit stream power is defined as shear stress times mean velocity:

$$\omega = \tau u \qquad \text{(eq. 11–7)}$$

where:
ω = unit stream power (lb/ft/s)
τ = shear stress (lb/ft^2)
u = mean velocity (ft/s)

Predicted sediment rating curves are converted to unit stream power for the same range of discharges by individual cells to demonstrate reduction or increase in coarse sediment transport.

Figure 11–11 Relation between grain diameter for entrainment and shear stress using Shields relations



Laboratory and field data on critical shear stress required to initiate movement of grains (Leopold, Wolman, and Miller 1964). The solid line is the Shields curve of *the threshold of motion;* transposed from the θ versus R_g form into the present form, in which critical shear is plotted as a function of grain diameter.

The use of reference dimensionless sediment rating curves by stream type and stability rating, (Troendle et al. 2001), as well as hydrology and hydraulic data, are all needed for the stability and design phases. Additional information will be presented in the respective sequential, analytical steps of each phase of the procedure. Local suspended sediment and bed-load data can be converted to regional sediment curves by plotting bankfull and suspended sediment data by drainage area. Examples of suspended sediment data plotted by 1.5-year recurrence interval discharge/drainage area for many regions of the United States as developed from USGS gage data by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) are presented in Simon, Dickerson, and Heins (2004). These relations can be used if a direct measurement of bankfull sediment cannot be obtained for subsequent analysis. Caution should be exercised in using an arbitrary bankfull value without field calibration of the bankfull discharge. The 1.5-year recurrence interval discharge is often greater than the actual bankfull value in wet climates and urban areas.

The disadvantage of using various suspended and bed load equations for the Rosgen geomorphic channel design methodology is the difficulty of determining sediment supply for sediment rating curves. It is common in the use of these models to have predicted values of many orders of magnitude different than observed values. The use of developed dimensionless ratio sediment rating curves for both suspended (less wash load) and bed load by stream type and stability is the improvement of predicted versus observed values. Results of an independent test of predicted versus observed values for a variety of USGS gage sites are shown in figures 11–12, 11–13, and 11–14. These figures show that predicted sediment rating curves match observed values for a wide range of flows. The model for bed-load transport reflects sediment transport based on changes in the channel hydraulics from a reference condition.

Validation of sediment competence or entrainment relations can also assist in the development and application of subsequent analysis. These data can be collected by installing scour chains and actual measurements of bed-load transport grain size for a given shear stress using Helley-Smith bed-load samplers. Plotting existing data collected by others in this manner can also help in developing a data base used in later analysis.

The use of reference dimensionless ratio sediment rating curves (bed load and suspended less wash load) requires field measured bankfull sediment and dis-

Figure 11–12 Comparison of predicted sediment rating curve to observed values from the Tanana River, AK, using the Pagosa Springs dimensionless ratio relation

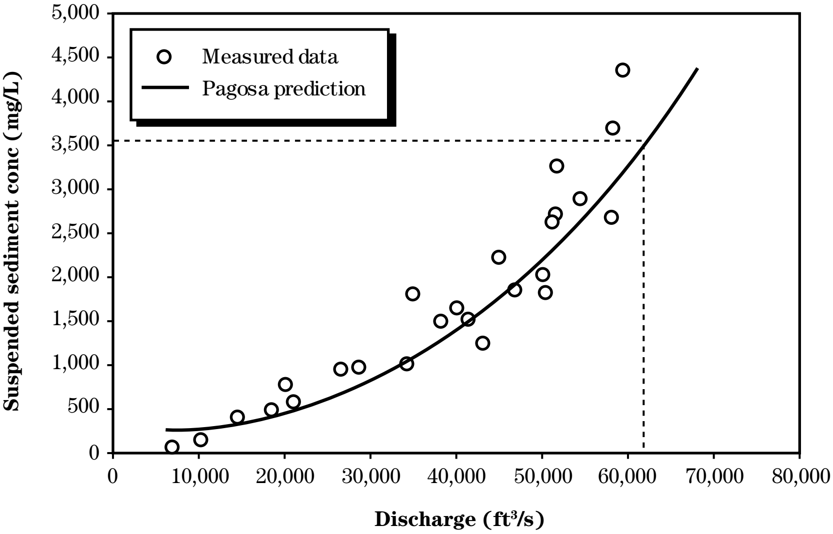
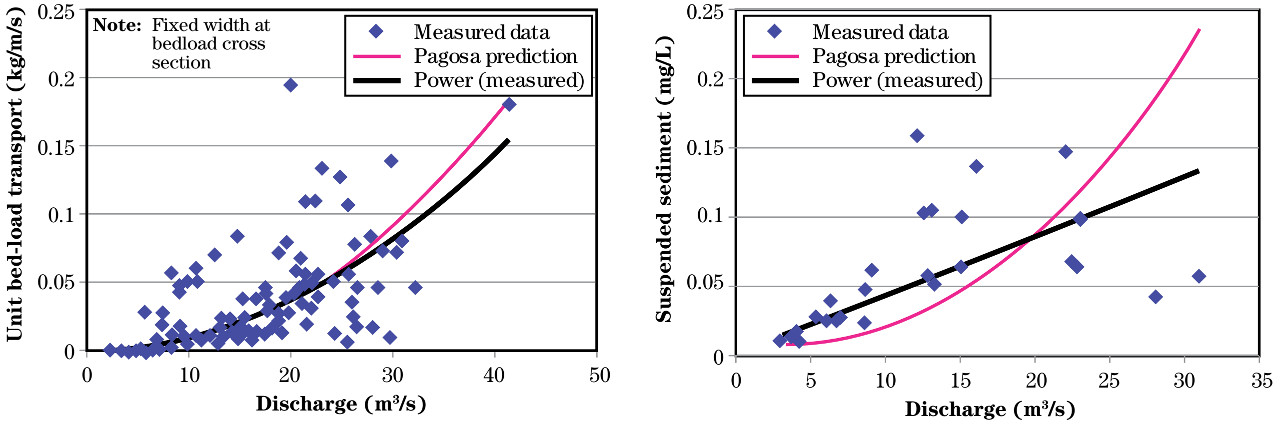
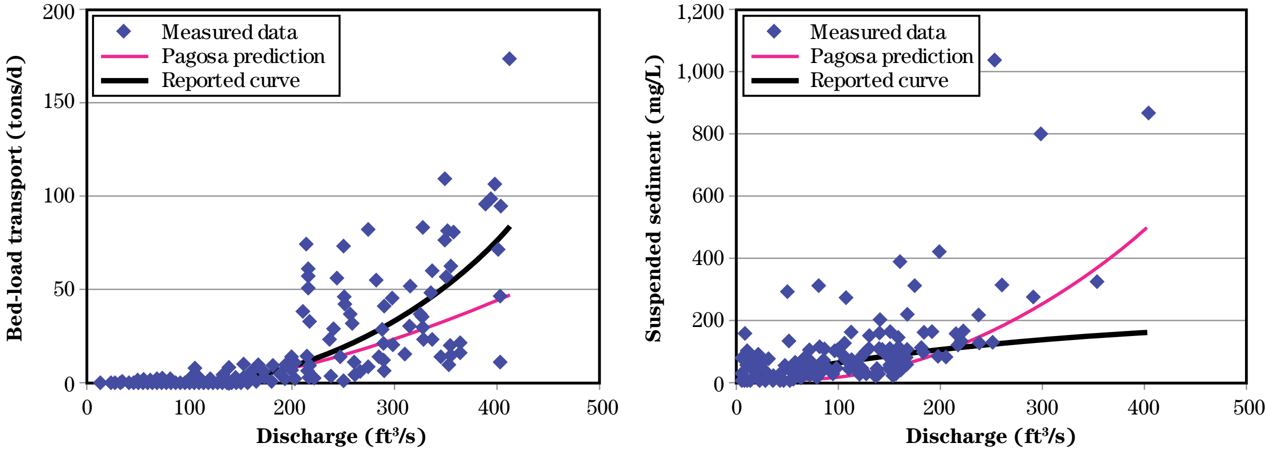


Figure 11–13 Predicted vs. measured sediment data using reference dimensionless rating curve (data from Leopold and Emmett 1997; Ryan and Emmett 2002)

East Fork River near Big Sandy, WY (from Leopold and Emmett 1997)



Little Granite Creek near Bondurant, WY (from Ryan and Emmett 2002)



Maggie Creek (F4)—NV

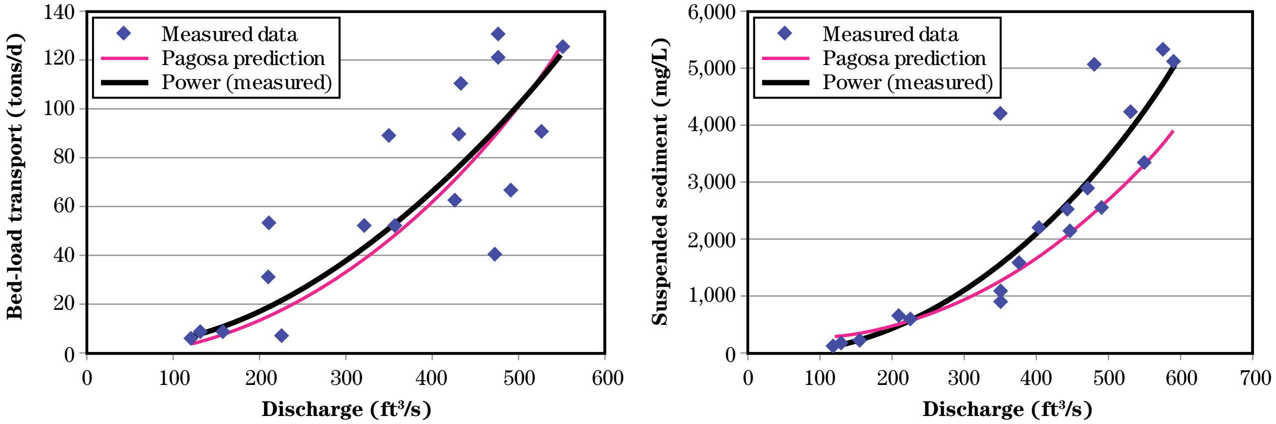
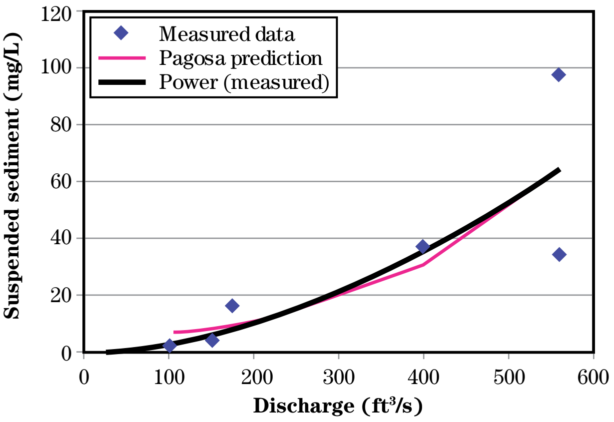
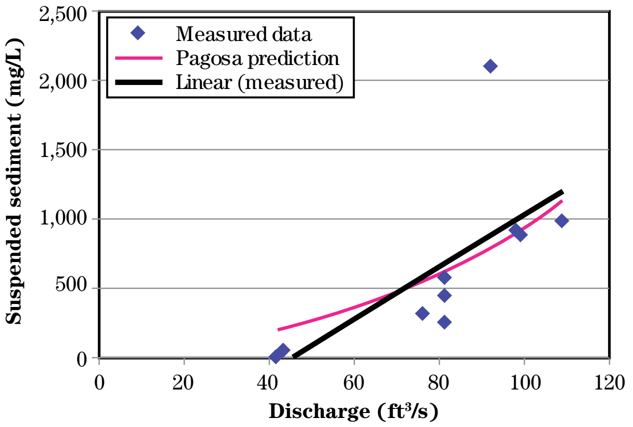


Figure 11–14 Predicted vs. measured suspended sediment data using dimensionless reference curve (data from Emmett 1975)

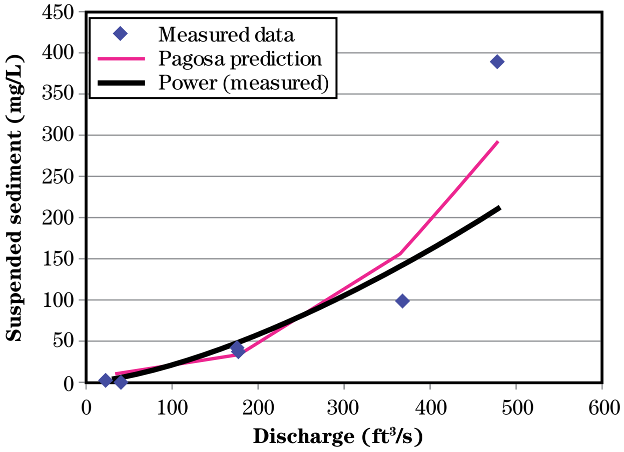
Warm Springs Creek near Clayton, ID 13297000



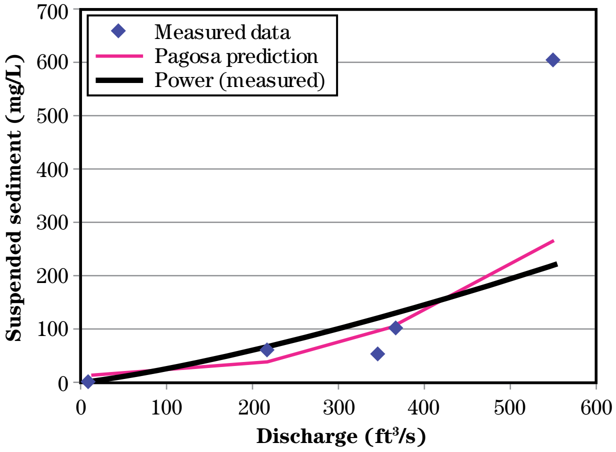
Upper Salmon Watershed 13297250



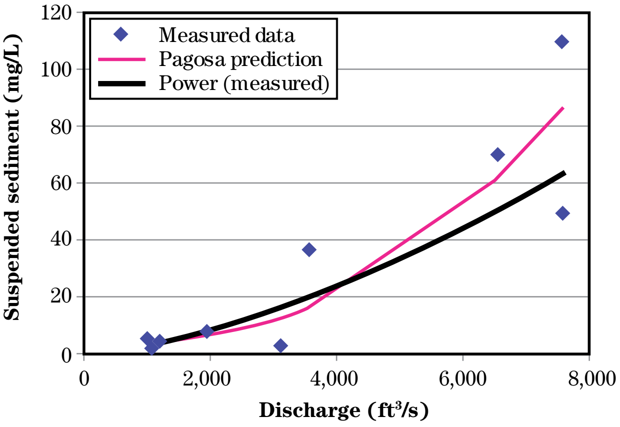
Upper Salmon Watershed 13297340



Upper Salmon Watershed 13297360



Upper Salmon Watershed 13297380



Upper Salmon Watershed 13297425

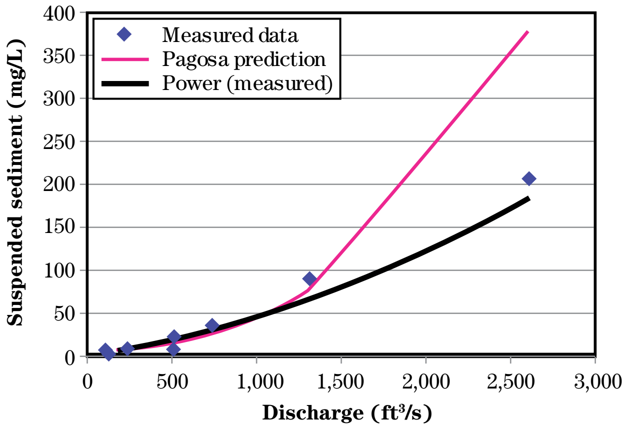
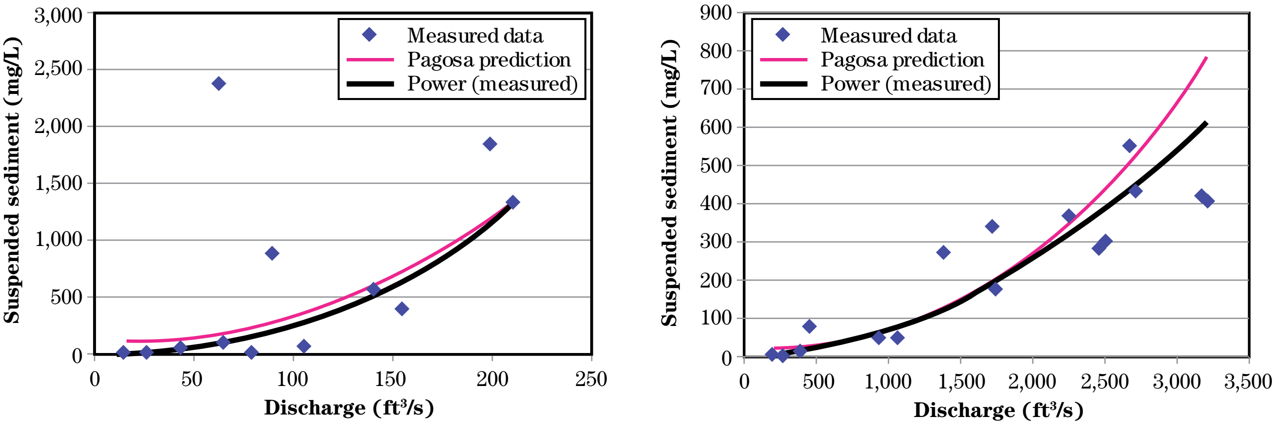
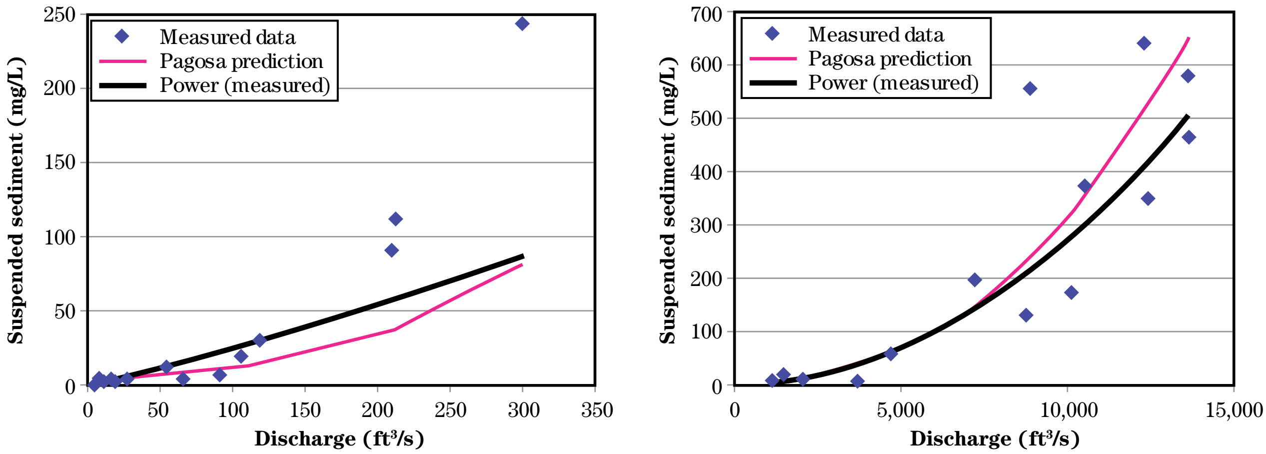


Figure 11–14 Examples of predicted vs. measured suspended sediment data using dimensionless reference curve (data from Emmett 1975)—Continued

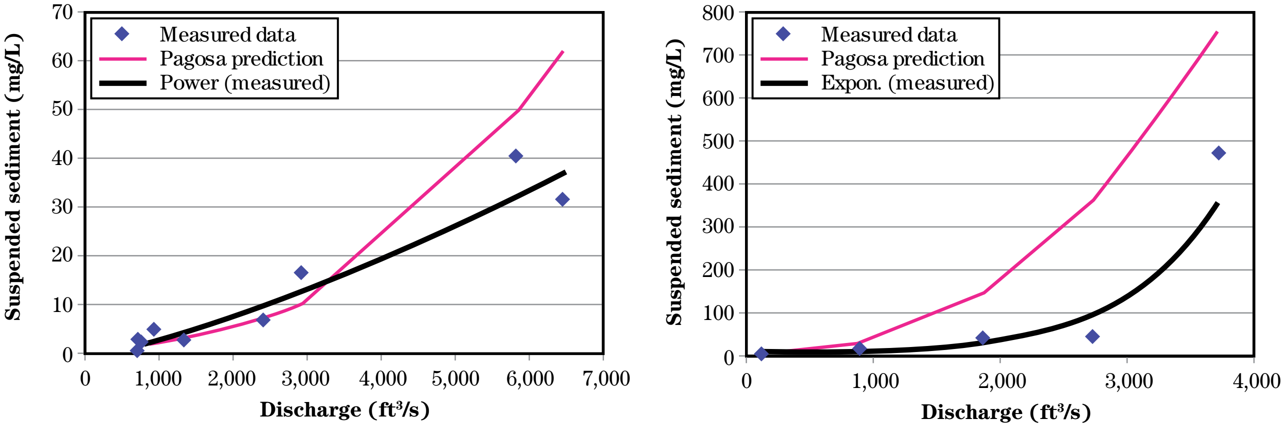
Big Boulder Creek near Clayton, ID 13297500 | **East Fork Salmon River near Clayton, ID 13298000**



Little Boulder Creek near Clayton, ID 13297450 | **Salmon River near Challis, ID 13298500**



Salmon River below Yankee Fork 13296500 | **Yankee Fork Salmon River near Clayton, ID 1329600**



charge. Regional bankfull sediment relations versus drainage area may be substituted if actual bankfull measurements are impossible to obtain, but must be extrapolated from streams of similar lithology, stream type, and stability. Examples of such relations using 1.5-year recurrence interval discharge for suspended sediment are shown in Simon, Dickerson, and Heins (2004). Dimensionless flow-duration curves are also used to produce total annual sediment yield once dimensionless ratio sediment and flow-duration curves are converted to dimensional relations. The examples of predicted sediment rating curves to observed values using a dimensionless sediment rating curve were presented in figures 11–12 to 11–14. Changes in unit stream power (eq. 11–7) are calculated to determine changes in transport rate due to change in depth, slope, and/or velocity. Dimensionless flow-duration curves are used to generate total annual sediment yield from the generated sediment rating curves and bed-load transport by unit stream power.

Streambank erosion—Streambank erosion rate (lateral erosion rate and sediment, tons/yr) is predicted as part of the river stability assessment. The influence of vegetative change, direct disturbance, and other causes of bank instability is quantitatively assessed. One of the major consequences of stream channel instability is accelerated streambank erosion and associated land loss. Fish habitat is adversely affected not only due to increased sediment supply but also by changes in pool quality, substrate materials, imbrication, and other physical habitat loss. Water temperatures are also adversely affected due to increases in width-to-depth ratio due to lateral accretion. The prediction methodology is presented in Rosgen (1996) and in Rosgen (2001d) utilizing a Bank Erodibility Hazard Index (BEHI) and Near Bank Stress (NBS) calculations.

Successional stages of channel evolution—A useful tool at this phase is the determination of various stream type scenarios and stages of channel evolution as depicted in figure 11–15. It is imperative to identify the present stage of the stream and predict the direction and consequence of change. The various stages and scenarios depicted in figure 11–15 assist the observer in this assessment. River channels undergo morphological change due to various disturbance and/or recovery (Rosgen 1996, 2001d, 2005). The assessment phase must identify current states and scenarios. For each state within a scenario, there are specific morphological, sedimentological, hydraulic, and biological relations depicted. The associated interpretations of these relations assist in river assessments.

River stability analysis—Additional stability variables are required for assessment, including the influence of large woody material, flow regime, depositional features, meander patterns, riparian vegetation, and channel stability ratings by stream type, and are summarized in the form shown in table 11–4.

Figure 11–15 Various stream type succession scenarios

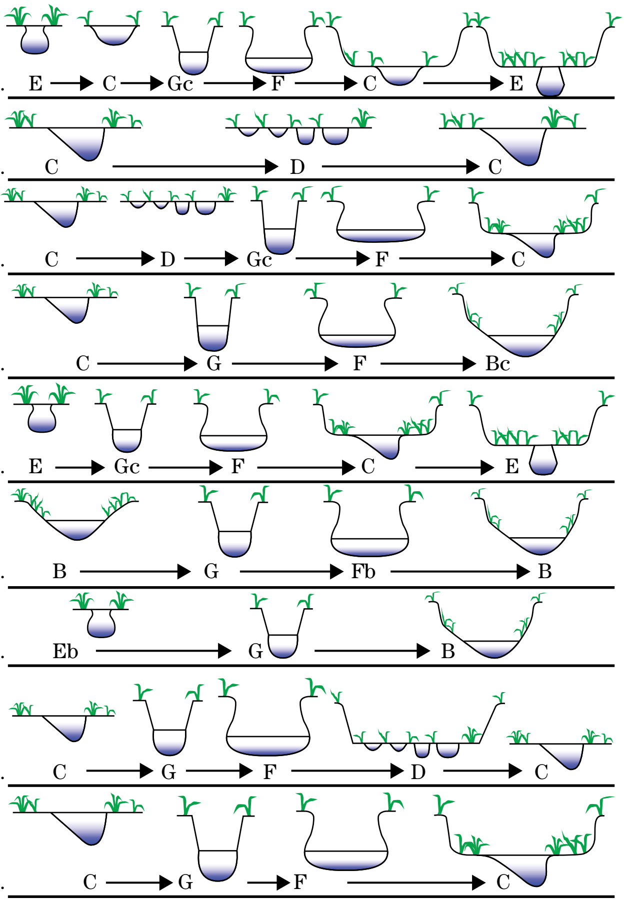


Table 11–4 Stream channel stability assessment summary form

Stream		**Stream**		**Date**		**Observers**								
Level III variables	Stream type		Flow regime		Stream size		Stream order		Meander pattern		Depositional pattern		Debris/channel blockage	
	Riparian vegetation	Current composition/density	Potential composition/density	Altered channel state (dimension, pattern, profile, materials)										
Channel dimension	Mean bankfull depth (ft)		Mean bankfull width (ft)		Cross section area (ft^2)		Remarks							
Channel dimension relationships	Width/depth ratio (W/D)		Reference condition width/depth ratio (W/D_{ref})		(W/D)/(W/D_{ref})		Circle	Stable	Moderately unstable	Unstable	Highly unstable			
Channel pattern	Mean (range)	MWR		Lm/W_{bkf}		Rc/W_{bkf}		Sinuosity						
River profile and bed features	Circle		Riffle/pool	Step/pool	Plane bed	Convergence/divergence	Dune/antidunes/smooth bed							
	Max bankfull depth (ft)	Riffle	Pool	Depth ratio (max/mean)	Riffle	Pool	Pool to pool spacing		Slope					
									Valley		Average bankfull			
Channel stability rating	Pfankuch rating		Pfankuch adjusted by stream type (use potential/reference reach)											
Bank erosion summary	Length of reach studied (ft)		Annual streambank erosion rate				Curved used	Remarks						
				(ton/yr)		ton/yr/ft								
Degree of confinement	Reference MWR		MWR/ Reference MWR		Unconfined (1.0–0.80)	Moderately confined (0.79–0.30)	Confined (0.29–0.1)	Severely confined (<0.1)						
Lateral stability	Circle		Stable		Moderately unstable		Unstable	Highly unstable (accelerated lateral erosion)						
Sediment capacity	Sufficient capacity		Insufficient capacity											
Stream channel scour/deposition	Largest particle-bar sample (mm)		τ_{ci}		Existing $depth_{bkf}$		Required $depth_{bkf}$		Existing $slope_{bkf}$		Required $slope_{bkf}$			
Degree of incision	Bank height ratio		Stable (no incision)	Slightly incised	Moderately incised	Deeply incised	Width of flood prone area (ft)		Entrenchment ratio					
Channel enlargement	Circle		Stable		Slight		Moderate		Extensive					
Stream successional stage		→		→		→		→		→		Existing stream state (type)		Potential stream state (type)
Vertical stability	Circle		Stable		Aggradation		Degradation							
Sediment supply (channel source)	Circle		Very high	High	Moderate	Low	Score		Remarks/causes					

Base-level change—A key part of channel stability analysis. Degree of channel incision (lowering of local base level) is determined by the ratio of the lowest bank height divided by maximum bankfull depth, called the bank height ratio. A stream may not be entrenched (vertically constrained), but may be partially incised, leading to entrenchment. A grade-control structure requirement is often associated with partially incised channels (Rosgen 1997a).

Direct disturbance and riparian vegetation—The direct disturbance of stream channels must be offset by correcting dimension, pattern, profile, and often channel materials. Levees adjacent to both banks should be set back allowing room for a flood plain. Riparian vegetation change is not only a major cause of instability and loss of function, but is a key solution in restoration and natural channel design. Riparian vegetation reestablishment should contain the correct overstory and understory species to be compatible for a self-sustaining, long-term solution.

Biological assessments—Biological assessments that describe fish species, food chains, diversity with broad categories of ecoregions, and stream types (habitat units) are currently collected with the assessment level for identifying biological potential. Limiting factor analysis provides information that identifies specific problems that may be corrected by changed management and/or restoration.

It is readily apparent that this procedure involves extensive field observations and an extensive data base followed by a thorough and detailed analysis. All of this must be completed prior to restoration planning, as it forms much of the foundation for what follows.

It is important to understand the various causes of instability responsible for loss of physical and biological function and corresponding loss of value. Recommendations that follow are critically linked to land uses, disturbance regime, and other problem sources. The flowchart (fig. 11–10) depicts the assessment criteria of channel stability.

(d) Phase IV—Passive recommendations for restoration

A first priority in restoration is to seek a natural recovery solution based on changes in the variables causing the instability and/or loss of physical and biological function. Changes in land use management can influence riparian vegetation composition, density and vigor, flow modifications (diversions, storage, and reservoir release schedule modifications based on the operational hydrology), flood control measures, road closures/stabilization, hillslope erosional processes, and other process influences of river stability. Often, a change in management strategies can be very effective in securing stability and function. This often has to be determined based on the recovery potential of various stream types and the short- and long-term goals associated with the stated objectives (including costs). The alternative of self-stabilization is always a key consideration in any stability assessment. The time-trend aerial photography from phase III may help to provide insight into stream recovery potential following disturbance.

Successional stages of channel adjustment (fig. 11–15) can also assist at looking at natural recovery potential. It is very important to ensure that objectives are met through effectiveness monitoring required to provide the documentation on the nature, magnitude, rate, and consequences of natural recovery. If natural recovery potential is poor and/or does not meet specific objectives, phase V would be appropriate (Rosgen geomorphic channel design methodology).

(e) Phase V—The stream restoration and natural channel design using the Rosgen geomorphic channel design methodology

Phase V involves combining the results of the previous phases. A good design can only follow a good assessment. It is preferred not to patch symptoms, but rather provide solutions to restoration that will offset the cause of the problem and allow for the river to be self-maintaining. The practitioner must be very familiar with the processes involved in hydrology, hydraulics, sedimentology, geomorphology, soil science, aquatic habitat, and riparian vegetation. Due to the inherent complexity, it is usually necessary to obtain technical assistance for assessment and design, depending on the practitioner's experience and training.

The conceptual, generalized flowchart shown in figure 11–16 depicts the general sequence of the mixed use of analog, empirical, and analytical methods in this design procedure. The early sequence is required to determine the existing valley type and potential stream type of the stable form. The proposed channel type must be converted to a dimension, pattern, and profile to initially test whether the hydraulic and sediment relations associated with the watershed are compatible prior to advancing through all of the procedural steps.

The watershed and river assessment that predicts the consequence of streamflow, sediment supply, and channel change is reflected in figure 11–17. The procedure is incorporated into the following sequential analysis steps.

Figure 11–16 Generalized flowchart representing Rosgen geomorphic channel design utilizing analog, analytical, and empirical methodologies

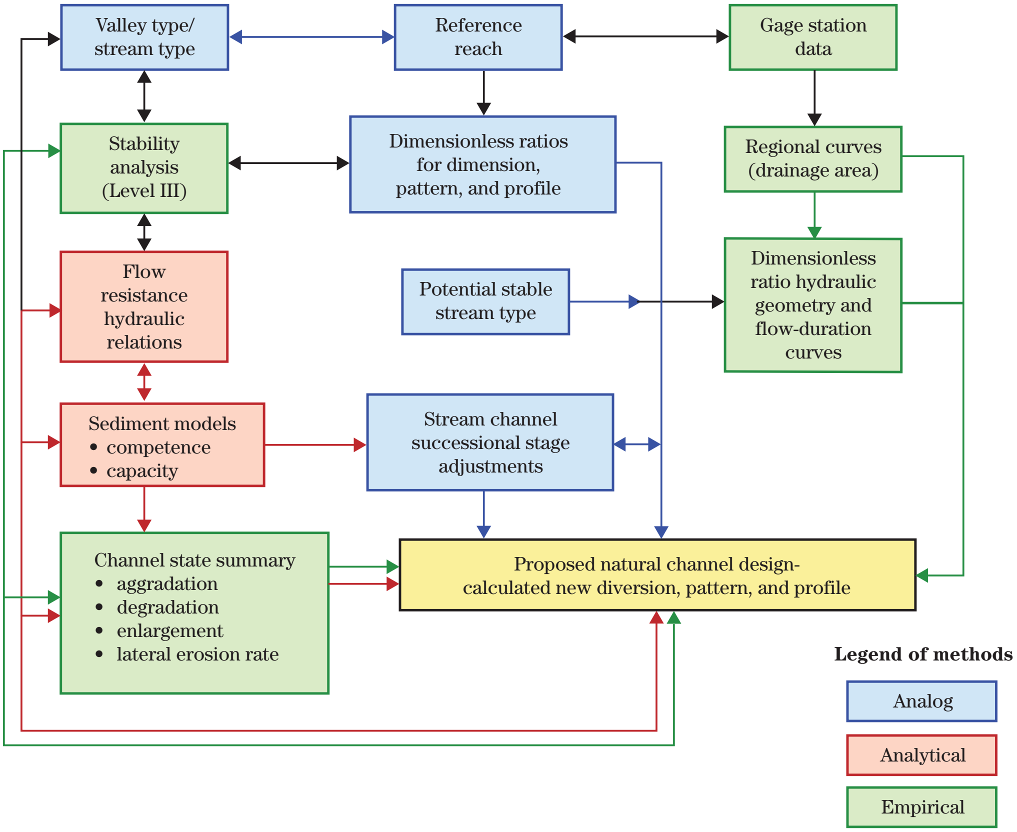
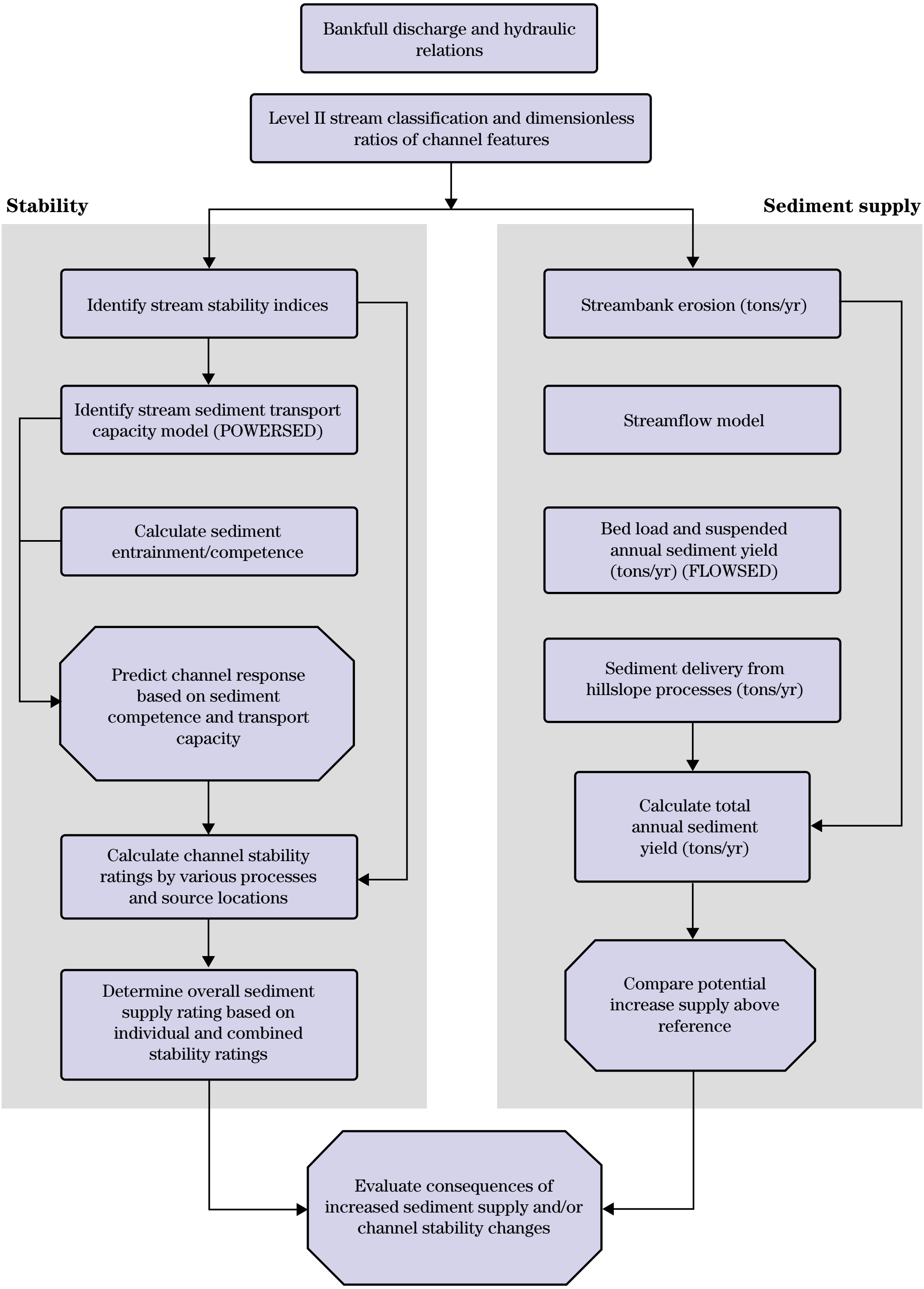


Figure 11–17 Flowchart for determining sediment supply and stability consequences for river assessment



The procedural sequence utilized in the Rosgen geomorphic channel design methodology is shown in the following operational steps:

Step 1 Obtain and/or verify regional curves (bankfull discharge, cross-sectional area, width and depth versus drainage area). The regional curves must be located in the same hydro-physiographic province as that of the restoration reach.

Step 2 Obtain hydraulic geometry (USGS 9–207 forms, summary of current meter measurements) from the gage station stratified by stream type and bed features.

Step 3 Create dimensionless hydraulic geometry by dividing all values by the bankfull value.

Step 4 Obtain flow-duration curves from the gage station for a representative hydro-physiographic region.

Step 5 Create dimensionless flow-duration curve by dividing all flow values by the bankfull discharge.

Step 6 Identify the valley type for the restoration reach(s). Identify stream type(s) of the restoration reach.

Step 7 Obtain corresponding reference reach data for the same valley and stream type. The reference reach is not required to be located within the same watershed or hydro-physiographic province. Examples of the dimensionless ratio and other reference reach data by stream type/valley type are presented in table 11–3.

Step 8 Complete and/or review the stability examination data for the restoration reach (fig. 11–10 and table 11–4). Evaluate variables/states that represent instability relations (width, depth, and slope values that do not meet sediment transport requirements).

Step 9 Select appropriate scenario of successional stages of channel adjustment for channel evolution scenario (fig. 11–15). This determines the stream type of the current state and the potential state to match the valley type. (This step is completed in the stability phase, phase III).

Step 10 Obtain drainage area (mi^2) for the restoration reach.

Step 11 Obtain bankfull cross-sectional area (A_{bkf}) from the regional curves (step 1).

Step 12 Obtain reference reach width-to-depth ratio associated with the stable design stream type commensurate with the valley type (step 7).

Step 13 Calculate design bankfull channel width of riffle reach:

$$W_{bkf} = \left[\left(\frac{W_{bkf}}{d_{bkf}}\right)_{ref} A_{bkf}\right]^{\frac{1}{2}} \qquad \text{(eq. 11– 8)}$$

Step 14 Calculate mean riffle depth:

$$d_{bkf} = \frac{A_{bkf}}{W_{bkf}} \text{ or } \left[\frac{W_{bkf}}{\left(\frac{W_{bkf}}{d_{bkf}}\right)_{ref}}\right] \qquad \text{(eq. 11–9)}$$

Step 15 Calculate meander wavelength (Lm) for average and range of values. Obtain meander length ratio average and range of values, where:

$$MLR = \left[\left(\frac{Lm}{W_{bkf}}\right)_{ref}\right] \text{ from reference reach data (step 7, table 11–3).}$$

$$Lm = \left[\left(MLR_{ref}\right)\right] W_{bkf} \text{ (from step 13)} \qquad \text{(eq. 11–10)}$$

Step 16 Calculate belt width (W_{blt}) for average and range of values from meander width ratios (MWR).

$$MWR = \left[\left(\frac{W_{blt}}{W_{bkf}}\right)_{ref}\right] \quad \text{(step 7, table 11–3).}$$

$$W_{blt} = [(MWR)_{ref}]\, W_{bkf} \qquad \text{(eq. 11–11)}$$

Step 17 Calculate radius of curvature (Rc) for average and a range of values from ratio of radius of curvature ratio. (step 7, table 11–3).

$$Rc = \left[\left(\frac{Rc}{W_{bkf}}\right)_{ref}\right] W_{bkf} \qquad \text{(eq. 11–12)}$$

Step 18 Obtain an aerial photo depicting vegetation, channel features and terrain character. Layout the range of values for meander length (Lm), belt width (W_{blt}) and radius of curvature (Rc) on aerial photo or detailed topographic map. Adjust pattern to utilize terrain features and existing vegetation where possible within the range of the pattern variables. Once the preliminary layout is complete, measure stream length (SL) of the proposed channel. Measure valley length (VL) by following the fall line of the valley, rather than straight line segments between meanders.

Step 19 Calculate sinuosity (k) of the proposed channel where:

$$k = \frac{SL}{VL} \qquad \text{(eq. 11–13)}$$

Step 20 Calculate valley slope (S_{val}). Measure the water surface elevation difference (DE) between the same bed features along the fall line of the valley using valley length (VL), where:

$$S_{val} = \frac{DE}{VL} \qquad \text{(eq. 11–14)}$$

Step 21 Calculate proposed channel average slope (S):

$$S = \frac{S_{val}}{k} \qquad \text{(eq. 11–15)}$$

Step 22 Calculate bankfull channel velocity (u_{bkf}) and check design bankfull discharge with velocity, cross-sectional area (continuity) regional curves:

$$uA = Q \qquad \text{(eq. 11–16)}$$

$$\frac{Q}{A} = u \quad \text{Compare to regional curve (step 1)} \qquad \text{(eq. 11–17)}$$

Steps 23 through 26 Predict stream competence (entrainment) by utilizing particle entrainment computations. A general flowchart depicting the procedural steps is shown in figure 11–18.

First, obtain bar sample gradation from field sampling and sieving procedure upstream of the proposed restoration (Rosgen 1996). A field procedure for bar sampling, pavement/subpavement sample and wet-sieving onsite is presented in tables 11–5 and 11–6. The user is advised to review additional details of particle size sampling by Bunte and Abt (2001). Sediment sampling is also addressed in NEH654 TS13A. Bar samples are field-sieved and recorded in the entrainment worksheet (table 11–7).

The sediment competence computations that determine bed stability (aggradation/degradation) are completed and summarized in table 11–8. This method has shown consistency when actual bed-load/scour chain data are compared to predicted values. Use the value of the largest particle in the bar sample (or subpavement sample), D_{max} in millimeters, and the revised Shields diagram to predict the shear stress required to initiate movement of the largest particle in the bar and/or subpavement (fig. 11–11).

If the protrusion ratios described in equations 11–3 or 11–4 are outside the ranges indicated in table 11–8, the user should use the shear stress equation (eq. 11–2) and apply it with a revised Shields relation using Colorado data or local data if available (fig. 11–11).

$$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872} \qquad \text{(eq. 11–3)}$$

$$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887} \qquad \text{(eq. 11–4)}$$

$$\tau = \gamma RS \qquad \text{(eq. 11–2)}$$

A grain size corresponding with shear stress is selected to determine what sizes the river can potentially move. Based on measured bed-load sizes, in a heterogeneous mixture of bed material comprised of a mixture of sand to gravel and cobble, the previously published Shields relation generally underestimates particle sizes of heterogeneous bed material in the shear stress range of 0.05 pounds per square foot to 1.5 pounds per square foot. The Shields relationship is appropriately used for entrainment sizes below and/or above this value range. Without this adjustment, most computations underestimate the largest sizes of heterogeneous bed material moved during bankfull discharge. The measured data in figure 11–11 indicate the magnitude of the underestimate of particle size entrainment from comparing published relations to measured values.

To determine the ability of the existing stream reach to transport the largest clast size of the bed-load sediment, it is necessary to calculate the bankfull dimensionless shear stress (τ*). This calculation determines the depth and slope necessary to mobilize and transport the largest particle made available to the channel. The dimensionless shear stress at bankfull stage is used in the entrainment

Figure 11–18 Generalized flowchart depicting procedural steps for sediment competence calculations

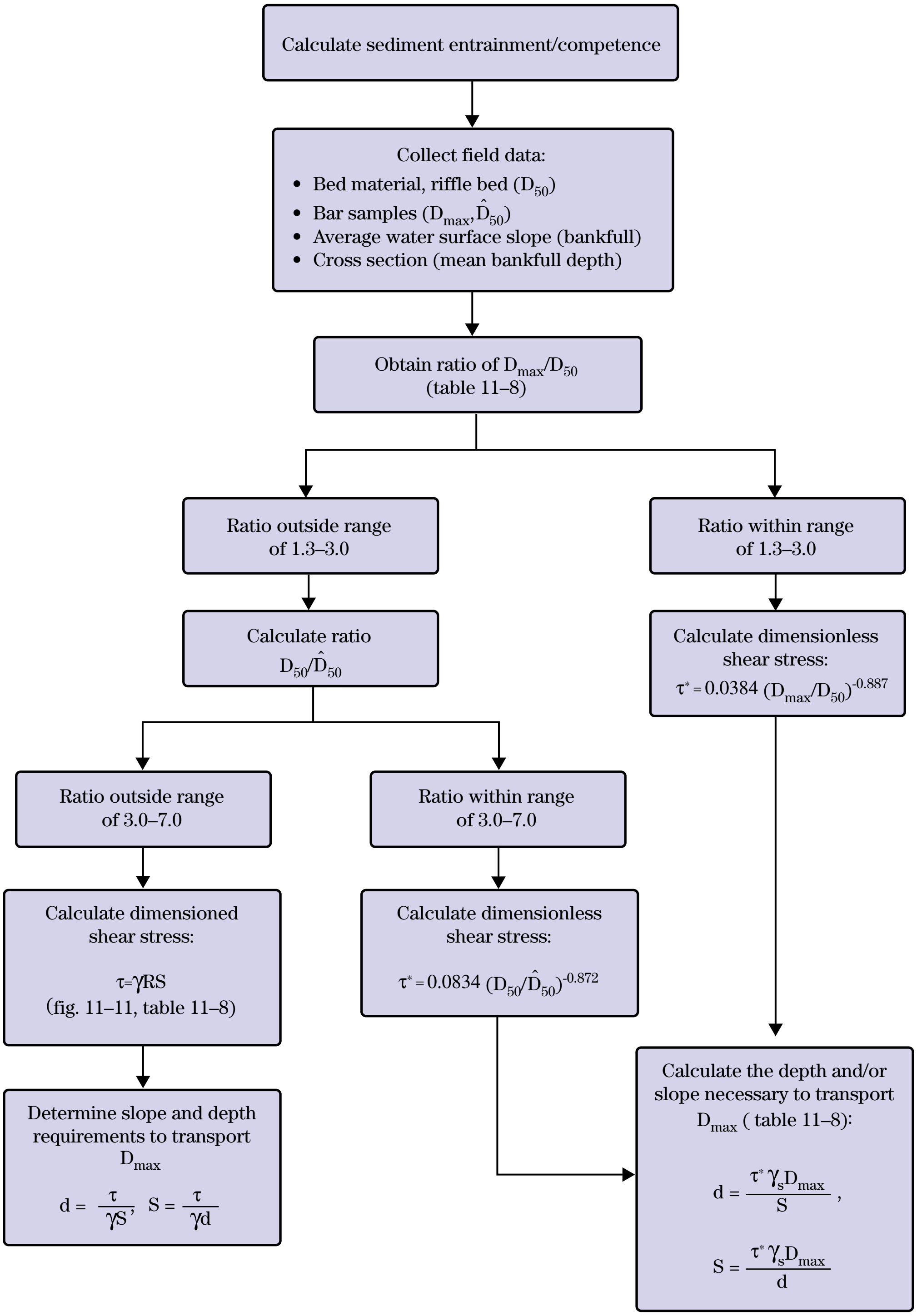


Table 11–5 Field procedure for bar samples*

Bar sample field procedure

Collect sediment core samples from point bars along the project and reference reaches. At least one sample should be collected from each reach associated with a change in stream type. Conduct a critical shear stress analysis using the following procedures:

> Locate a sampling point on the downstream a third of a meander bend. The sample location on the point bar is halfway between the thalweg elevation (the point of maximum depth) and the bankfull stage elevation. Scan the point bar in this area to determine the sampling location by observing the maximum particles on the surface of the bar.
>
> Place a 5-gallon bottomless bucket at the sampling location over one of the representative larger particles that are observed on the lower third of the point bar. Remove the two largest particles from the surface covered by the bottomless bucket. Measure the intermediate axis for each particle and individually weigh the particles. Record these values. The largest particle obtained is D_{max}, the largest particle from the bar sample. Push the bottomless bucket into the bar material. Excavate the materials from the bottomless bucket to a depth that is equal to twice the intermediate axis width of the largest surface particle. Place these materials in a bucket or bag for sieving and weighing.
>
> For fine bar materials, follow the directions above, except that when the bottomless bucket is pushed into the bar material, excavate materials from the bucket to a depth of 4 to 6 inches. Place these materials in a bucket or bag for sieving and weighing.
>
> Wet-sieve the collected bar materials using water and a standard sieve set with a 2-millimeter screen size for the bottom sieve. Weigh the bucket with sand after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand.
>
> Weigh the sieved materials and record weights (less tare weight) by size class. Be sure to include the intermediate axis measurements and individual weights of the two largest particles that were collected.
>
> Determine a material size class distribution for all of the collected materials. The data represents the range of channel materials subject to movement or transport as bed-load sediment materials at bankfull discharge.
>
> Plot data; determine size-class indices, D_{16}, D_{35}, D_{50}, D_{84}, D_{95}. The D_{100} should represent the actual intermediate axis width and weight (not the tray size) when plotted. The largest size measured will be plotted at the D_{100} point (Note: $D_{100} = D_{max}$). The intermediate axis measurement of the second largest particle will be the top end of the catch range for the last sieve that retains material (use the record data in the entrainment worksheet, table 11–7).
>
> Survey a typical cross section of a riffle reach at a location where the stream is free to adjust its boundaries. Plot the survey data. Determine the hydraulic radius of the cross section.
>
> Conduct a Wolman Pebble Count (100 count in riffle) of the bed material in the coarsest portion of the wetted riffle area (active channel). The pebble count should be conducted at multiple transects that represent the riffle. Plot data and determine the size-class indices.

*Sediment sampling is also addressed in NEH654 TS13A.

Table 11–6 Field procedure for pavement/sub-pavement samples

Pavement/subpavement sample field procedure (alternate procedures for obtaining a pavement/sub-pavement sample if you are unable to collect a bar sample)

Locate a sampling point in the same riffle where cross-sectional survey was conducted. The sampling point should be to the left or right of the thalweg, not in the thalweg, in a coarse-grain size portion of the riffle.

Push a 5-gallon bottomless bucket into the riffle at the sampling location to cut off the streamflow. The diameter of the bucket (sample size) should be at least twice the diameter of the largest rock on the bed of the riffle.

Remove the pavement material (surface layer only) by removing the smallest to the coarsest particles. Measure the intermediate axis and weight of the largest and second largest particles. Record these values. Place the remaining pavement materials into a bucket or bag for sieving and weighing.

Remove the sub-pavement material to a depth that is equal to twice the intermediate axis width of the largest particle in the pavement layer, or at least 150-millimeter depth. Caution: if a coarser bed material persists under the sub-pavement, it generally is material remnant of the previous bed. Stop at this condition and do not excavate deeper, even if the depth is not at twice the maximum pavement particle diameter. This residual layer is generally not associated with the size distribution of bed load transported at the bankfull stage. Collect the sub-pavement materials into a separate bucket or a bag. Measure the intermediate axis and weight of the two largest particles in the sub-pavement sample. Record these values. Sieve and weigh the remaining sub-pavement materials. The sub-pavement sample is the equivalent of the bar sample; therefore, use the largest particle from the sub-pavement sample in lieu of the largest particle from a bar sample in the entrainment calculations. Note: If the largest particle collected from the sub-pavement is larger than the pavement layer, the largest rock should be discarded from the sub-pavement layer. Drop back to the next largest particle size to determine the largest particle size to be used in the entrainment calculation.

Wet-sieve the collected pavement materials and then the subpavement materials using water and a standard sieve set with a 2-millimeter screen size for the bottom sieve. Weigh the bucket with sand after draining off as much water as possible. Subtract the tare weight of the bucket to obtain the net weight of the sand.

Weigh the sieved materials and record weights (less tare weight) by size class for both the pavement and sub-pavement samples. Be sure to include the mean intermediate axis width and individual net weights of the two largest particles that were collected (table 11–7).

Determine a material size-class distribution for the materials. The subpavement data represent the range of channel materials subject to movement or transport as bed-load sediment materials at bankfull discharge.

Plot data; determine size-class indices, D_{16}, D_{35}, D_{50}, D_{84}, D_{95}. The D_{100}, should represent the actual intermediate axis width and weight (not the tray size) when plotted. The largest size measured will be plotted at the D_{100} point. (Note: $D_{100} = D_{max}$). The intermediate axis measurement of the second largest particle will be the top end of the catch range for the last sieve that retains material.

The pavement material size class distribution may be used to determine the D_{50} of the riffle bed instead of doing the 100 count in the riffle bed.

Determine the average bankfull slope (approximated by the average water surface slope) for the study reach from the longitudinal profile.

Calculate the bankfull dimensionless shear stress required to mobilize and transport the largest particle from the bar sample (or sub-pavement sample). Use the equations and record the data in the entrainment worksheet (table 11–8).

Table 11–7 Bar sample data collection and sieve analysis form

Point / Side BAR-BULK MATERIALS SAMPLE DATA: Size Distribution Analysis

Party:

Location:

Date:

Notes:

SUBSAMPLES	Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE		Sieve SIZE	
	Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight		Tare Weight	
	Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights		Sample Weights	
	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net	Total	Net
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
11																		
12																		
13																		
14																		
15																		
Net Wt. Total																		
% Grand Tot.																		
Accum. % =<			→		→		→		→		→		→		→		→	

SURFACE MATERIALS DATA
(Two Largest Particles)

No.	Dia.	WT.
1		
2		

Bucket
+ Materials
Weight___________

Bucket
Tare
Weight___________

Materials
Weight___________
(Materials less than:
___________mm.)

Be Sure to Add Separate Material Weights to Grand Total

GRAND TOTAL SAMPLE WEIGHT

NOTES										

Table 11–8 Sediment competence calculation form to assess bed stability (steps 23–26)

Stream:			Reach:		
Observers:				Date:	
Enter required information					
	D_{50}	Riffle bed material D_{50} (mm)			
	$\hat{D}_{50}$	Bar sample D_{50} (mm)			
	D_{max}	Largest particle from bar sample (ft)		**(mm)**	304.8 mm/ft
	S	Existing bankfull water surface slope (ft/ft)			
	d	Existing bankfull mean depth (ft)			
1.65	γ_s	Submerged specific weight of sediment			

Select the appropriate equation and calculate critical dimensionless shear stress				
	$D_{50}/\hat{D}_{50}$	Range: 3 – 7	Use equation 1:	$\tau^* = 0.0834\left(\frac{D_{50}}{\hat{D}_{50}}\right)^{-0.872}$
	D_{max}/D_{50}	Range: 1.3 – 3.0	Use equation 2:	$\tau^* = 0.0384\left(\frac{D_{max}}{D_{50}}\right)^{-0.887}$
	τ^*	Bankfull dimensionless shear stress	Equation used:	

Calculate bankfull mean depth required for entrainment of largest particle in bar sample			
	d	Required bankfull mean depth (ft)	$d = \frac{\tau^* \gamma_s D_{max}}{S}$
	Circle:	Stable Aggrading Degrading	

Calculate bankfull water surface slope required for entrainment of largest particle in bar sample			
	S	Required bankfull water surface slope (ft/ft)	$s = \frac{\tau^* \gamma_s D_{max}}{d}$
	Circle:	Stable Aggrading Degrading	

Sediment competence using dimensional shear stress	
	Bankfull shear stress $\tau = \gamma d S$ (lb/ft^2) (substitute hydraulic radius, R, with mean depth, d)
	Moveable particle size (mm) at bankfull shear stress (fig. 11-11)
	Predicted shear stress required to initiate movement of D_{max} (mm) (figure 11-11)
	Predicted mean depth required to initiate movement of D_{max} (mm) $d = \frac{\tau}{\gamma S}$
	Predicted slope required to initiate movement of D_{max} (mm) $S = \frac{\tau}{\gamma d}$

analysis for both the reference reach and project reach. This analysis of the reference, stable condition is compared to the potentially disturbed reach. To maintain stability, a stream must be competent to transport the largest size of sediment and have the capacity to transport the load (volume) on an annual basis. These calculations provide a prediction of sediment competence as required in steps 23 through 26.

Step 27 Compute sediment transport capacity. Following this analysis, the depth and/or slope may need to be adjusted by recalculating steps 14 through 27.

FLOWSED and POWERSED are sediment supply/sediment transport models that predict the following:

- total annual suspended sediment yield
- total annual suspended sand sediment yield
- total annual bed-load sediment yield
- potential aggradation and/or degradation
- flow-related annual sediment yield due to changes in streamflow magnitude and duration

The models are based on the use of dimensionless reference sediment rating and flow-duration curves. The normalization parameters include:

- bankfull discharge
- bankfull stage bed load
- suspended and suspended sand sediment

The appropriate dimensionless sediment curves are selected for representative stream types and stability ratings. The dimensionless flow-duration curves are developed from representative hydrophysiographic province data from USGS stream gage data.

The FLOWSED model reflects sediment supply and generates the total annual sediment yield for both suspended and bed load. Changes in flow are also reflected in flow-duration curves and corresponding sediment yield. To determine annual sediment yield, near-bankfull stage values must be field measured to convert dimensionless sediment and flow-duration curves to actual values.

The POWERSED model compares sediment transport capacity from a stable, reference condition by predicting transport rate change due to channel hydraulics. The hydraulics reflect potential change in morphological variables such as channel width, depth, and slope. The corresponding changes in flow resistance are used to predict velocity, shear stress, and unit stream power (velocity multiplied by shear stress). Sediment rating curves from the FLOWSED model are converted from discharge to unit stream power for a wide range of flows. Revised values of annual sediment transport can then be compared to the reference condition from the subsequent change in the hydraulic geometry of the stream channel and corresponding response in sediment transport. Any flow modifications can also be simulated by revised flow-duration curves.

Detailed descriptions and model tests are provided for FLOWSED/POWERSED in Rosgen (2006). This analysis is complicated and detailed. However, it can be computed by spreadsheet or commercially available computer programs (RIVERMorph® 4.0). The basis of the calculations and model descriptions, however, are described to better understand how the models work. Table 11–9 lists the data required to run the FLOWSED and POWERSED models. With these data, the user can generate average annual sediment yields (tons/yr).

Table 11–9 Data required to run the FLOWSED and POWERSED supply/sediment transport models

Data requirements for FLOWSED/POWERSED
• Background reference data (flow and sediment) – Dimensionless suspended sediment rating curves by stream type or stability – Dimensionless bed-load rating curves by stream type or stability – Dimensionless flow duration (from local or representative hydro-physiographic province) – Momentary maximum bankfull discharge – Mean daily bankfull discharge (the mean daily discharge the day bankfull occurs at a gage station) – Flow-duration curves indicating change in flow regime (increase and/or decrease)
• Field measured values (for both reference and impaired condition) – Cross section – Longitudinal profile – Pebble count on active riffle bed to obtain D_{50} and D_{84} of bed material – Stream classification (level II) – Pfankuch channel stability rating – Measured bankfull discharge (ft^3/s) – Measured suspended sediment (mg/L) – Measured suspended sand sediment (mg/L) – Measured bed-load sediment (kg/s) (Helley-Smith bed-load sampler)

FLOWSED

The FLOWSED model is graphically depicted in figures 11–19 and 11–20. The procedure in table 11–10 and accompanying worksheet depicted in table 11–11 provide a more detailed understanding of the model. The following provides insight into the basis of the model.

Predict runoff response—Several applicable models for runoff exist, including TR–55, WRENSS (EPA 1980), the unit hydrograph approach (U.S. Army Corps of Engineers (USACE) 1998b), and others (EPA 1980; Troendle, Swanson, and Nankervis 2005). This step also considers operational hydrology from reservoirs, diversions, and other flow modifications that influence the magnitude, duration, and timing of streamflow. The input variables for most models are precipitation data, a vegetation alteration map by aspect and elevation, drainage area computations, percent of drainage area in impervious condition, and similar data specified based on the specific model being selected. The output from these models needs to be in the form of flow-duration curves. Flow-duration curves must represent reference conditions (full hydrologic utilization or recovery) and existing departures from reference. Because few stream gages are located on smaller watersheds, dimensionless ratio procedures become essential for data extrapolation in flow models. The data are entered into the flow-duration portion of the FLOWSED worksheet (table 11–11).

Develop dimensionless flow-duration curves—If a water yield model or operational hydrology data with actual flow-duration curve data are not available, it will be necessary to utilize dimensionless flow-duration curves. This information is obtained from gage station data and made dimensionless by dividing the mean daily discharge data by bankfull discharge. Bankfull discharge data are divided into all of the ranges of mean daily discharge and then plotted; see figures 11–9 and 11–21 as an example of the application for Weminuche Creek. The user must develop dimensionless flow-duration curves from gaging stations that represent a hydro-physiographic region similar to the impaired stream being assessed. If the user is applying these relations to a stormflow-generated hydrograph, rather than snowmelt (as in the case of Weminuche Creek), the following changes are recommended:

- Convert bankfull discharge (momentary maximum discharge in ft^3/s) to mean daily bankfull. This is accomplished by obtaining the mean daily discharge on the day during which bankfull discharge occurs. This ratio of mean daily discharge divided by momentary maximum discharge is used to develop the dimensionless flow-duration curves for a stormflow-dominated region. For example, if the mean daily discharge from a gage in a stormflow-dominated hydrograph was 125 cubic feet per second, but bankfull was 550 cubic feet per second, the ratio is 0.227. This ratio would be multiplied by the bankfull discharge from the regional curves or from a flood-frequency curve relation to convert bankfull discharge from a momentary maximum to a mean daily discharge value.

- Divide the mean daily discharge values by mean daily bankfull to establish the dimensionless relations similar to those in figures 11–9 and 11–21.

- Convert from dimensionless to dimensioned mean daily bankfull values. The momentary maximum value must be adjusted by the appropriate ratio, then multiplied by the appropriate ratio value in the dimensionless flow-duration curve. The dimensioned flow-duration curve data are entered into the FLOWSED worksheet (table 11–11). This would be done separately for reference or baseline conditions, and then would be compared to impaired or impacted watershed conditions to calculate annual streamflow and sediment yield.

FLOWSED—Continued

Collect bankfull discharge, suspended sediment, and bed-load sediment—This step is eventually used to convert the reference dimensionless sediment rating curves to actual values. It is very important to capture the bankfull discharge and have several data points to compute an average of the flow and sediment values due to the high spatial and temporal variability of sediment movement. Field methods and equipment used should follow the procedures outlined in book 3, chapter C2 of Field Methods for Measurement of Fluvial Sediment (USGS 1999).

It may be necessary to separate the wash load (silt/clay fraction) from the total suspended sediment load for calculation and interpretation. For channel stability purposes, the silt/clay fraction is not energy limited or hydraulically controlled, and in some settings, it can be subtracted from the suspended sediment yield data for the prediction of potential aggradation. This would not be the case, however, if there were concerns over accelerated fine sediment deposition into extremely low-gradient streams, deltas, reservoirs, lakes, marshes, or estuaries. Colloidal sediments can present problems for impaired waters; thus, wash load may need to be retained in suspended sediment analysis. Enter these measurements in the FLOWSED worksheet (table 11–11).

Obtain or establish reference dimensionless suspended and bed-load rating curves—These curves should be developed for stable reference reach sites representing stable streams. A similar relation can be stratified for poor stability or unstable streams. These reference curves are used to establish sediment rating curves for the calculation of flow-related sediment increases and to establish an annual sediment yield estimate for proportioning contributing sediment sources. The equations for these curve relations are used in the FLOWSED worksheet (table 11–11).

Convert dimensionless suspended and bed-load sediment rating curves to actual (dimensioned) values—Convert dimensionless values by multiplying the field-measured bankfull discharge and sediment values by each of the ratios appropriate for the relation selected. Dimensionless ratio bed-load and suspended rating curves are used to convert data to dimensioned rating curves (fig. 11–20). Examples of dimensioned bed-load and suspended sediment rating curves are shown in figures 11–22 and 11–23 for the Weminuche Creek in Colorado. Tests of this relation are reported in the text in figures 11–13, 11–14, and 11–15, where reference dimensionless rating curves were used to establish sediment rating curves.

If it is not possible to obtain measured bankfull discharge, suspended sediment, and bed-load sediment data to convert dimensionless sediment rating curves to actual values, regional curves can be temporarily substituted. The user must obtain drainage area in square miles to calculate bankfull discharge from a similar hydro-physiographic province. The bankfull flow is used to convert the dimensionless flow-duration to dimensioned flow duration. The bankfull discharge is also used to convert the dimensionless discharge portion of the dimensionless bed-load and suspended rating curve to actual values. The sediment data obtained from the drainage area must be derived from existing measured bankfull suspended sediment and bed-load sediment data, then converted to unit area sediment values from the corresponding drainage area. These data need to represent the same lithology, stream type and stability condition of the stream being evaluated. These data are entered in the FLOWSED worksheet (table 11–11).

An example of unit area suspended sediment data from USGS sites throughout the United States is shown in Simon, Dickerson, and Heins (2004). These measured sediment values were separated by evolutionary stages. Additional stability or stream type data may help to identify appropriate relations for extrapolation. This drainage area extrapolation procedure represents only an interim procedure until measured bankfull values can be obtained.

FLOWSED—Continued

Convert dimensionless flow duration to dimensioned flow duration—The bankfull discharge is multiplied by each of the ratios to convert dimensionless data to actual discharge values representing mean daily discharge for each percentile. An example of a dimensioned flow-duration curve using bankfull discharge to convert from the dimensionless relation (fig. 11–21) is shown in figure 11–24.

Calculate annual sediment yield for both suspended and bed-load sediment—This is accomplished by taking the dimensioned flow-duration curve and multiplying flow increments for duration of time in days by the sediment yield associated with that flow. Enter these calculations in the FLOWSED worksheet (table 11–11).

Calculate flow-related sediment yield—This calculation is accomplished using the output of the flow-duration curves showing the increase in magnitude and duration of flow. The post-treatment flows are routed through the calculation in the FLOWSED worksheet (table 11–11). The excess water calculation output from the WRENSS snowmelt model (EPA 1980) or a similar model integrates the flow with flow-duration changes. Dimensionless flow-duration curves are also converted to dimensioned values by multiplication of the bankfull discharge value. Reference conditions for watersheds in relative hydrologic recovery are compared to watersheds where streamflow has been increased or decreased by change in vegetation or by reservoirs and/or diversions.

Stormflow models, such as TR–55, need to be used to compute new bankfull values, converting dimensionless values to new dimensioned flow durations. It is important to calibrate the bankfull discharge, as the precipitation probability for a given antecedent moisture content and runoff curve number that generates the bankfull discharge needs to be determined. Any greater flow will be distributed on flood plains or a flood-prone area if the stream is not entrenched. Thus, flow-related sediment changes are determined by the use of dimensionless sediment rating curves and dimensionless flow-duration curves. Other appropriate models can also be used for this step, based on the user's familiarity with the various models selected. The output required, regardless of the model, is bankfull discharge and pre- and post-treatment flow-duration curves.

Figure 11–19 General overview of the FLOWSED model

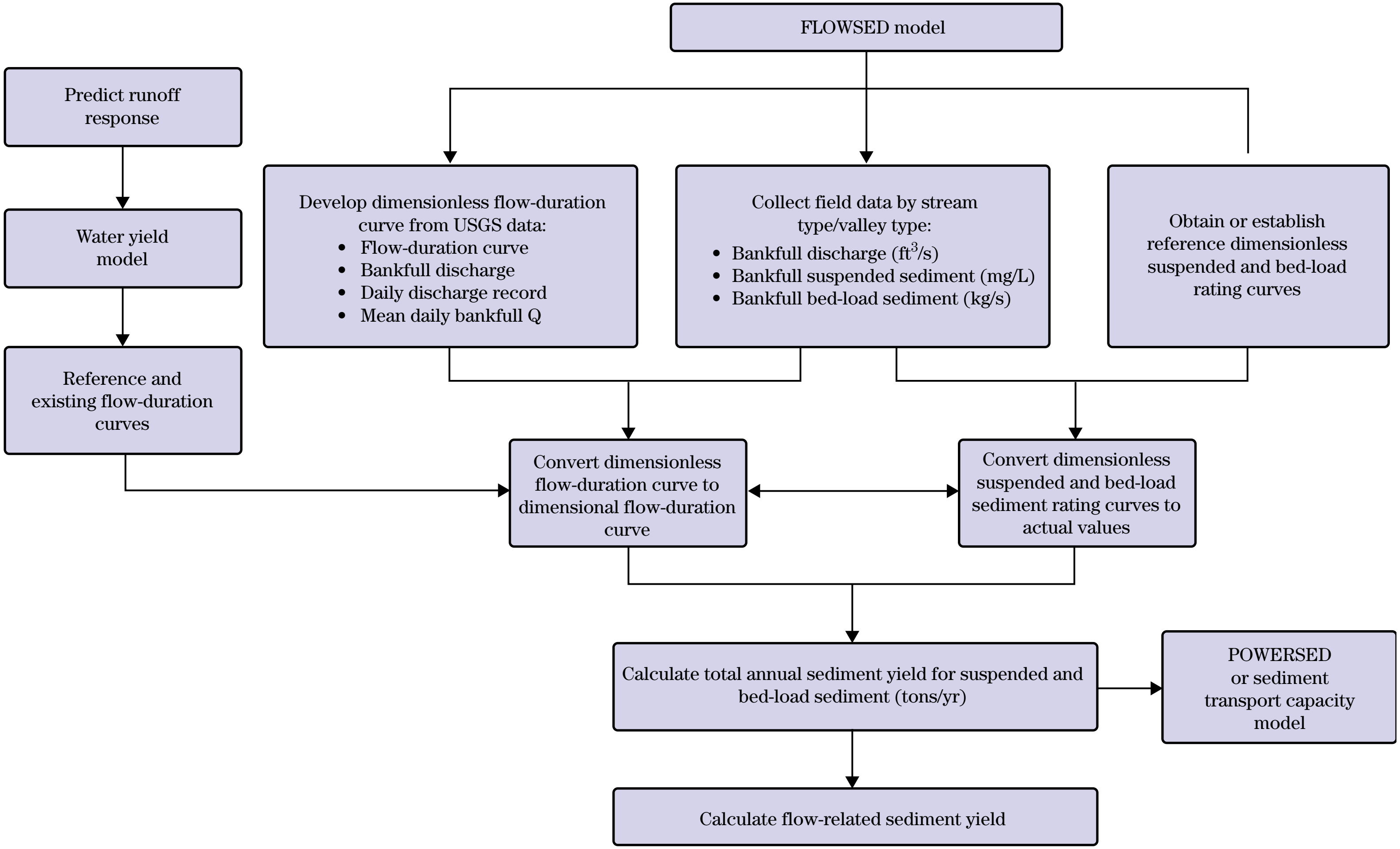


Figure 11–20 Graphical depiction of the FLOWSED model

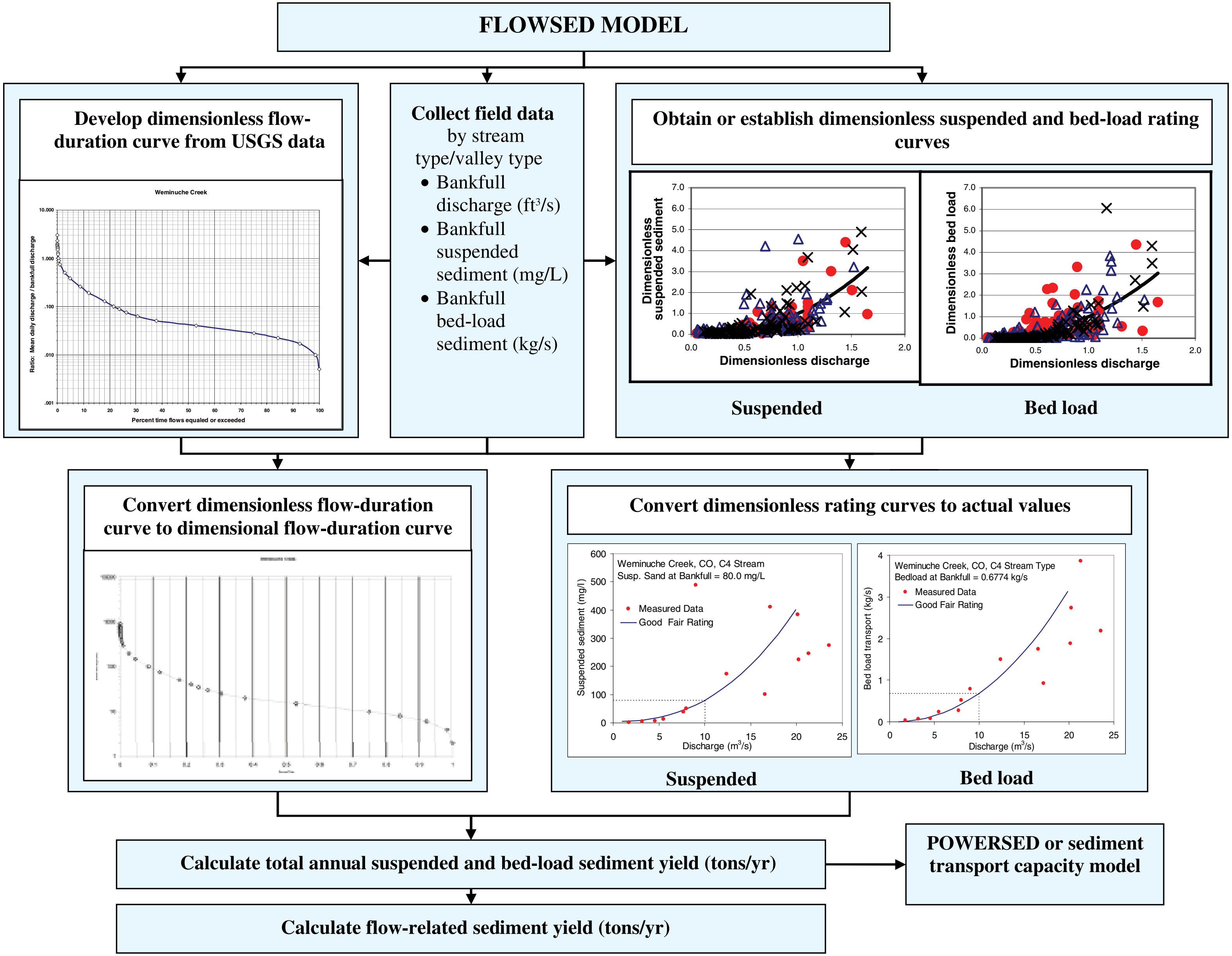


Table 11–10 FLOWSED model procedure to calculate annual bed-load and suspended sediment yield

FLOWSED procedure	
FS–1	Measure stream cross section (on riffle), profile, pattern, and materials.
FS–2	Measure bankfull width, mean depth, and velocity, and compute discharge.
FS–3	Measure suspended sediment at the bankfull stage; separate wash load in lab
FS–4	Measure bed-load sediment at the bankfull stage, sieve particle sizes, and measure largest size.
FS–5	Compute average water surface slope.
FS–6	Collect point bar sample, weigh by size fraction and record D_{50} and largest size (D_{max}).
FS–7	Collect pebble count on active riffle bed: obtain D_{50}, D_{84} sizes (mm).
FS–8	Determine stream type.
FS–9	Conduct channel stability assessment procedure, including Pfankuch channel stability rating.
FS–10	Obtain reference dimensionless bed-load sediment rating curve for appropriate stream type/stability rating.
FS–11	Obtain reference dimensionless suspended sediment rating curve for appropriate stream type/stability rating.
FS–12	Determine ratio of wash load/suspended sediment by Q/Q_{bkf} relation.
FS–13	Construct a bed-load rating curve (enter range of Q/Q_{bkf} ratios into the reference bed-load relation from step 10 and multiply by the measured bankfull bed load from step 4).
FS–14	Construct suspended sediment rating curve in the same manner as in step 13 using reference dimensionless sediment relations (step 11) and bankfull suspended sediment (step 3).
FS–15	Construct a suspended sediment rating curve less wash load (silt/clay) for potential settleable sediment by multiplying ratio of wash load/suspended sediment for appropriate Q/Q_{bkf}.
FS–16	Convert suspended sediment less wash load from mg/L to tons/day on rating curve: tons/d = 0.0027×ft^3/s×mg/L.
FS–17	Convert suspended sediment less wash load from mg/L to tons/d as in step 16.
FS–18	Convert bed load in lb/s to tons/d, where tons/d = (lb×86,400)/2000 (if metric, convert kg/s to lb/s by multiplying by 2.205).
FS–19	Obtain dimensionless flow-duration curve from either water yield model or regionalized relation.
FS–20	Develop the dimensionless flow-duration curves using the normalization parameter of mean daily bankfull discharge, rather than momentary maximum values from flood-frequency data. Divide the mean daily discharge (the day bankfull discharge occurs) by the momentary maximum value to determine the appropriate conversion ratio.
FS–21	Convert dimensionless flow-duration curve to actual flow by multiplying bankfull discharge (step 2) times the Q/Q_{bkf} ratios from dimensionless flow-duration curve (step 19).
FS–22	Calculate total annual sediment yield for suspended sediment, suspended sediment less wash load, and bed load from sediment rating curve/flow-duration curve procedure (table 11–11). Obtain flow from the water yield model for hydraulically recovered condition to compare departure from existing/proposed condition (step 22). This represents the pre-treatment flow duration/sediment relation.
FS–23	To determine flow-related increase in sediment, multiply post-treatment flow-duration curve times appropriate sediment rating curves for suspended, bed-load and total sediment rating curves to calculate total annual sediment yield using the same procedure as step 21 (table 11–11).

Table 11–11 FLOWSED calculation of total annual sediment yield

Stream: **Notes:**

From flow-duration curve						From sediment rating curves					Calculate	Calculate daily mean sediment yield				
Flow exceedance	Daily mean discharge	Mid-ordinate streamflow	Increment	Mid-ordinate streamflow	Dimensionless streamflow	Dimensionless suspended sediment discharge	Suspended sediment discharge	Suspended sediment minus wash load	Dimensionless bed-load discharge	Bed load	Time adjusted streamflow	Suspended sediment	Suspended sediment minus wash load	Bed load	Bed load plus suspended	Bed load plus suspended minus wash load
(%)	(ft^3/s)	(%)	(%)	(ft^3/s)	(Q/Q_{bkf})	(S/S_{bkf})	(tons/d)	(tons/d)	(b_s/b_{bkf})	(tons/d)	(ft^3/s)	(tons/d)	(tons/d)	(tons/d)	(tons/d)	(tons/d)
									Annual totals:		(acre-ft)	tons/yr)	(tons/yr)	(tons/yr)	(tons/yr)	(tons/yr)

Bankfull discharge (ft^3/s)	
Bankfull bed load (kg/s)	
Bankfull suspended (mg/L)	

Dimensionless sediment rating curve used

Type	**Intercept**	**Coefficient**	**Exponent**	**X**	**Y**	**Form**	**Notes**
Bed load							
Suspended							

Figure 11–21 Dimensionless flow-duration curve for Weminuche Creek, CO

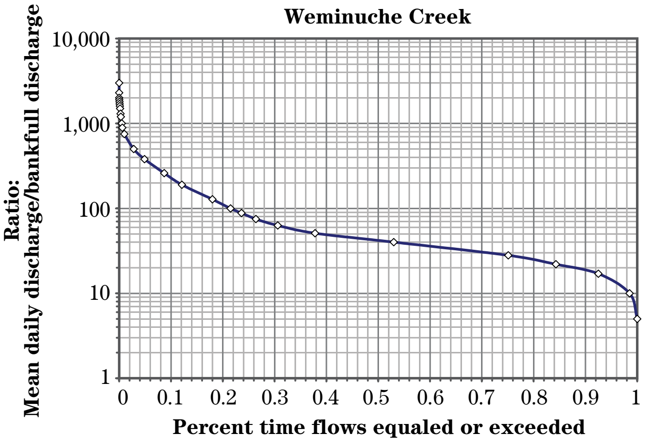


Figure 11–23 Suspended sediment rating curve for Weminuche Creek, CO

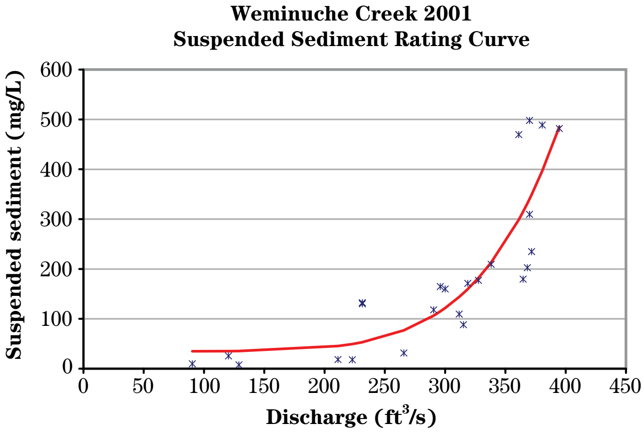


Figure 11–22 Bed-load sediment rating curve for Weminuche Creek, CO

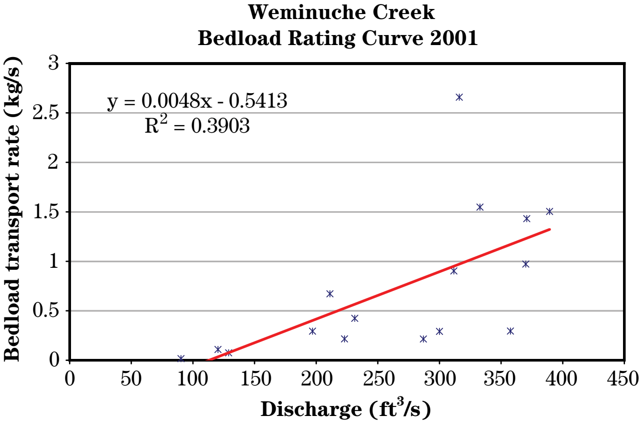
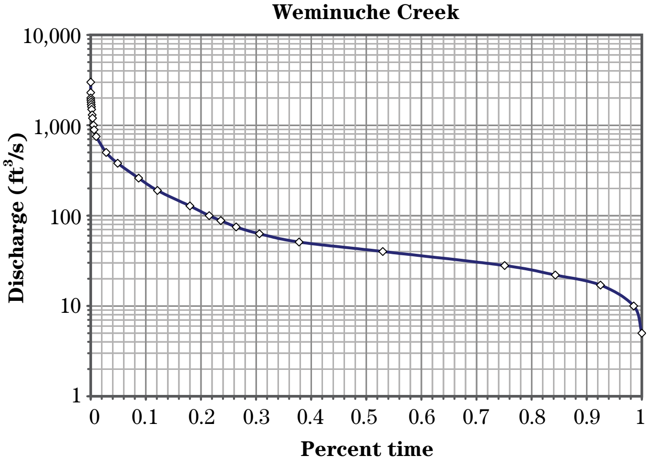


Figure 11–24 Dimensioned flow-duration curve for Weminuche Creek, CO



POWERSED

A generalized flowchart depicting the POWERSED model is shown in figure 11–25, and a graphical depiction of the model is shown in figure 11–26.

Evaluate channel characteristics that change hydraulic and morphological variables—Changes in the cross section and/or pattern (slope) for potentially impaired reaches are measured to determine width, depth, slope and calculated velocity. Comparisons are made between hydraulic characteristics of the reference versus the impaired reach. This analysis is used in the bed-load transport model (POWERSED) or in a comparable bed-load model selected by the user. Shear stress and unit stream power are calculated using equations 11–2 and 11–7:

$$\tau = \gamma d S \qquad \text{(eq. 11–2)}$$

where:
γ = specific weight of the fluid
d = mean depth
S = water surface slope

Unit stream power or power per unit of streambed area (ω_a) is defined as:

$$\omega_a = \tau u \qquad \text{(eq. 11–7)}$$

where:
τ = bankfull shear stress (lb/ft^2)
u = mean velocity

POWERSED can be used to simulate hydraulic geometry (width, depth, slope, velocity, and discharge) for a wide range of stages for reference and impaired reach hydraulic evaluations. POWERSED can also be used to compute changes in hydraulic character due to modified channel dimension, pattern, profile or materials. This information is used to determine changes in unit stream power for increased or decreased discharge. This model predicts channel stability response to imposed sediment load, change in flow, and/or change in distribution of energy due to channel change. The model determines sediment transport and predicts aggradation, stability, or degradation, depending on the nature and extent of the channel and/or flow change. The hydraulic/sediment departure is compared to the corresponding reference or stable condition. A recent comparison of predicted to observed values on an independent data set was shown in Rosgen (2006) where predicted annual sediment yield values were predicted within 3 percent of measured values for a C4 stream type and within 6 percent of measured values for a D4 stream type on Weminuche Creek, Colorado.

Calculate bed-load and suspended sand-bedmaterial load transport (stream power)—Bed load and suspended sand-bed material load transport calculations may use various equations, such as the Bagnold equation. The POWERSED model (figs. 11–25, 11–26 and tables 11–12 and 11–13) assists in the analysis of sediment transport and channel response. This model was developed to predict the effects of channel instability and sediment supply changes in sediment transport. Other bed-load and suspended sand-bed material load transport models can be employed by the user, based on familiarity with and calibration/validation of the model for application to the particular stream types being analyzed.

The POWERSED model applies the suspended sand-bed material and bed-load sediment rating curves/flow duration/revised unit stream power-transport curves or a comparable model selected by the user to predict sediment transport and channel stability. The prediction includes river stability and total annual bed-load sediment yield in tons/year. The equations or computer program generates a change in coarse bed-load transport that will be influenced by changes in channel cross section and/or slope. Changes in streamflow, velocity, unit stream power, critical dimensionless shear stress, and other variables due to land use changes predict changes

POWERSED—Continued

in river stability and total annual bed-load sediment yield. The sediment supply component is predicted using the FLOWSED model and is derived from dimensionless bed-load and suspended sediment rating curves for corresponding stream and stability types. These changes are compared to stable reference conditions for a departure comparison.

Procedural steps for computations of the POWERSED model are presented in table 11–12. Bed-load transport and suspended sand-bed material load is calculated using the POWERSED worksheet (table 11–13).

The POWERSED model is used to predict the transport rate and capacity for each reach independently. Reaches may be stable (sediment in versus sediment out), aggrading, or degrading. The model identifies reaches that may have serious instabilities due to changes in sediment supply and/or hydraulic characteristics. The analysis assists in pinpointing various river reaches for mitigation. The sediment transport changes reflect the sediment supply of the existing condition compared to the reference condition. Annual streambank erosion rates and other sources are compared to the total annual sediment yield.

Figure 11–25 POWERSED model to predict bed-load and suspended sand-bed-material load transport

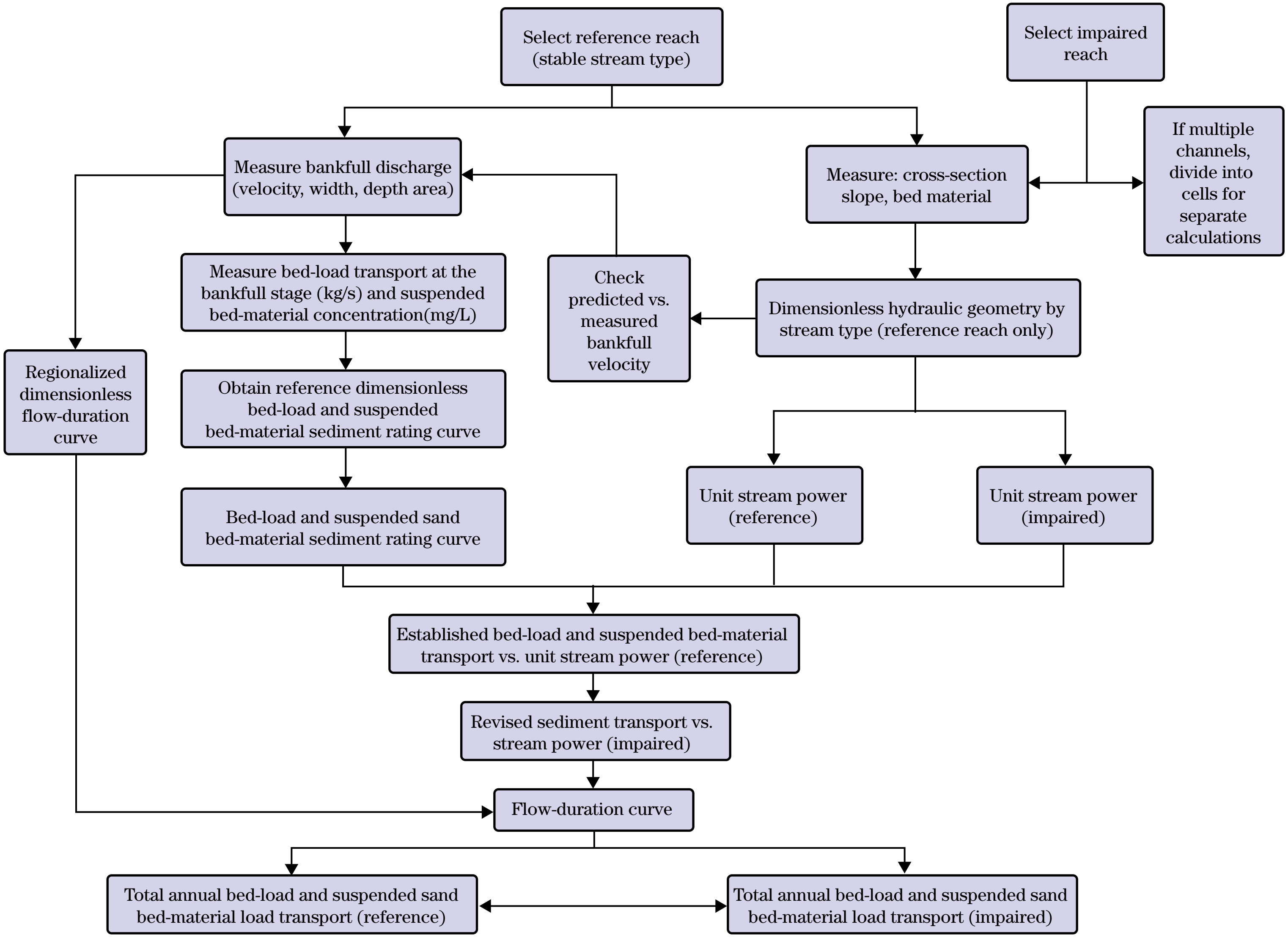


Figure 11–26 Graphical depiction of POWERSED model

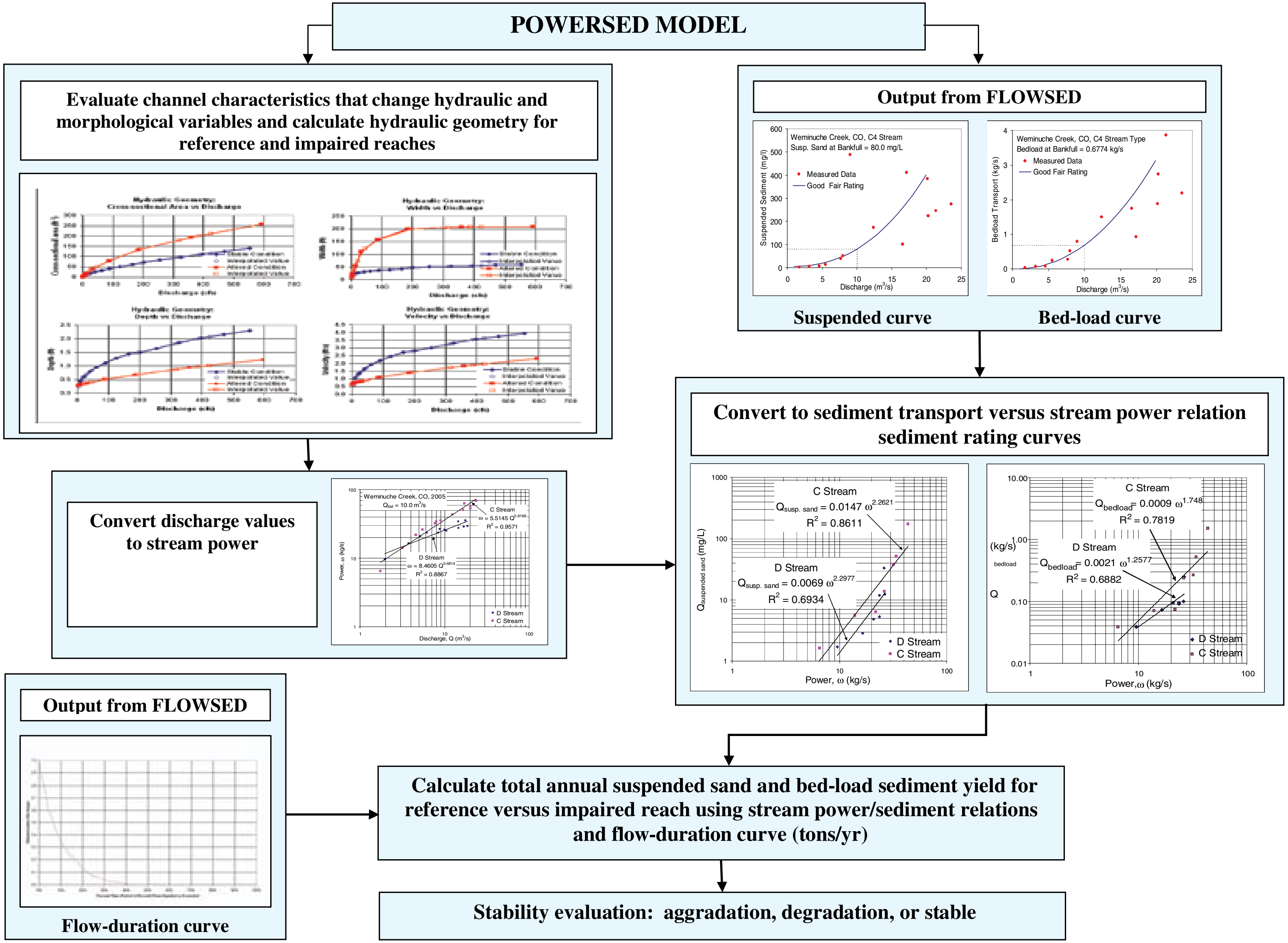


Table 11–12 POWERSED procedural steps of predicted bed-load and suspended sand-bed material transport changes due to alterations of channel dimension or slope (same stream with different bankfull discharges)

POWERSED procedure	
PS–1	Select a reference reach: a. Survey a stable cross section; measure the stream gradient and bed material. b. Measure bankfull discharge (ft^3/s). c. Measure bankfull bed load (kg/s).
PS–2	Obtain an appropriate dimensionless bed load and suspended sand sediment rating curve: a. Construct a dimensional bed load and suspended sand sediment rating curve for the defined range of flow using the measured bankfull discharge, bankfull bed load transport and suspended sand-bed material load.
PS–3	Obtain the drainage area of the reference reach: a. Predict bankfull discharge and cross-sectional dimensions using regional curves. b. Validate the regional curves using the measured bankfull discharge and cross-sectional dimensions.
PS–4	Use dimensionless hydraulic geometry by stream type to predict the hydraulic geometry of the stable cross section for a full range of discharge (baseflow to above bankfull): a. Construct hydraulic geometry curves. b. Check predicted versus measured bankfull velocity. c. Obtain hydraulic geometry for each discharge value within the defined range of flow. d. Calculate unit stream power for each discharge value within the defined range of flow.
PS–5	Select an impaired reach on the same stream: a. Obtain the drainage area. b. Predict bankfull discharge from the validated regional curve. c. Survey the cross section, and measure the stream gradient and bed material.
PS–6	Obtain the stable (potential) dimension, pattern, and profile for the impaired reach. If reference reach is not immediately upstream and/or is of different size or drainage area, complete the following procedure: a. Slope = valley slope/sinuosity. b. Obtain appropriate cross-sectional area from regional curve. c. Obtain width-to-depth ratio (W/d) from reference dimensionless ratios by stream type. d. Calculate appropriate width.
PS–7	Use the RIVERMorph® procedure or applicable spreadsheet calculations to predict the hydraulic geometry of the impaired and potential cross sections for a full range of discharge (baseflow to above bankfull). Follow the step below for the impaired and potential cross sections: a. Construct hydraulic geometry curves. b. Obtain hydraulic geometry for each discharge value within the defined range of flow. * If channel has multiple channels, divide the channels into thirds and treat as a separate channel c. Calculate unit stream power for each discharge value within the defined range of flow.
PS–8	Plot unit stream power vs. bed load and suspended sand-bed material transport for the stable cross section.
PS–9	Construct a unit stream power versus bed-load transport curve for the impaired and potential cross sections using the relationship constructed in step 8.
PS–10	Obtain a dimensionless flow-duration curve for the appropriate region: a. Create a dimensional flow-duration curve using the bankfull discharge for the stable reach. b. Create a dimensional flow-duration curve using the bankfull discharge for the impaired reach.

Table 11–12 POWERSED procedural steps of predicted bed-load and suspended sand-bed material transport changes due to alterations of channel dimension or slope (same stream with different bankfull discharges)—Continued

POWERSED procedure	
PS–11	Calculate total annual sediment yield (bed-load and suspended sand-bed-material load) in tons/yr for all three (stable, impaired, potential) cross sections using the appropriate flow-duration curve: a. Convert the predicted bed-load transport for each discharge value within the defined range of flow from kg/s to tons/d by multiplying kg/s by 95.24. Convert values of suspended sand-bed material load in mg/L to tons/d by multiplying (mg/L)(.0027)(ft^3/s). b. Multiply the predicted bed-load and suspended sand-bed material load transport (tons/d) by the percent time factor from flow-duration curve. c. Sum the time adjusted bed-load transport and multiply by 365 days to obtain annual bed load yield in tons/yr. d. Divide the annual yield for both bed-load and suspended sand-bed material load by the drainage area to obtain the annual unit area bed-load and suspended sand-bed material load yield (tons/yr/mi^2). e. Compare the annual unit area bed-load and suspended sand-bed material load yield predicted for all three conditions (stable, impaired and potential).
PS–12	Record data for impacted and reference condition (separately) in POWERSED worksheet (table 11–13).

Table 11–13 POWERSED model to predict bed-load and suspended sand and bed-material load transport*

Stream: **Gage station#:** **Date:**

Equation type	B0	B1	B2	Form	Equation name	Enter equation number (1 or 2)	Bankfull discharge (ft^3/s)	Bankfull bed load (lb/s)	Suspended bed-material load (mg/L)
1 Dimensional									
2 Dimensionless									
3 Bed load									
4 Suspended sand-bed concentration									

Flow-duration curve		Calculate	Hydraulic geometry				Measure	Calculate									
Exceedance probability	Daily mean discharge	Mid-ordinate stream-flow	Area	Width	Depth	Velocity	Slope	Shear stress	Stream power	Unit power	Time increment	Daily mean bed-load transport	Time adjusted bed-load transport	Daily mean suspended transport	Time adjusted suspended transport	Time adjusted total transport
(%)	(ft^3/s)	(ft^3/s)	(ft^2)	(ft)	(ft)	(ft/s)	(ft/ft)	(lb/ft^2)	(lb/s)	(lb/ft/s)	(%)	(tons/d)	(tons)	(tons/d)	(tons)	(tons)
										Annual total sediment yield (tons/yr):					

*Use this model for both reference and impaired conditions separately. Calculate bed load separately from suspended bed-material load.

Step 28 Obtain maximum bankfull riffle depth (d_{max}) from ratio of maximum riffle depth divided by mean bankfull depth from dimensionless ratios of reference reach data (step 7) (table 11–3).

$$d_{mbkf} = \left[\left(\frac{d_{mbkf}}{d_{bkf}}\right)_{ref}\right] d_{bkf} \qquad \text{(eq. 11–18)}$$

Step 29 Determine entrenchment ratio of proposed channel by measuring the width of the flood-prone area at an elevation of twice the maximum bankfull depth ($d_{max\ bkf}$). Entrenchment ratio is calculated by:

$$ER = \frac{W_{fpa}}{W_{bkf}} \qquad \text{(eq. 11–19)}$$

Step 30 Calculate flood-prone area capacity. This involves estimating velocity associated with the cross-sectional area and slope of the stream channel and flood-prone area. Determine cross-sectional area of the flood-prone area. Plot the bankfull cross-section and flood-prone area elevation ($2 \times d_{max\ bkf}$) and width. Use valley slope for hydraulic calculations for the flood-prone area. Estimate roughness from Manning's equation based on vegetative cover and other roughness elements. HEC–2, HEC–RAS, or other models can be used to obtain the corresponding discharge of the flood-prone area. Calculate the 50- and 100-year flood levels based on the proposed design. Use the bankfull channel capacity from step 22.

Step 31 Calculate depth of pool (ratios from table 11–3):

$$d_{mbkfp} = \left[\left(\frac{d_{mbkfp}}{d_{bkf}}\right)_{ref}\right] d_{bkf} \qquad \text{(eq. 11–20)}$$

Step 32 Calculate depth of glide (ratios from table 11–3):

$$d_g = \left[\left(\frac{d_g}{d_{bkf}}\right)_{ref}\right] (d_{bkf}) \qquad \text{(eq. 11–21)}$$

Step 33 Calculate depth of run (ratios from table 11–3):

$$d_{run} = \left[\left(\frac{d_{run}}{d_{bkf}}\right)_{ref}\right] (d_{bkf}) \qquad \text{(eq. 11–22)}$$

Step 34 Calculate slope of pool (ratios from table 11–3):

$$S_p = \left[\left(\frac{S_p}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–23)}$$

Step 35 Calculate slope of glide (ratios from table 11–3):

$$S_g = \left[\left(\frac{S_g}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–24)}$$

Step 36 Calculate slope of run (ratios from table 11–3):

$$S_{run} = \left[\left(\frac{S_{run}}{S}\right)_{ref}\right] S \qquad \text{(eq. 11–25)}$$

Step 37 Calculate pool-pool spacing (from plan view and profile layout).

Step 38 Design stabilization/fish habitat enhancement measures (grade control, energy dissipation, bank stability, holding cover). See phase VI.

Step 39 Prepare revegetation plan compatible with native plants, soil, and site conditions. Make recommendations on vegetative maintenance and management for long-term solutions.

Step 40 Design a monitoring plan including effectiveness, validation, and implementation monitoring. Prepare maintenance plan to ensure long-term success.

The variables associated with existing, proposed, gage station, and reference reach data are summarized in the form as demonstrated in table 11–14 (Rosgen 1998). The variables used in table 11–14 and forms used in field data collection are in the Reference Reach Field Book (Rosgen, Leopold, and Silvey 1998; Rosgen and Silvey 2005).

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data

Restoration site (name of stream and location):
Reference reach (name of stream and location):

Variables		**Existing channel**	**Proposed reach**	**USGS station**	**Reference reach**
1	Stream type				
2	Drainage area, mi^2				
3	Mean riffle depth, ft (d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
4	Riffle width, ft (W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
5	Width-to-depth ratio (W_{bkf}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
6	Riffle cross-sectional area, ft^2 (A_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
7	Max riffle depth (d_{mbkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
8	Max riffle depth/mean riffle depth (d_{mbkf}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
9	Mean pool depth, ft (d_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
10	Mean pool depth/mean riffle depth	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
11	Pool width, ft (W_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
12	Pool width/riffle width	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
13	Pool cross-sectional area, ft^2 (A_{bkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
14	Pool area/riffle area	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
15	Max pool depth (d_{mbkfp})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
16	Max pool depth/mean riffle depth (d_{mbkfp}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		Existing channel	Proposed reach	USGS station	Reference reach
17	Low bank height (LBH)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
18	Low bank height to max riffle depth (LBH/d_{mbkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
19	Width of flood-prone area, ft (W_{fpa})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
20	Entrenchment ratio (W_{fpa}/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
21	Point bar slope	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
22	Bankfull mean velocity, ft/s (u_{bkf})				
23	Bankfull discharge, ft^3/s (Q_{bkf})				
24	Meander length, ft (Lm)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
25	Meander length ratio (Lm/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
26	Radius of curvature, ft (Rc)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
27	Ratio of radius of curvature to bankfull width (Rc/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
28	Belt width, ft (W_{blt})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
29	Meander width ratio ($W_{b/t}/W_{bkf}$)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
30	Individual pool length, ft	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
31	Pool length/riffle width	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
32	Pool to pool spacing (based on pattern), ft (p-p)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		Existing channel	Proposed reach	USGS station	Reference reach
33	Ratio of p-p spacing to bankfull width (p-p/W_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
34	Stream length (SL)				
35	Valley length (VL)				
36	Valley slope (VS)				
37	Average water surface slope (S)		S = VS/k		
38	Sinuosity (k)	SL/VL:	SL/VL:	SL/VL:	SL/VL:
		VS/S:		VS/S:	VS/S:
39	Riffle slope (water surface facet slope) (S_{rif})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
40	Ratio riffle slope to average water surface slope (S_{rif}/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
41	Run slope (water surface facet slope) (S_{run})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
42	Ratio run slope/average water surface slope (S_{run}/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
43	Pool slope (water surface facet slope) (S_p)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
44	Ratio of pool slope/average water surface slope (S_p/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
45	Glide slope (water surface facet slope) (S_g)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
46	Ratio glide slope/average water surface slope (S_g/S)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
47	Max run depth, ft (d_{run})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
48	Ratio max run depth/ bankfull mean depth (d_{run}/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:
49	Max glide depth, ft (d_g)	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Table 11–14 Morphological characteristics of the existing and proposed channel with gage station and reference reach data—Continued

Variables		**Existing channel**	**Proposed reach**	**USGS station**	**Reference reach**
50	Ratio max glide depth/ bankfull mean depth (d_g/d_{bkf})	Mean:	Mean:	Mean:	Mean:
		Range:	Range:	Range:	Range:

Materials					
51	Particle size distribution of channel material (active bed)				
	D_{16} (mm)				
	D_{35} (mm)				
	D_{50} (mm)				
	D_{84} (mm)				
	D_{95} (mm)				
52	Particle size distribution of bar material				
	D_{16} (mm)				
	D_{35} (mm)				
	D_{50} (mm)				
	D_{84} (mm)				
	D_{95} (mm)				
	Largest size particle at the toe (lower third) of bar (mm)				

Sediment transport validation (Based on Bankfull Shear Stress)		**Existing**	**Proposed**
Calculated shear stress value (lb/ft^2) from curve			
Size from Shields diagram - Original data (mm)			
Size from Shields diagram - Colorado data (mm)			
Largest size (mm) to be moved (D_{max})			
Dimensionless shear stress (τ^*)			
Mean d_{bkf} (ft) calculated using dimensionless shear stress equations for given slope			

Remarks:

(f) Phase VI—Selection and design of stabilization and enhancement structures/methodologies

The objectives of river structures are often primarily designed to:

- buy time to protect the new channel from excess erosion until significant riparian vegetation can become established
- reduce accelerated streambank erosion
- provide grade control
- provide recreational boating
- obtain stable flow diversions
- enhance fish habitat including instream cover, holding cover, spawning habitat, and habitat diversity
- reintroduce and stabilize large wood for fishery, stability, and aesthetic purposes
- protect infrastructure adjacent to streams
- protect bridges, culverts, and drainageway crossings
- reduce flood levels
- transport sediment
- provide energy dissipation

River stabilization and enhancement structures are numerous and continue to be improved and developed. The effort here will not be to make a complete listing, but rather present methods used in the Rosgen geomorphic channel design methodology consistent with the objectives. The structures and methods primarily utilize native materials such as natural boulders, logs, rootwads, and vegetative transplants.

Design objectives will be presented to provide the user with alternatives to standard or traditional structures.

Grade control

Often cross-channel check dams are used for grade control. NRCS has successfully used many types of channel grade control structures, but streams with high sediment loads have experienced some adverse channel adjustment in some case. The adjustments are associated with aggradation, lateral erosion, flood stage increase, migration barriers for fish, increased recreational boating risk, land loss, channel incision through lateral migration and channel avulsion. To prevent these stability problems, the cross vane was developed (fig.11–27 (Rosgen 2001e)).

Application of this design is also very effective for bridge pier scour reduction (Johnson, Hey, et al. 2002). A photograph depicting the structure as constructed on the lower Blanco River, Colorado, is shown in figure 11–28. The structure also decreases near-bank shear stress, minimizing streambank erosion.

The photographs in figures 11–29 and 11–30 demonstrate the use of cross vanes in river restoration. In this example, a reconstructed river project on the East Fork Piedra River, Colorado, in a valley type V (glacial trough), converted a braided (D4) stream type to a meandering (C4) stream type. The use of the cross vane structure was effective at maintaining grade control, transporting excessive coarse bed load, reducing bank erosion, buying time for riparian vegetation colonization, and providing trout habitat. The structures located along 3 miles of this project withstood floods at twice the bankfull discharge magnitude in 2004. Logs and rootwads can also be utilized in this structure as designed in Rosgen (2001e) and as shown in figure 11–31. The use of large wood in this structure assists in the visual, as well as biological enhancement objectives. The step in the upper third of the structure dissipates energy, reduces footer scour, and minimizes risk for recreational boating and fish passage.

A structure designed for larger rivers for grade control and streambank protection is the W-weir. This structure can also be effectively used for irrigation diversions, protection of central piers and approach sections on bridges, bed-load transport, recreational boating, and fish habitat. Visually, it is improved over a line of rock often used in grade control. It resembles natural bedrock features in stream channels. Figure 11–32 depicts the design (Rosgen 2001e), and figure 11–33 shows a typical W-weir structure as installed on the Uncompahgre River in Colorado.

Streambank stabilization

Most stream restoration projects require some degree of streambank stabilization. Often the stabilization involves riparian vegetation reestablishment or change in management. Regardless, there is a time element that is needed to establish rooting depth, density, and

Figure 11–27 Cross section, profile, and plan view of a cross vane

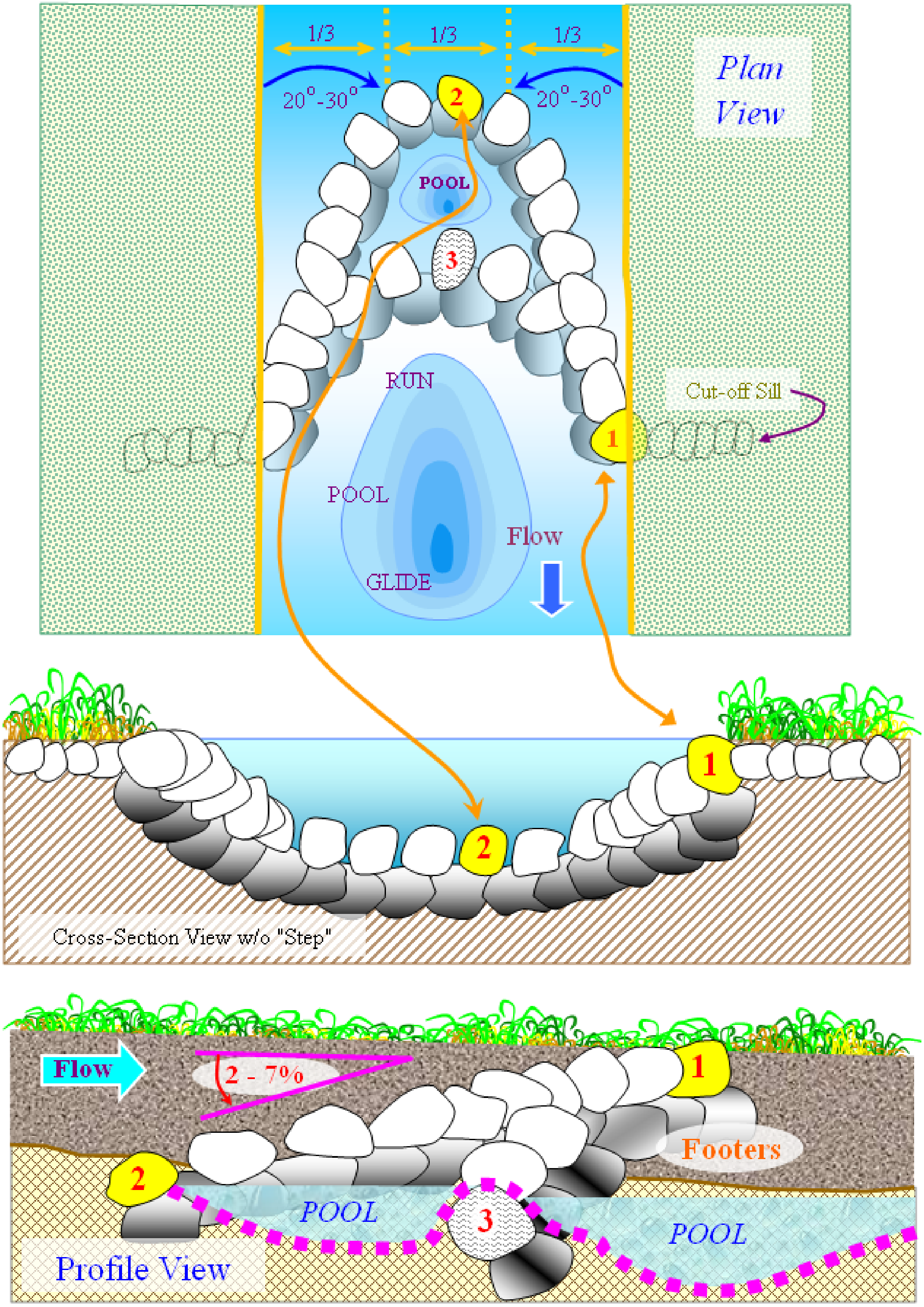


Figure 11–28 Cross vane installed on the lower Blanco River, CO

Figure 11–29 Cross vane structure with step on the East Fork Piedra River, CO

Figure 11–30 Cross vane/step-pool on the East Fork Piedra River, CO

Figure 11–31 Cross vane/rootwad/log vane step-pool, converting a braided D4→C4 stream type on the East Fork Piedra River, CO

Figure 11–32 Plan, cross section, and profile views of a W-weir structure

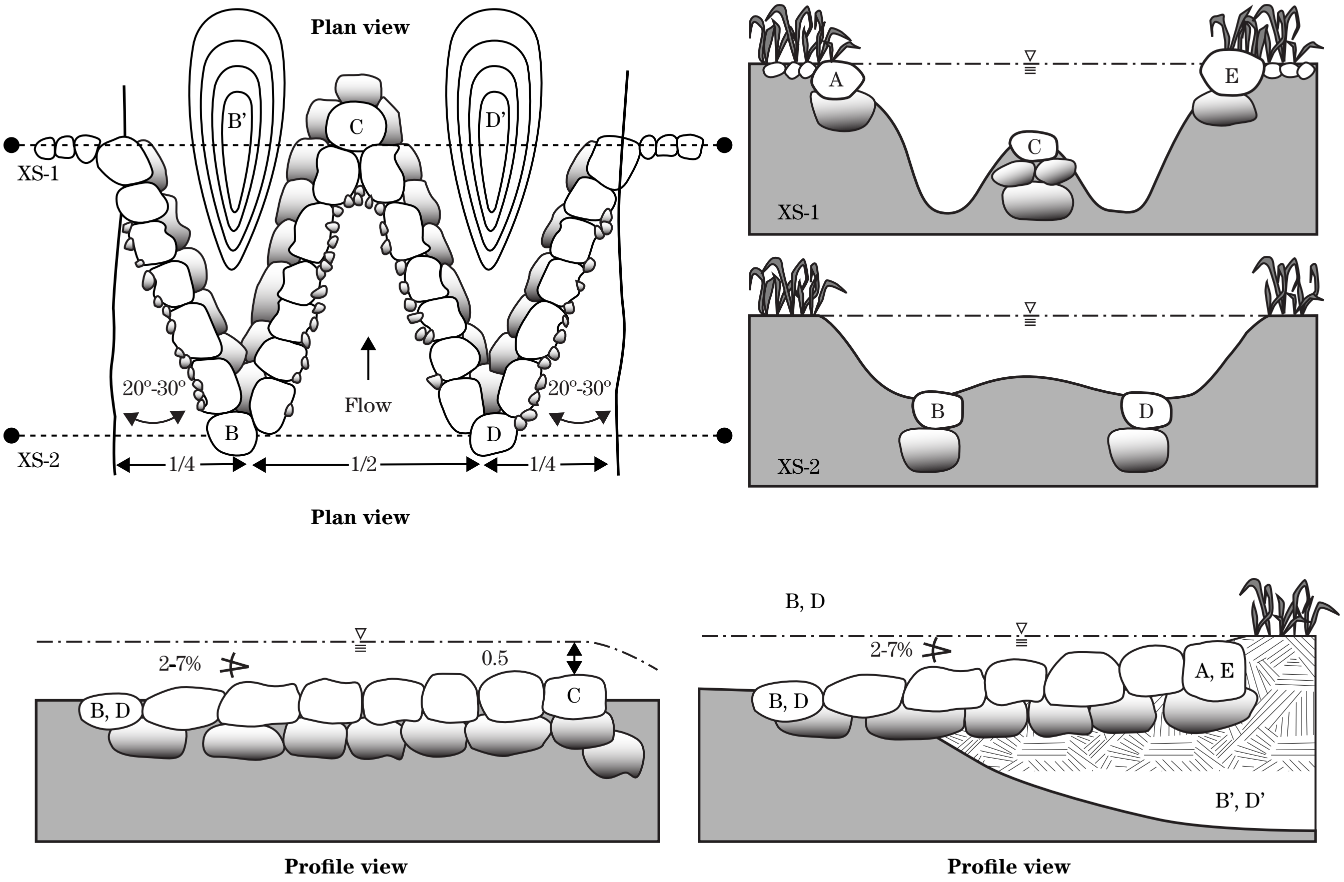


Figure 11–33 W-weir installed on the Uncompahgre River, CO

Figure 11–34 Plan, profile, and section views of the J-hook vane structure

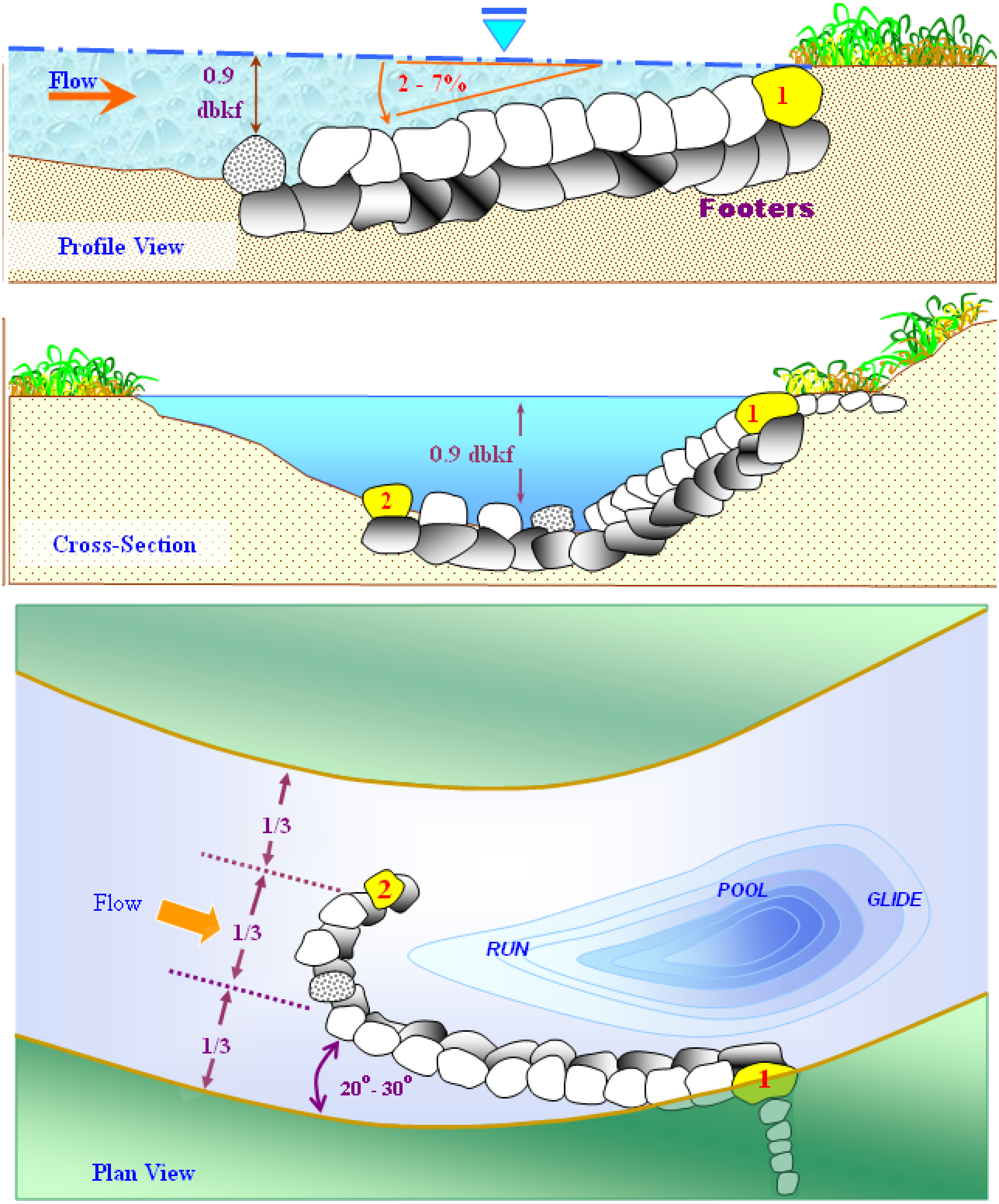


Figure 11–35 Log vane/J-hook combo with rootwad structure

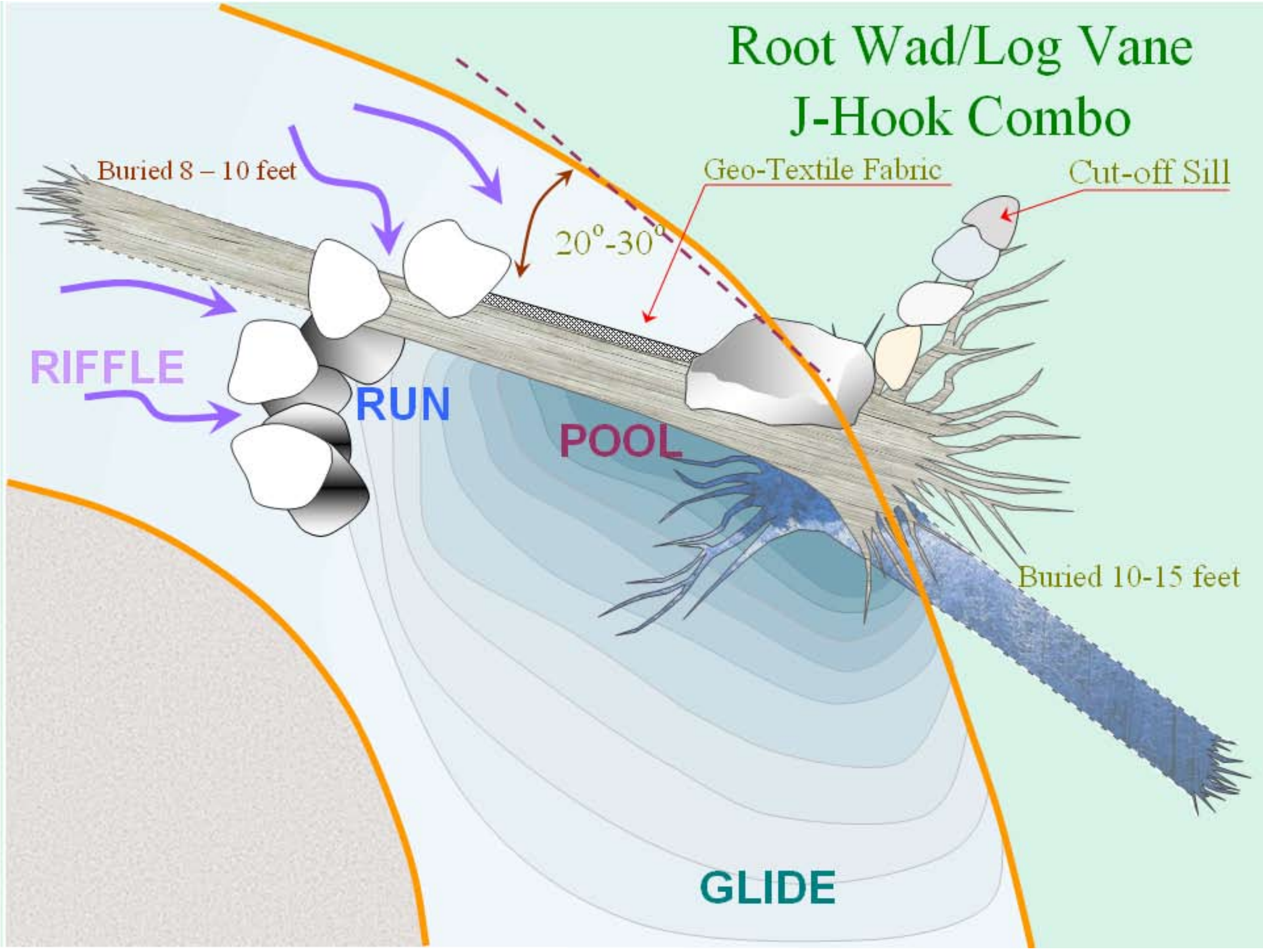


Figure 11–36 Rock vane/J-hook combo with rootwad and log vane footer

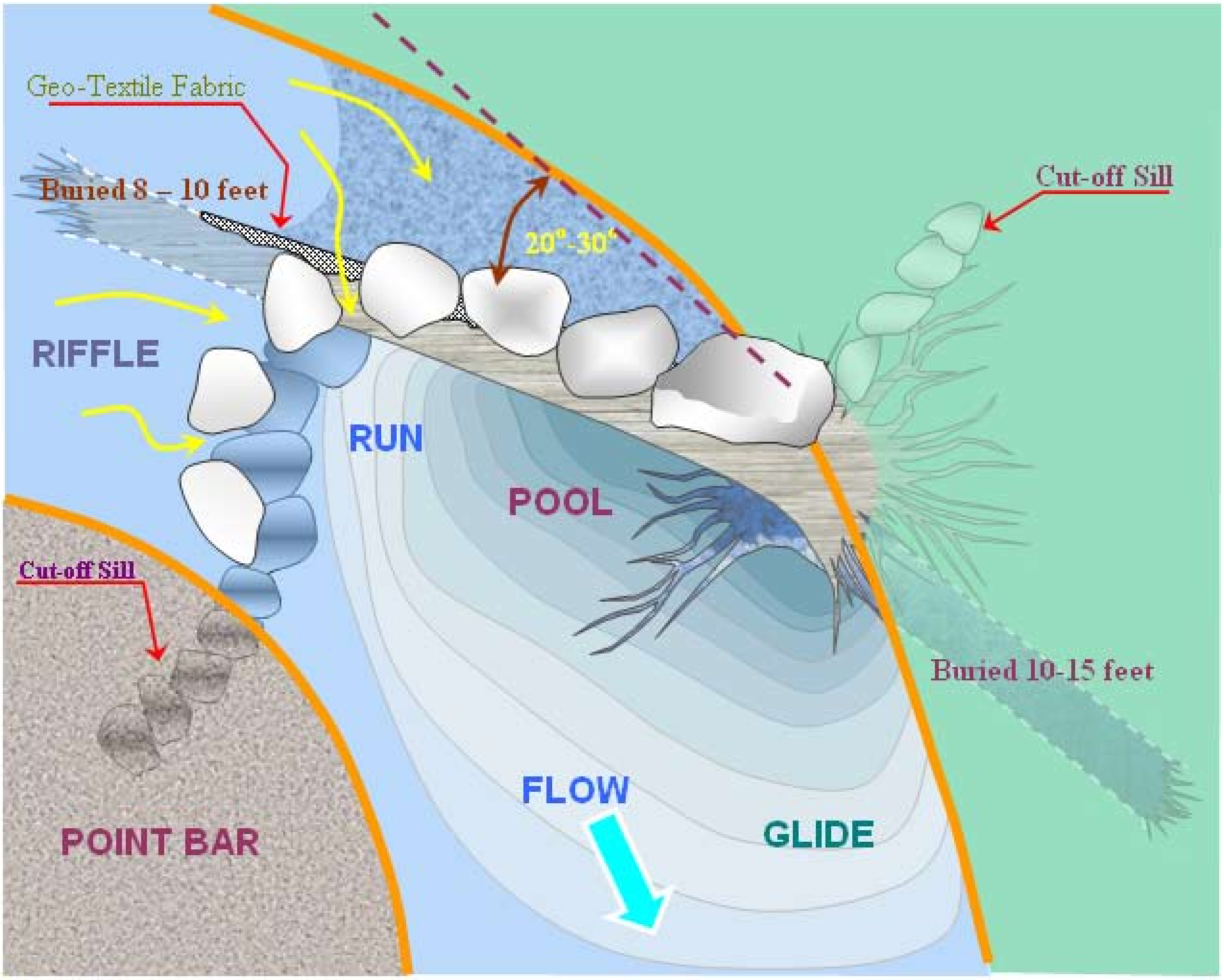
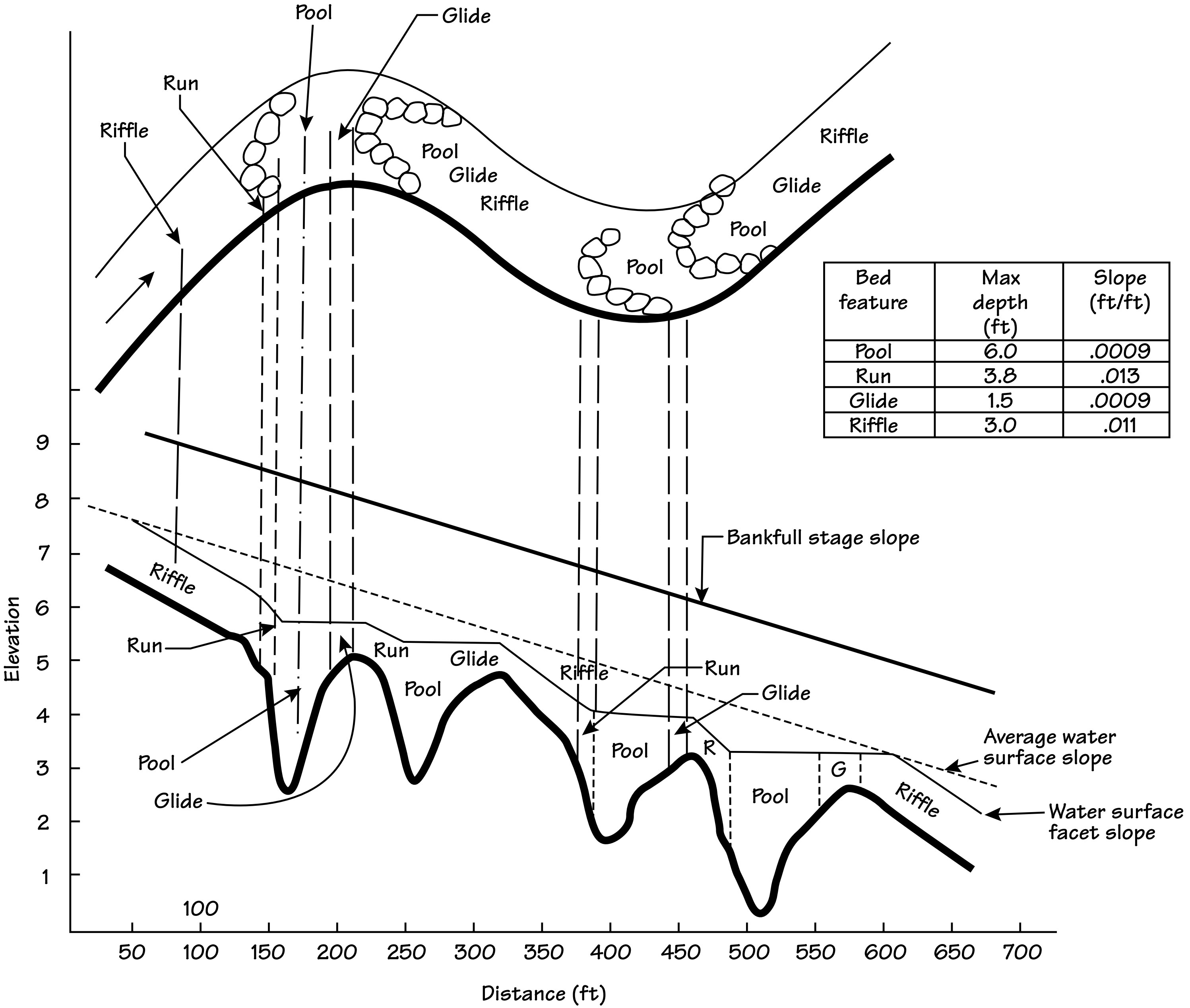


Figure 11–37 Native boulder J-hook with cut-off sill, East Fork Piedra River, CO

Figure 11–39 J-hook/log vane/log step with cut-off sill, East Fork Piedra River, CO

Figure 11–38 Rootwad/log vane/J-hook structure, East Fork Piedra River, CO

Figure 11–40 Longitudinal profile of proposed C4 stream type showing bed features in relation to structure location



Bed feature	Max depth (ft)	Slope (ft/ft)
Pool	6.0	.0009
Run	3.8	.013
Glide	1.5	.0009
Riffle	3.0	.011

Figure 11–41 Boulder cross vane and constructed bankfull bench

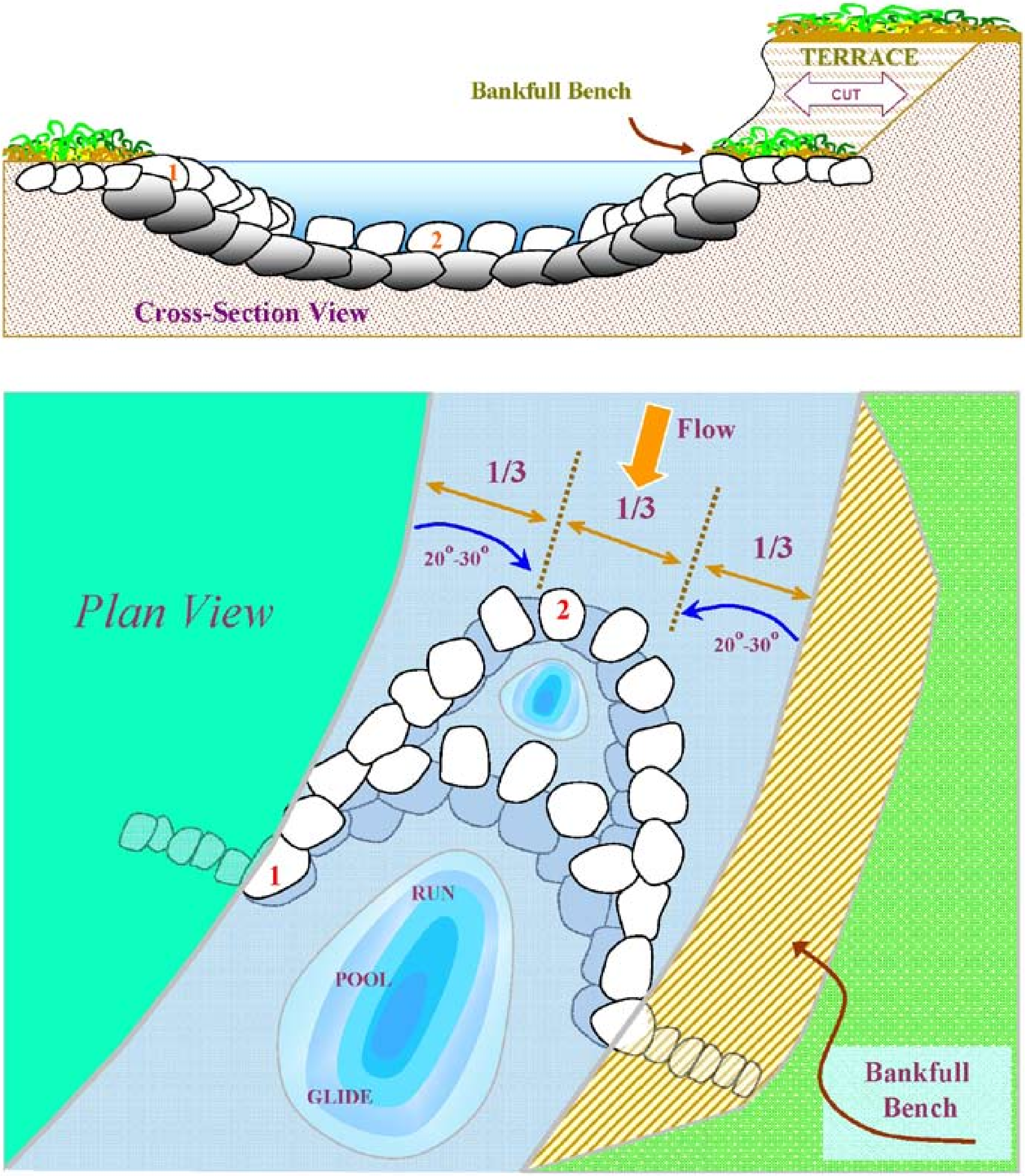
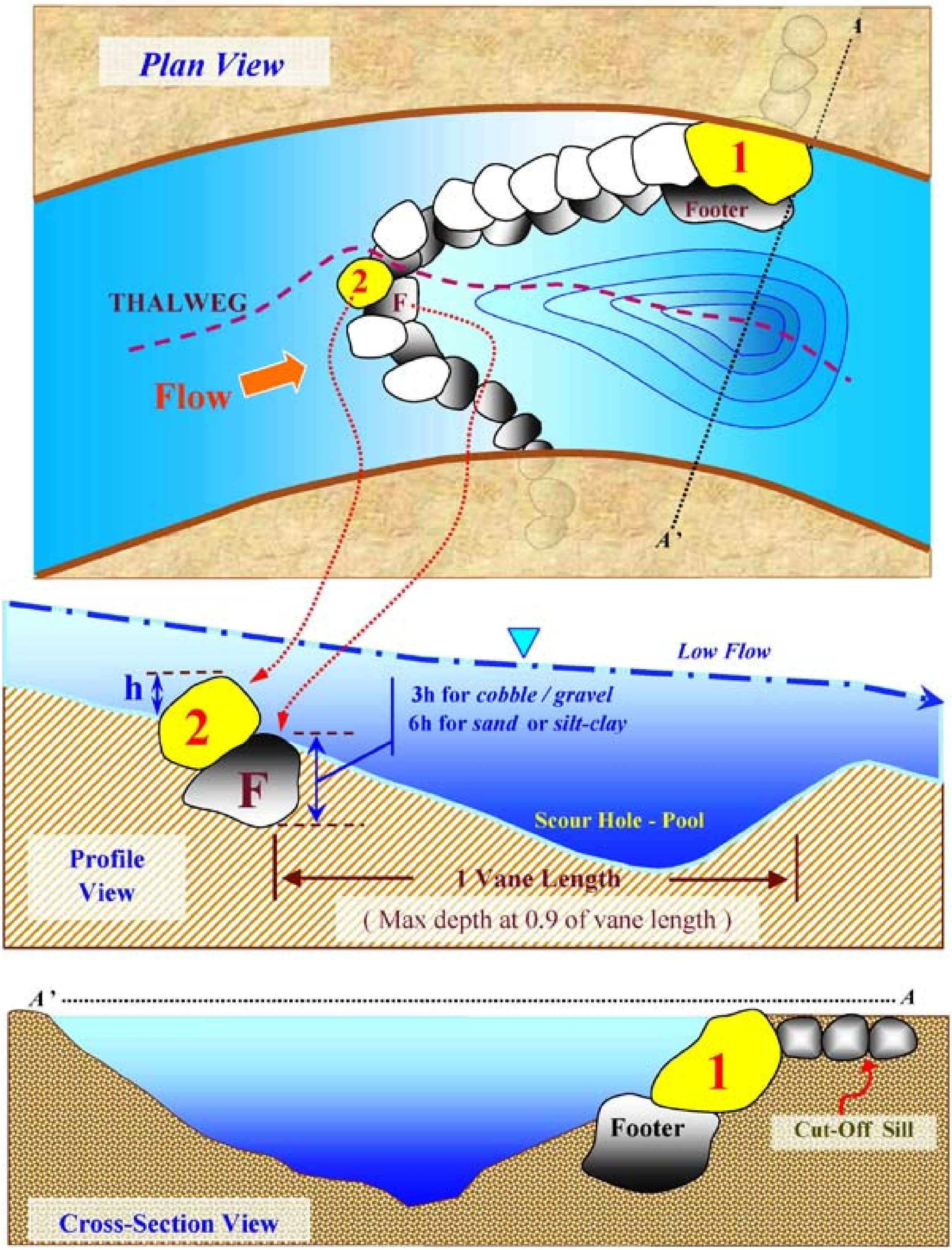


Figure 11–42 Locations/positions of rocks and footers in relation to channel shape and depths



strength to help maintain bank stability. The use of the J–hook (or fish hook) vane was developed to reduce near-bank stress to buy time for root development. The design is shown in figure 11–34 (Rosgen 2001e). Materials other than boulder are used in the J–hook vane. Logs and rootwads can be effectively used for multiple objectives (fig. 11–35 (Rosgen 2001e)). Variations in the use of materials are shown in figure 11–36 (Rosgen 2001e). An example of a J–hook vane is shown in figure 11–37, as constructed out of native boulders located in a reconstructed East Fork Piedra River. The structure also provides fish habitat, energy dissipation, bed-load transport, and provides protection of developments along streambanks. The use of a J–hook vane reduces the need for toe rock stabilization or a surfacing or hardening of the bank with riprap or other resistant structure. The length of bank protected is approximately two and a half to three times the length of the vane. The J–hook vane also is used to protect bridges and structures (Johnson, Hey, et al. 2001). Figures 11–38 and 11–39 provide examples of a J–hook vane using logs, rootwads, and log steps, as well as native boulders.

An example of the use of structure location forming compound pools consistent with meander curvature and bed features is shown in figure 11–40. The accompanying data indicate the slope and depth of the corresponding bed features. Regardless of structures, riparian vegetation establishment and management must be an active part of Rosgen geomorphic channel design.

Vane design specifications

The use of structures must be compatible with curvature and bed features of natural rivers. Figures 11–41 and 11–42 illustrate the use of rock for cross vanes, as well as for footers. Figure 11–43 provides guidance on rock sizing.

Vane slope—The slope of the vane extending from the bankfull stage bank should vary between 2 to 7 percent. Vane slope is defined by the ratio of bank height/vane length. For installation in meander bends, ratios of J-hook vane length/bankfull width is calculated as a function of the ratio of radius of curvature/bankfull width and departure angle (table 11–15). Equations for predicting ratios of J-hook vane spacing/bankfull width on meander bends based on ratio of radius of curvature/bankfull width and departure angle are shown in table 11–16. Vane length is the distance measured from the bankfull bank to the intercept with

Figure 11–43 Rock size

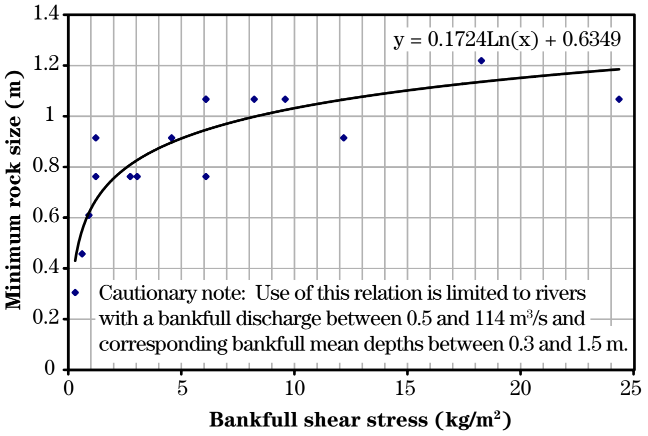


Table 11–15 Equations for predicting ratio of vane length/bankfull width (V_L) as a function of ratio of radius of curvature/width and departure angle, where W = bankfull width (SI units)

Rc/W	Departure angle (degrees)	Equation
3	20	$V_L = 0.0057\ W + 0.9462$
3	30	$V_L = 0.0089\ W + 0.5933$
5	20	$V_L = 0.0057\ W + 1.0462$
5	30	$V_L = 0.0057\ W + 0.8462$

Table 11–16 Equations for predicting ratio of vane spacing/width (V_s) as a function of ratio of radius of curvature/width and departure angle, where W = bankfull width (SI units)

Rc/W	Departure angle (degrees)	Equation
3	20	$V_s = -0.006\ W + 2.4781$
3	30	$V_s = -0.0114\ W + 1.9077$
5	20	$V_s = -0.0057\ W + 2.5538$
5	30	$V_s = -0.0089\ W + 2.2067$

the invert elevation of the streambed at a third of the bankfull channel width for either cross vanes or J-hook vanes. For very large rivers, where it is impractical to extend the vane length to a third of the bankfull width, vane slope is calculated based on the specified angle of departure and the ratio of bank height/vane length where the vane arm intercepts the proposed invert of the structure.

The spacing of J-hook vanes can be increased by 0.40W for a low BEHI of less than 30 (Rosgen 1996, 2001b).

Bank height—The structure should only extend to the bankfull stage elevation. If the bank is higher, a bankfull bench is constructed adjacent to the higher bank, and the structure is integrated into the bench. The use of a cross vane is shown in figure 11–41 where a bankfull bench is created adjacent to a terrace bank.

Footers—The minimum footer depth at the invert for cobble and gravel-bed streams is associated with a ratio of three times the protrusion height of the invert rock. This is applicable to all three structures and is shown in figure 11–41 for a J-hook vane. For sand-bed streams, the minimum depth is doubled due to the deeper scour depths that occur. All rocks for all three structures require footers. If spaces are left between the invert rocks for cross vane and W-weirs, the top of the footer rocks becomes the invert elevation for grade control. If no gaps are left, the top of the surface rock becomes the base level of the stream.

Rock size—The relationship of bankfull shear stress to minimum rock size used for all three structures is shown in figure 11–43. The application of this empirical relation is limited to size of rivers whose bankfull discharge varies from 0.56 cubic meters per second (20 ft^3/s) to 113.3 cubic meters per second (4,000 ft^3/s). For example, appropriate minimum rock sizes for values of bankfull shear stress less than 1.7 kilograms per square meter (0.35 lb/ft^2) are associated only with stream channel bankfull depths from 0.26 to 1.5 meters (2–5 ft). This relation would not be appropriate for applications outside the limits of the data for a river slope of 0.0003 and a mean depth of 6.1 meters, even though a similar shear stress results, as in the example presented.

(g) Phase VII—Design implementation

A key requirement at this phase is to correctly implement the proposed design. This involves the layout, construction supervision, and water quality controls during construction.

Layout

It is necessary to pre-stake the alignment of the channel and to provide for protection of existing vegetation outside of the construction alignment. The layout involves making necessary onsite adjustments to the design based on constraints that may have been previously overlooked. Terrain irregularities, vegetation, property boundaries, and channel changes since the field data were collected can all require local modifications to placement. Staging areas for materials must be located for both the collection and temporary storage of materials. Stockpile areas, vegetative donor sites, and boundary references/facilities requiring special identification must be flagged. Locations of structure placement and type must be flagged.

Construction supervision (oversight)

Without exception, it is critical to have daily onsite inspection and construction coordination. It is essential to check grades, dimensions, structure placement, slopes, angles, and footers as an on-going requirement. It is most effective to coordinate this work during construction, rather than wait and provide a postconstruction inspection and find problems after the work is completed. The daily field review and documentation at this phase is very helpful to properly implement the design.

Water quality controls

As part of the layout, sediment detention basins, diversions, silt fences, and pump sites must be located to prevent onsite and downstream sediment problems and as required by Federal, state, and local ordinances. Staging of construction should also be conducted in such a manner to minimize sedimentation problems. Monitoring of water quality during construction may be required; thus, preventative measures will reduce future potential problems.

(h) Phase VIII—Monitoring and maintenance

Monitoring

The key to a successful monitoring program is the focus on the question or the specific objectives of monitoring. Monitoring is generally recommended to:

- measure the response of a system from combined process interaction due to imposed change
- document or observe the response of a specific process and compare to predicted response for a prescribed treatment
- define short-term versus long-term changes
- document spatial variability of process and system response
- ease the anxiety of uncertainty of prediction
- provide confidence in specific management practice modifications or mitigation recommendations to offset adverse water resource impacts
- evaluate effectiveness of stabilization or restoration approaches
- reduce risk once predictions and/or practices are assessed
- build a data base to extrapolate for similar applications
- determine specific maintenance requirements

Watershed and river assessments leading to restoration involve complex process interactions, making accurate predictions somewhat precarious. Measured data reflecting specific processes will continually improve understanding and prediction of sedimentological, hydrological, morphological, and biological process relations. Another great benefit resulting from monitoring is the demonstration of the effectiveness of reduced sediment problems and improved river stability due to management/mitigation—the central purpose of watershed and sediment assessments and restoration.

The state of the science cannot be advanced, nor can the understanding of complex processes be improved without monitoring. This phase is divided into three major categories:

- implementation monitoring to ensure restoration designs were laid out and constructed correctly
- validation monitoring (matching predicted to observed response, including model calibration and model validation)
- effectiveness monitoring (response of a process or system to imposed change)

Field methods/procedures are also addressed.

Implementation monitoring—Often the best-laid design plans are not implemented correctly due to various reasons. Response of a process and/or system must first address the question or possible variable of potential problem in instituting the design and stabilization/enhancement structures correctly. Riparian vegetation response may be ineffective if heavy grazing of livestock occurred. Exclusion fence maintenance can also be a key in vegetative recovery. If restoration designs were correct, but the contractor installed structures at the wrong angle, slope, or position on the bank, then near-bank stress reduction or erosion rate would not be a correct design implementation related to the effectiveness of the mitigation structure.

As-built measurements of dimension, pattern, and profile are essential to compare to design plans. Documentation of exact locations and types of stabilization and/or enhancement structures is also required. Many failures observed in monitoring are due to poor structure placement locations, construction problems, as well as inability to implement correct design specifications.

Vegetation establishment problems are often traced to establishing the wrong plant associations (species), planting at the wrong time of year and at the wrong elevations on the bank (water table), using the wrong techniques in transplanting and/or cutting plantings, and lacking an irrigation plan, if needed. This monitoring leads the designer to be very thorough in the vegetative planning and implementation phase of restoration.

Validation monitoring—For every prediction methodology, there is a procedure to validate the model. Some methods are more difficult and time consuming to validate than others, while some results can be determined on a short-term, rather than a long-term basis.

The monitoring will improve predictive capability for the future and potentially reduce mitigation measures that would not be effective for continued implementation. Conversely, if management practices indicate that sediment and/or stability conditions create obvious impairment, revised practices or specific process-based mitigation such as restoration may be recommended. The restoration specialist will gain the most confidence in the procedure only by field measurements, which not only validate a prediction, but determine if the initial assessment objectives were met. The various categories of validation monitoring include calibration and validation.

- **Validation**—Model validation involves testing of a model with a data set representing local field data. This data set represents an independent source (different from the data used to develop the relation). Often these data are used to extend the range of conditions for which the model was developed. Due to the uncertainty of prediction, this step is very important prior to widespread application of model output. Models can be extremely helpful in comparative analysis, even if observed values depart from measured. It is important, however, to be aware of the variability in the prediction. Often this monitoring outcome develops tighter relations or subsets of the initial relation, improving the understanding of the processes being predicted. An example of this type of monitoring would be similar to the effectiveness monitoring of streambank erosion rates presented previously. However, beyond measuring bank erosion rate, the observer is additionally required to measure the same parameters used to predict streambank erosion. The streambank prediction involves calculating a bank erosion hazard index (BEHI) and near-bank stress (NBS) (Rosgen 1996, 2001b). The analysis involves plotting the observed values with the predicted values for the same prediction variables. In many cases (with sufficient numbers of observations), this monitoring can lead to improved local or regional models, adapted for unique soil types and vegetation. Validation modeling provides documentation not only on how well the mitigation performed but also on the performance of the model.

  Validation modeling is designed to answer specific questions at specific sites/reaches. Design must be matched with a strong understanding of the prediction model. Validation modeling for the dimensionless ratio sediment rating curves would involve sampling sediment over the full range of streamflows to compare predicted to observed values. The measurements would need to be stratified by the same stream type and stability rating used for the prediction.

- **Calibration**—Models are often used to predict potential impairment. Model calibration is the initial testing of a model and tuning it to a set of field data. Field data are necessary to guide the modeler in choosing the empirical coefficients used to predict the effect of management techniques. An example of this is the data set of measured suspended sediment and bed-load sediment by stream type and stability to establish dimensionless ratio sediment rating curves used for design. These data were not collected in all areas where the model would potentially be applied; thus, another type of monitoring (validation) is helpful to determine if the model is appropriate for extrapolation to a particular region.

Effectiveness monitoring—The specific restoration design and implementation needs to be monitored. Monitoring will determine the appropriateness or effectiveness of specific designs and is implemented to reduce potential adverse sediment and/or river stability effects. Since monitoring requires site-specific measurements, temporal, spatial, scale, streamflow variation, and site/reach, monitoring is required to properly represent such variability and extrapolate findings of a process and/or system response to imposed change. Such variability factors are summarized as:

- **Temporal**—To isolate the variability of season and/or annual change, designs of monitoring should include monitoring over time scales. For example, measuring annual lateral erosion rates should include measurements once per year at the same time of year. If the objectives are to identify seasons where disproportionate erosion occurs, measurements may be obtained during snowmelt runoff, later post stormflow runoff, ice-off, and other periods of time associated with a given erosional process. Annual replicate surveys of particle size gradation of bed material under a permanent glide cross section will provide valuable information of magnitude, direction, and consequence of annual shifts. Temporal measurements must also cover a range of time during bed-load sampling as surges occur or slugs of bed load often appear as discontinuities of time. Sampling over recommended time periods for a given flow (generally 20 minutes) helps the probability of observing this variability (as opposed to an instantaneous point sample). Short-term versus long-term monitoring must also be considered based on the probability of change, the severity and consequence of effects, and the likelihood of variation. Sampling over many years, although costly, may be warranted to cover changes in wet/dry periods.

- **Spatial**—Variability of change/response involving spatial considerations can be identified by measurements of the same process at more than one site (cross section) or even more intense on the same site. For example, a longitudinal profile measured over a couple of meander wavelengths will indicate changes in the maximum depth and/or slope of pools, rather than just monitoring one pool at one location. Identifying more than one reach of the same morphological type can also be used to understand response trends. Sampling the spatial variability (both vertically and laterally) within a cross section of velocity and sediment helps identify or at least integrate such variability into a documented observation.
- **Scale**—Monitoring streams of various sizes and/or stream orders, but of the same morphological type and condition, will help identify variability in system response for proper extrapolation of results. For example, vertical stability measurements should be made on river reaches of the same condition and the same type, but at locations that reflect various stream widths (size) and stream order.
- **Streamflow variation**—Measurements of channel process relations need to be stratified over a range of seasonal and annual flows. For example, both suspended and bed-load sediment should be measured over a wide range of flows during the freshet, low-elevation snowmelt, high-elevation snowmelt, rising versus recession stages, stormflow runoff, and baseflow. This stratification for streamflow allows the field observer to plot a sediment rating curve that represents the widest range of seasonal flows where changes in sediment supply can vary.
- **Site or reach variation**—Monitoring a site for soil loss should include a soil type designation for potential extrapolation for similar conditions on similar soil types. The same is true for stream types. Sediment, hydraulic, and stability monitoring need to be stratified by stream type since such data will naturally vary for the reference (stable) reach between stream types. This information is helpful to be able to readily detect departure from a reference stream type, rather than differences between stream types.
- **Design concepts for effectiveness monitoring**—The key information summary from the assessments used to identify impairment and resultant restoration designs are as follows:
  - Summarize the causes of land use impacts responsible for the impairment.
  - Understand the processes affected.
  - Identify specific locations and reaches associated with adverse impacts.
  - Determine the time trends of impacts (potential recovery periods).
  - Identify the specific nature of impairment (direction, magnitude, and trend of change).
  - Evaluate the consequence of change.
  - Determine the nature, location, extent and quality of mitigation (implementation).

The information supplied in the following list leads the observer to identify the locations, nature of processes affected, the extent of the impact, and quality of the mitigation implementation. For example, if the dominant process impacted by a land use is causing disproportionate sediment supply, land loss and river instability, and is determined to be accelerated streambank erosion, then the lateral stability monitoring would emulate the following design:

- Locate reaches of the same stream type that represent an unstable bank.
- Locate reaches of the same stream type that represent a stable bank.

- Install permanent cross sections on each set of reaches.
- Install bank pins (if conditions warrant) and/or toe pins (see monitoring methods).
- Inventory vegetation, bank material, and slope for each site (see monitoring methods).
- Resurvey both streambanks at least once per year to measure soil loss (lateral erosion) and total volume (in cubic feet and tons/year).
- Compare annual lateral erosion rates over time to the stable reach and document rate of recovery based on the nature of the mitigation.

Vertical stability and enlargement rates and direction can also be monitored using permanent cross sections in a similar stratification procedure (comparison to reference reach, above versus below, before versus after).

Physical and biological monitoring—The sediment and river stability changes associated with assessment and design are primarily related to physical changes. However, the consequences of such physical changes are directly related to potential impairment of the biological function. Changes in river stability, such as aggradation, degradation, enlargement, and stream type changes, are also related to habitat and food chains. Limiting factor analyses assesses habitat loss due to river instability and/or excess sediment such as relations of holding cover, instream/overhead cover, water temperature, dissolved oxygen, and benthics. A range of information associated with stream condition can be stratified by stream type by stream stability including diversity index, population dynamics, age class distribution, spawning, rearing habitat, and many more attributes related to stream health. Biological monitoring should follow similar rules of inventory stratification based on the diverse nature of streams and their natural variability.

If a biologist is studying only the biological parameters within a specific ecoregion, the natural stable differences between reference reach stream types cannot be identified if the stratification of the inventory does not include stream types. In other words, a stable C4 stream type will not have the attributes of a stable E4 or B4 stream type, even though they are all gravel-bed streams. If the biological inventory is not stratified by stream type or stream stability, departure of habitat conditions between a stable C4 and an unstable C4 cannot be easily identified. Reference conditions that reflect biological potential must be stratified as a minimum by stream type and stream stability for adequate departure analysis to identify degree, direction, and magnitude of impairment. Companion biological inventories of assessment and monitoring can be very compatible with the monitoring methods of the physical system described.

Once this information is analyzed, the monitoring design can proceed. The next step is to identify a strategy of monitoring. Effectiveness monitoring should always be conducted near the activity responsible for the initial impairment. Four primary design strategies often utilized are as follows:

- Measurements obtained before versus after the initiation of a management change in the land use activity, mitigation, restoration, and enhancement. This can be very effective as it establishes a precalibration period that identifies premitigation variability of the measured parameters. Following mitigation, departure can be readily determined, assuming measurements take into consideration the aforementioned variability factors.
- Measurements or observations taken above versus below impact areas related to specific land uses and specific mitigation. For example, if two different grazing strategies are implemented, measurements of effectiveness can be observed above versus below fence line contrasts. This can also be implemented where a mitigation may only influence the lower reach of a river compared to the upper reach (assuming the same stream type).
- Measurements obtained determining departure from a paired watershed are often helpful as similar climatic events similarly impact both watersheds. The pairing would contrast a watershed that had extensive mitigation or land management change with one that had not been changed. This also assumes variability of scale, temporal, and spatial variability and comparisons of similar landscapes and stream types have been identified.

- Measurements obtained of a disturbed reach or site, receiving mitigation compared to a reference condition. This type of monitoring can occur at locations far removed from the reference reach. The reference condition, however, must be of the same soil type, stream type, valley type, lithology, and vegetative type.

Maintenance plan

To ensure that the implemented design is successful, it is key to have a maintenance plan. The maintenance plan must ensure the following:

- Survival of the riparian vegetation reestablishment—This could involve an irrigation supply or replanting/interplanting.
- Structure stability—Post-runoff inspections must be conducted of structures for grade control, bank stabilization and/or fish habitat enhancement. Maintenance needs are assessed and implemented to prevent future failures and to secure proper function.
- The dimension, pattern, and profile must stay within the natural variability or range as depicted in table 11–5 for each variable. Maintenance of these variables is recommended only if the values exceed the design channel ranges.
- The biological maintenance may involve reestablishment of described populations of various age classes and/or species of fish and/or food sources.

654.1103 Conclusion

The individual(s) responsible for the project should also become experienced by being involved in all phases of this methodology. If the same individual conducts the assessment and also completes the design, implementation, and monitoring, the desired objectives of restoration are the most likely to be accomplished. The complexity of this method requires great attention to detail, training, and an understanding of processes. The monitoring of the project, including the implementation, validation and effectiveness procedures, is the best approach to become experienced and knowledgeable about the Rosgen geomorphic channel design methodology.

Mathematical definitions

Variables	
Riffle cross-sectional area at bankfull	A_{bkf}
Pool cross-sectional area at bankfull	A_{bkfp}
Mean riffle depth at bankfull	d_{bkf}
Mean pool depth at bankfull	d_{bkfp}
Maximum glide depth at bankfull	d_g
Maximum riffle depth at bankfull	d_{mbkf}
Maximum pool depth at bankfull	d_{mbkfp}
Maximum run depth at bankfull	d_{run}
Diameter of riffle particle at 50% finer than size	D_{50}
Diameter of bar sample particle at 50% finer than size	$\hat{D}_{50}$
Diameter of riffle particle at 84% finer than size	D_{84}
Maximum size of particle on bar	D_{max}
Gravitational acceleration	g
Weight density of water	γ
Sinuosity	k
Low bank height	LBH
Meander length	Lm
Meander-length ratio	(Lm/W_{bkf})
Manning's *n*	*n*
Pool-to-pool spacing (based on pattern)	(p-p)
Bankfull discharge	Q_{bkf}
Hydraulic radius	R
Radius of curvature of meander	Rc
Average water surface slope (bankfull slope)	S
Slope of glide (water surface facet slope)	S_g
Stream length	SL
Slope of pool (water surface facet slope)	S_p
Slope of riffle (water surface facet slope)	S_{rif}
Slope of run (water surface facet slope)	S_{run}
Bankfull shear stress	τ
Dimensionless bankfull shear stress	τ^*
Bankfull mean velocity	u_{bkf}
Shear velocity	u^*

Variables	
Valley length	V_L
Valley slope	V_S
Riffle width at bankfull	W_{bkf}
Width-to-depth ratio at bankfull	(W_{bkf}/d_{bkf})
Width-to-depth ratio at bankfull of reference reach	$(W_{bkf}/d_{bkf})_{ref}$
Pool width at bankfull	W_{bkfp}
Belt width	W_{blt}
Meander-width ratio	(W_{blt}/W_{bkf})
Width of flood-prone area	W_{fpa}
Entrenchment ratio	(W_{fpa}/W_{bkf})
Stream power	ω

Subscripts	
Bankfull	bkf
Meander belt	blt
Flood-prone area	fpa
Glide	g
Maximum at bankfull	mbkf
Maximum at bankfull in pool	mbkfp
Pool	p
Reference reach	ref
Riffle	rif
Run	run

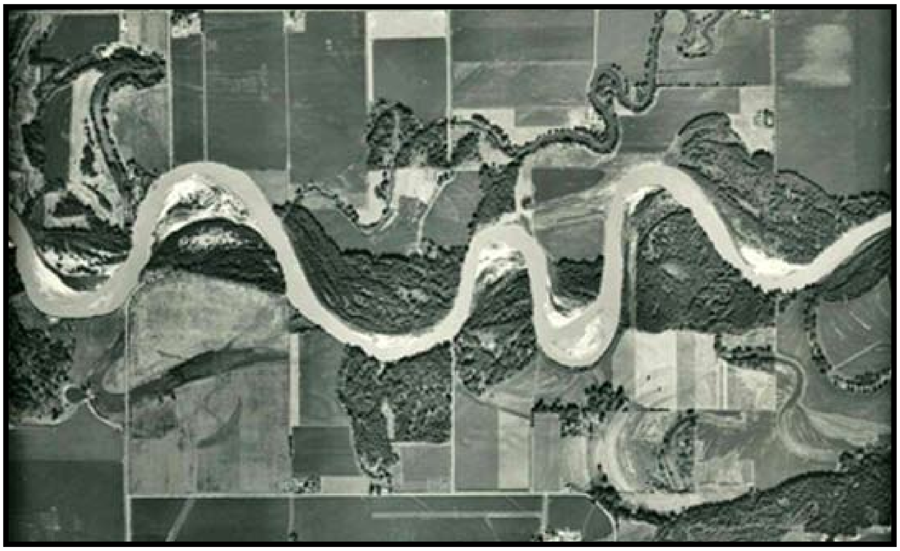
United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 12

Channel Alignment and Variability Design



Issued August 2007

Cover photo: Where alteration of a stream or channel is needed, planform may be modified to achieve the designed flow velocities by changing the channel length, as well as the gradient.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 12 Channel Alignment and Variability Design

Contents

Tables

Figures

Chapter 12

Channel Alignment and Variability Design

654.1200 Purpose

Natural channel design includes establishment of a stable planform and often the incorporation of variability within the channel. The designer of a channel is also often asked to provide an assessment of natural bankline migration, as well. The purpose of this chapter is to provide systematic hydraulic design methodologies that can be used in the performance of these tasks. A wide variety of sources and techniques are available to the designer to make these assessments. This chapter provides overviews, descriptions, and examples illustrating some of the most common design techniques.

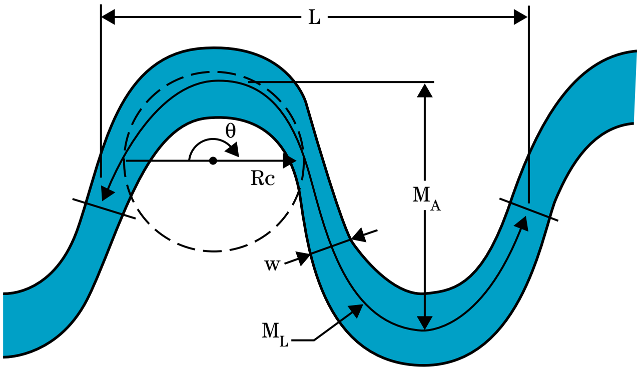
654.1201 Introduction

Natural channels are rarely perfectly linear and straight. While there are exceptions, and while boundary constraints may require a straight constructed channel, most natural channels exhibit at least some degree of sinuosity in their planform. Therefore, the assessment and design of a stable channel planform is an important part of any open channel design.

Planform design parameters include the meander wavelength, radius of curvature, sinuosity, and general alignment. Several of these variables are illustrated in figure 12–1 (Federal Interagency Stream Restoration Working Group (FISRWG) 1998). Several techniques that can be used to approximate natural channel alignments are presented in this chapter.

Natural channels rarely exhibit a uniform cross section. In fact, the variability often provides important ecological benefits. Since variability in a channel section is expected in natural channels, the designer of a natural channel restoration project is often asked to incorporate similar variability into the design. Generalized morphologic relationships for channel variability in streams and rivers are described in this chapter. Material from regionally specific studies is presented for illustration.

Figure 12–1 Variables used to describe channel alignment and planform



L	Meander wavelength
M_L	Meander arc length
w	Average width at bankfull discharge
M_A	Meander amplitude
Rc	Radius of curvature
θ	Arc angle

654.1202 Planform

This step in the design process involves laying out a planform after determining a meander wavelength and an appropriate channel length for one meander wavelength. Channel sinuosity is defined as the channel centerline length divided by the length of the valley centerline. It is determined from the calculated channel slope and valley slope. Analogy, hydraulic geometry, and analytical methods are employed to determine both the meander wavelength and a planform.

To apply the analogy method, a reference or control reach is located on either the study stream or another suitable stream. From this reach, a template for the meander planform is developed. This may be problematic due to the nonavailability of a suitable reference reach or subtle, but important fluvial, sedimentary, or morphological differences between a reference reach and the study reach.

Alternatively, meander wavelength can be determined using hydraulic geometry techniques. The most reliable hydraulic geometry relationship is wavelength versus width. As with the determination of channel width, preference is given to wavelength predictors from stable reaches of the existing stream either in the project reach or in reference reaches. The channel trace may also be determined analytically using the sine-generated curve. Finally, a string cut to the appropriate length can be laid on a map and fit to existing constraints and to the proper wavelength to form a meandering planform.

When uncertain about the appropriate technique, many practitioners use both analogy and hydraulic geometry and look for points of convergence in the recommendations. It is also important to note that planform flexibility may be limited by riparian features, infrastructure, land use, or other restrictions on the right-of-way. These factors may preclude the use of meanders with the amplitudes suggested from the described analogy or hydraulic geometry methods.

Braided channel systems are an important exception to much of the material presented in this chapter. Braided stream systems can exist naturally in estuarine, lacustrine, and glacial landscapes and valleys. These systems have depositional requirements and physical characteristics that are very different from single-thread channels. For braided streams, a single or dual thread channel reconstruction may be inappropriate and carry a potentially high risk of failure.

(a) Hydraulic geometry for meander wavelength

A composite relationship has been developed by Thorne and Soar (2001), combining 9 data sets and 438 sites. Their mean linear regression predictor for wavelength is:

$$\lambda = 10.23W \qquad \text{(eq. 12–1)}$$

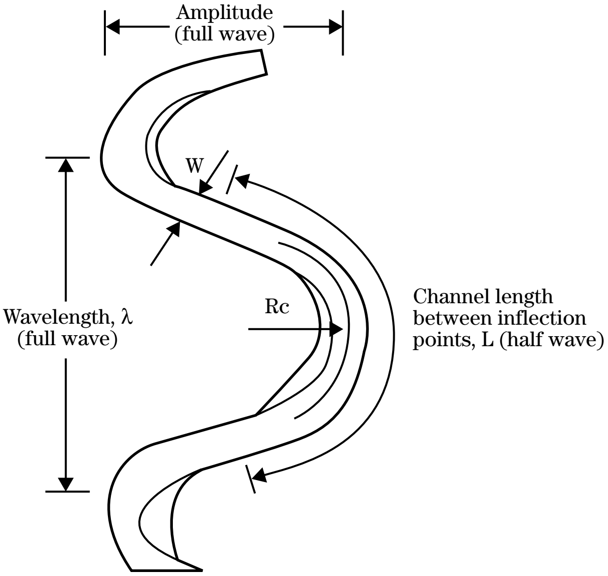
where:

λ = meander wavelength

W = channel width in any consistent units of measurement

Definitions of planform descriptive variables are shown in figure 12–2. Confidence bands about this equation are shown in figure 12–3. The r^2 for the

Figure 12–2 Planform descriptive variables



wavelength equation was 0.88 for a linear regression equation, with a variable exponent on W. This exponent was found not to be significantly different from 1.0, so the exponent was fixed at 1.0 for convenience. Only sites with sinuosities of at least 1.2 and bankfull widths between 1 meter and 1,000 meters were used in development of this regression equation. Within these constraints, meander wavelengths range between 10.4 meters and 19,368 meters, and sinuosity values range between 1.2 and 5.3. The equation, corrected for bias, is:

$$\lambda = 11.85W \qquad \text{(eq. 12–2)}$$

An unbiased hydrologic equation for meander wavelength suitable for engineering design, within 95 percent confidence limits on the mean response is:

$$\lambda = (11.26 \text{ to } 12.47)W \qquad \text{(eq. 12–3)}$$

According to Hey (1976) and Thorne (1997), twice the distance between successive riffles (or pools) in a straight channel should equal 4πW, or 12.57W. This is based on the assumption that the average size of the largest macroturbulent eddies (or helical flow cell) is half the channel width. Equation 12–3 shows that the upper range of stable meander wavelengths is numerically very close to this value and similar to the coefficient of 12.34 given by Richards (1982). This corroborates the assertion by Leopold and Wolman (1957, 1960) that the matching of waveforms in bed topography and planform is related to the mechanics of the flow and, in particular, to the turbulent flow structures responsible for shaping the forms and features of meandering channels.

Table 12–1 shows the data sources (438 sites) used in the development of these equations.

Figure 12–3 Hydraulic geometry relationship for meander wavelength with confidence intervals, λ = 10.23W, based on a composite data set of 438 sites in a variety of areas

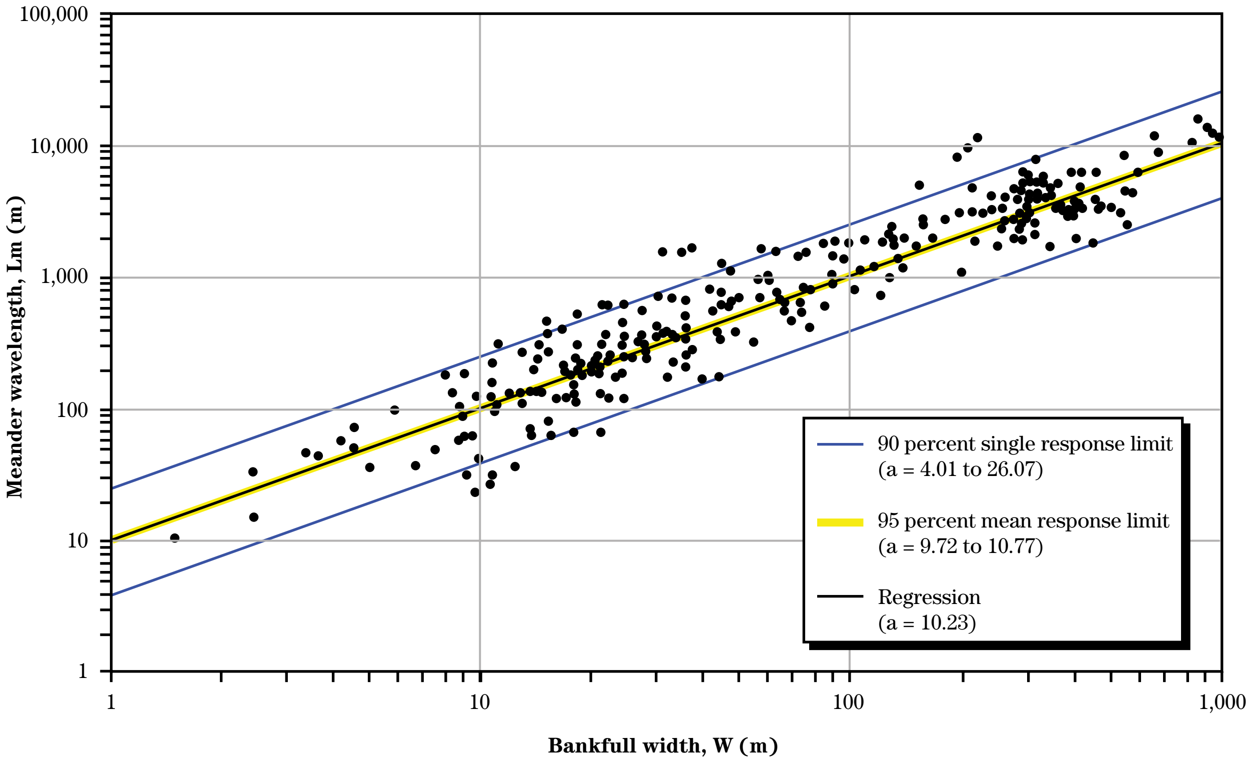


Table 12–1 Research and data sources for meander wavelengths

Researchers	Locations		No. of sites
Leopold and Wolman (1957)	United States rivers		21
Leopold and Wolman (1960)	Various sources	France	1
		United States	34
		Model river	1
		Total	36
Carlston (1965)	United States rivers		29
Schumm (1968)	Midwestern United States rivers		25
Chitale (1970)	Large alluvial rivers	Africa	1
		Canada	1
		India	16
		Pakistan	2
		United States	1
		Total	21
Williams (1986)	Various sources	Australia	2
		Canada	7
		Sweden	17
		Russia	1
		United States	16
		Model river	1
		Total	44
Thorne and Abt (1993)	Red River	1966	35
		1981	39
	Hydrographic surveys between Index, AR, and Shreveport, LA		1
		India	12
		Netherlands	1
		United Kingdom	48
		United States	18
		Total	154
Annable (1996)	Alberta, Canada		30
Cherry, Wilcock, and Wolman (1996)	United States rivers, predominantly sand bed		79

Leopold (1994) provided a hydraulic geometry relationship for meander wavelength as a function of both channel width and mean radius of curvature (fig 12–4 (FISRWG 1998)). His data include measurements from rivers, flumes, the Gulf Stream, and glaciers. He suggested that the relationships could be used to indicate stream instability if meander wavelength for a given stream did not plot closely to the predicted relationship.

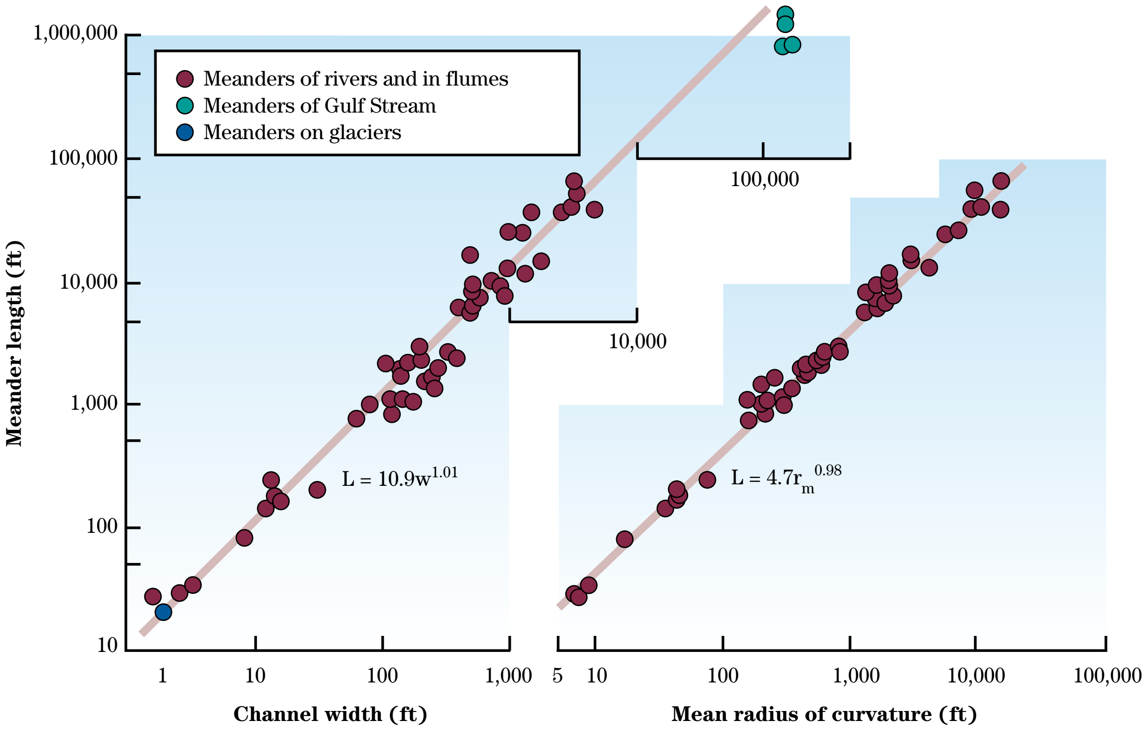
Other hydraulic geometry relationships for meander wavelength from the literature are given in table 12–2.

Additional guidance for determining meander geometry, including wavelength, along channel bend length, meander belt width, radius of curvature, and sinuosity are provided in Leopold (1994).

The channel meander length is simply the meander wavelength times the valley slope divided by the channel slope.

$$\text{channel meander length} = \frac{\text{wavelength} \times \text{valley slope}}{\text{channel slope}} \tag{eq. 12–4}$$

Figure 12–4 Planform geometry relationships



From Leopold (1994)

Table 12–2 Hydraulic geometry relationships for meander wavelength

Author	Equation	Units
Leopold and Wolman (1960)	$\lambda = 10.9\ W^{1.01}$	ft
Inglis (1941)	$\lambda = 6.06\ W^{0.99}$	ft
Yalin (1992)	$\lambda = 6\ W$	length
Dury (1965)	$\lambda = 30\ Q_{bf}^{0.5}$	ft, ft^3/s
Carlston (1965)	$\lambda = 8.2\ Q_{bf}^{0.62}$	ft, ft^3/s
Carlston (1965)	$\lambda = 106.1\ Q_{ma}^{0.46}$	ft^3/s
Schumm (1967)	$\lambda = 1890\ Q_{ma}^{0.34}\ M^{0.74}$	ft, ft^3/s

Notes: λ = meander wavelength
W = width
Q_{bf} = bankfull discharge
Q_{ma} = mean annual discharge
M = silt-clay factor

(b) Layout and sine-generated curve

Once meander wavelength is determined, planform can be determined using an analogy method or by using the sine-generated curve. Using a reference reach as a guide, planform can be laid on a map with a string cut to the appropriate channel length. Assuming that the planform can be approximated by the sine-generated curve is a more analytical approach and was suggested by Langbein and Leopold (1966). Their theory of minimum variance is based on the hypothesis that the river will seek the most probable path between two fixed points (the path that provides the minimum variance of bed shear stress and friction). The sine-generated curve is defined in figure 12–5 and by the following dimensionless equation:

$$\phi = \omega \cos \frac{2\pi s}{M} \qquad \text{(eq. 12–5)}$$

where:

ϕ = angle of meander path with the mean longitudinal axis (degrees or radians)
ω = maximum angle a path makes with the mean longitudinal axis (degrees or radians)
s = curvilinear coordinate along the meander path (ft or m)
M = meander arc length (ft or m)

The shape parameter, ω, is a function of the channel sinuosity, P, which can be solved by numerical integration, or may be approximated by the following equation (Langbein and Leopold 1966), in which ω is in radians:

$$\omega = 2.2\sqrt{\frac{P-1}{P}} \qquad \text{(eq. 12–6)}$$

The shape parameter of a sine-generated curve defines the shape of the stream as shown in figure 12–6 (Langbein and Leopold 1966).

Calculation of the points on a sine-generated curve is a rather tedious numeric integration for ϕ. However, the integration can be accomplished using a computer program such as the one in the U.S. Army Corps of Engineers (USACE) Hydraulic Design Package: SAM (Thomas, Copeland, and McComas 2003). The sine-generated curve produces a very uniform meander pattern. The alignments of natural channels are rarely perfect sinusoids. Channels that are constructed as such, therefore, appear strange. A combination of the string layout method and the analytical approach would produce a more natural looking planform.

Figure 12–5 Definition of sine-generated curve

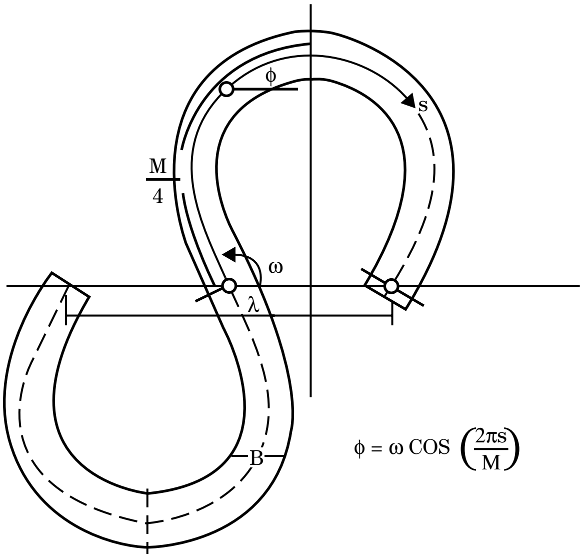
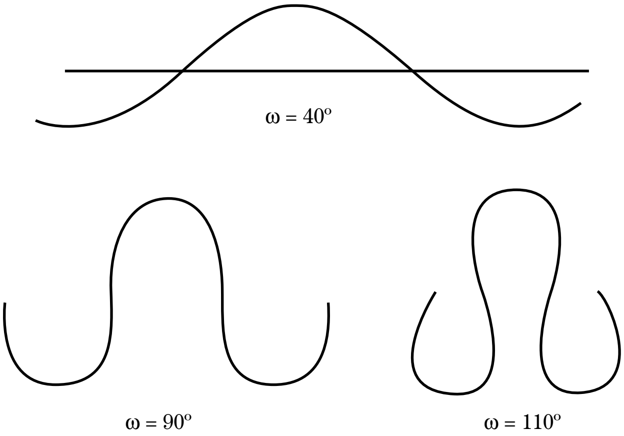


Figure 12–6 Effect of the shape factor on channel sinuosity with the sine-generated curve



Example problem: Channel alignment

Objective: Determine the planform layout for the channel designed in the previous problem. Use the sine-generated curve.

Given:

Base width = 80 ft
Depth = 2.9 ft (at channel-forming discharge)
Side slopes = 1V:2.5H
Channel slope = 0.0050
Valley slope = 0.0055

Solution:

Step 1 Calculate the top width of the channel for the channel-forming discharge.

$$\mathrm{TW} = 2zy + \mathrm{BW}$$

$$\mathrm{TW} = (2)(2.5)(2.9) + 80 = 94.5 \text{ say } 95 \text{ ft}$$

Step 2 Determine the meander wavelength directly from figure 12–3 or from the mean regression equation for the meander wavelength (fig. 12–4). If figure 12–3 is used directly, the top width must be converted to meters (95 divided by 3.281 which equals 29 m). If the equations from figure 12–4 are used, the unit conversion is not needed because the regression equation is dimensionless.

$$\lambda = 10.23\mathrm{TW}$$

$$\lambda = 10.23(95) = 972 \text{ ft}$$

Step 3 Determine the distance along the channel for one wavelength.

$$\mathrm{M} = \frac{\lambda(\text{Valley slope})}{\text{Channel slope}}$$

$$\mathrm{M} = \frac{972(0.0055)}{(0.0050)} = 1{,}069 \text{ ft}$$

Step 4 Calculate xy coordinates for the channel using a spreadsheet or the USACE Hydraulic Design Package, SAM (Thomas, Copeland, and McComas 2003). Input is wavelength, λ, and channel length, M. Output is shown in table 12–3. The calculated shape factor, ω, is 34.9 degrees. The calculated planform amplitude is 199 feet. A planform plot developed from the SAM output is shown in figure 12–7. Note that this planform is very regular and does not replicate natural meanders. The designer should use the sine-generated curve layout as a guide and manipulate the actual centerline layout based on site constraints.

Table 12–3 Output for hydraulic computations using the SAM model

```
*****************************************************************
* SAMwin Software Registered to the US Army Corps of Engineers  *
*****************************************************************
*                              HYDRAULIC CALCULATIONS          *
*                                    Version 1.0
* A Product of the Flood Control Channels Research Program      *
* Coastal & Hydraulics Laboratory, USAE Engineer R & D Center   *
*                                in cooperation with
*           Owen Ayres & Associates, Inc., Ft. Collins, CO     *
*****************************************************************
TABLE 1. LIST INPUT DATA.

T1 Gravel bed River Example
T1 Base width 80 ft
T1 Depth 2.9 ft
T1 Side Slopes 1V : 2.5H
T1 Top Width 95 ft
MG  972  1069
$$END

INPUT IS COMPLETE.
   **********************************************************
   *
   *  PLANFORM GEOMETRY FOR A MEANDERING Sand bed STREAM
   *
   **********************************************************

                                      MAXIMUM
    WAVE     MEANDER                 DEFLECTION
   LENGTH     LENGTH     SINUOSITY    ANGLE-DEG      AMPLITUDE
   972.00    1069.00        1.10        34.933         198.97

  COORDINATES ALONG ONE MEANDER WAVELENGTH

  ALONG THE       DEFLECTION      PERPENDICULAR TO      ALONG THE
   CHANNEL          ANGLE           VALLEY SLOPE      VALLEY SLOPE
                   DEGREES

      S             THETA                Y                  X

      0.00           34.93              0.00               0.00
     10.69           34.86              6.12               8.77
     21.38           34.66             12.21              17.55
     32.07           34.31             18.26              26.36
     42.76           33.84             24.25              35.22
     53.45           33.22             30.16              44.13
     64.14           32.48             35.96              53.11
```

Table 12–3 Output for hydraulic computations using the SAM model—Continued

```
     S             THETA                Y                 X

    74.83           31.61             41.63               62.17
    85.52           30.61             47.15               71.32
    96.21           29.49             52.51               80.58
   106.90           28.26             57.67               89.94
   117.59           26.92             62.62               99.41
   128.28           25.47             67.34              109.00
   138.97           23.91             71.80              118.72
   149.66           22.27             76.00              128.55

   160.35           20.53             79.90              138.50
   171.04           18.72             83.49              148.57
   181.73           16.83             86.75              158.75
   192.42           14.87             89.67              169.03
   203.11           12.86             92.23              179.41
   213.80           10.79             94.42              189.87
   224.49            8.69             96.23              200.41
   235.18            6.55             97.65              211.00
   245.87            4.38             98.67              221.64
   256.56            2.19             99.28              232.31
   267.25            0.00             99.48              243.00
   277.94           -2.19             99.28              253.69
   288.63           -4.38             98.67              264.36
   299.32           -6.55             97.65              275.00
   310.01           -8.69             96.23              285.59
   320.70          -10.79             94.42              296.13
   331.39          -12.86             92.23              306.59
   342.08          -14.87             89.67              316.97
   352.77          -16.83             86.75              327.25
   363.46          -18.72             83.49              337.43
   374.15          -20.53             79.90              347.50
   384.84          -22.27             76.00              357.45
   395.53          -23.91             71.80              367.28
   406.22          -25.47             67.34              377.00
   416.91          -26.92             62.62              386.59
   427.60          -28.26             57.67              396.06
   438.29          -29.49             52.51              405.42
   448.98          -30.61             47.15              414.68
   459.67          -31.61             41.63              423.83
   470.36          -32.48             35.96              432.89
   481.05          -33.22             30.16              441.87
   491.74          -33.84             24.25              450.78
   502.43          -34.31             18.26              459.64
   513.12          -34.66             12.21              468.45
   523.81          -34.86              6.12              477.23
```

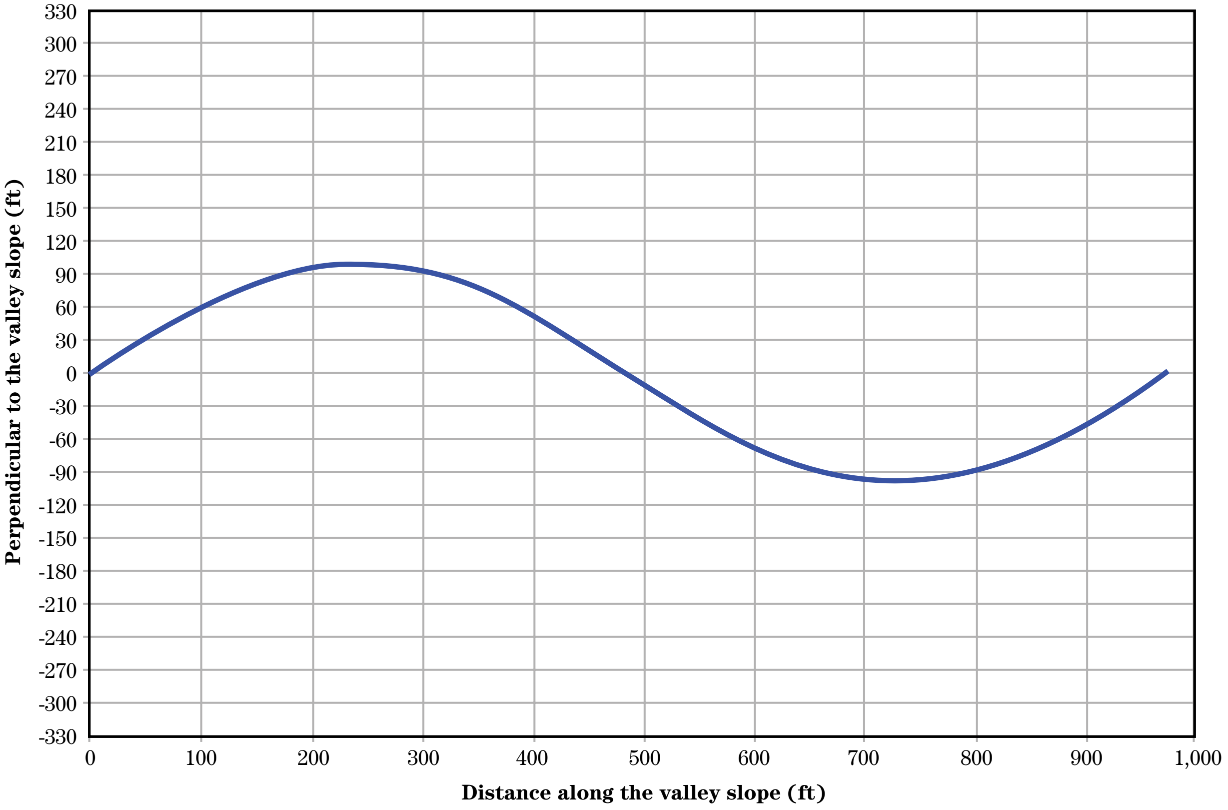
Table 12–3 Output for hydraulic computations using the SAM model—Continued

```
      S              THETA               Y                 X

    534.50          -34.93              0.00             486.00
    545.19          -34.86             -6.12             494.77
    555.88          -34.66            -12.21             503.55
    566.57          -34.31            -18.26             512.36
    577.26          -33.84            -24.25             521.22
    587.95          -33.22            -30.16             530.13
    598.64          -32.48            -35.96             539.11
    609.33          -31.61            -41.63             548.17
    620.02          -30.61            -47.15             557.32
    630.71          -29.49            -52.51             566.58
    641.40          -28.26            -57.67             575.94
    652.09          -26.92            -62.62             585.41
    662.78          -25.47            -67.34             595.00
    673.47          -23.91            -71.80             604.72
    684.16          -22.27            -76.00             614.55
    694.85          -20.53            -79.90             624.50
    705.54          -18.72            -83.49             634.57
    716.23          -16.83            -86.75             644.75
    726.92          -14.87            -89.67             655.03
    737.61          -12.86            -92.23             665.41
    748.30          -10.79            -94.42             675.87
    758.99           -8.69            -96.23             686.41
    769.68           -6.55            -97.65             697.00
    780.37           -4.38            -98.67             707.64
    791.06           -2.19            -99.28             718.31
    801.75            0.00            -99.48             729.00
    812.44            2.19            -99.28             739.69
    823.13            4.38            -98.67             750.36
    833.82            6.55            -97.65             761.00
    844.51            8.69            -96.23             771.59
    855.20           10.79            -94.42             782.13
    865.89           12.86            -92.23             792.59
    876.58           14.87            -89.67             802.97
    887.27           16.83            -86.75             813.25
    897.96           18.72            -83.49             823.43
    908.65           20.53            -79.90             833.50
    919.34           22.27            -76.00             843.45
    930.03           23.91            -71.80             853.28
    940.72           25.47            -67.34             863.00
    951.41           26.92            -62.62             872.59
    962.10           28.26            -57.67             882.06
    972.79           29.49            -52.51             891.42
    983.48           30.61            -47.15             900.68
```

Table 12–3 Output for hydraulic computations using the SAM model—Continued

```
      S             THETA              Y                  X

   994.17           31.61           -41.63             909.83
  1004.86           32.48           -35.96             918.89
  1015.55           33.22           -30.16             927.87
  1026.24           33.84           -24.25             936.78
  1036.93           34.31           -18.27             945.64
  1047.62           34.66           -12.21             954.45
  1058.31           34.86            -6.12             963.23
  1069.00           34.93             0.00             972.00
```

Figure 12–7 Planform layout for one meander wavelength from sine-generated curve for example problem: wavelength = 972 ft; amplitude = 199 ft; sinuosity = 1.1



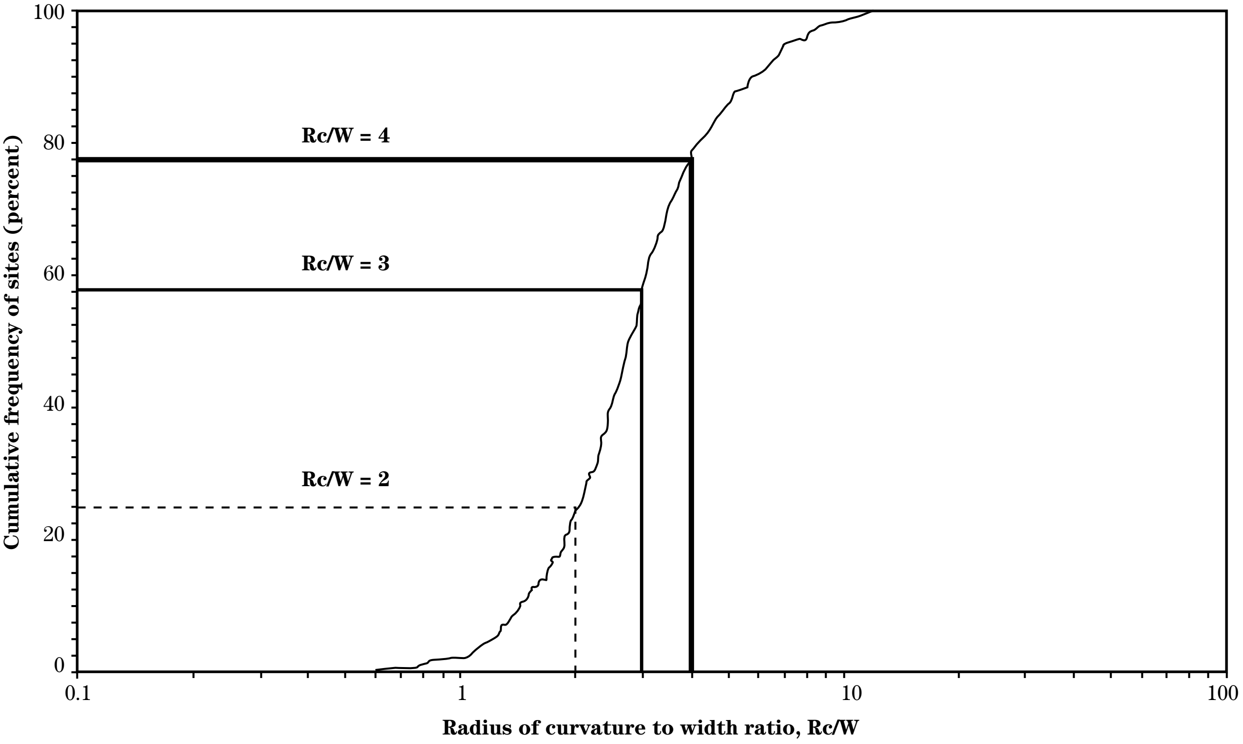
(c) Radius of curvature

The radius of planform curvature is not constant in the sine-generated curve, but ranges from a maximum value at the inflection point to a minimum curvature around the bend apex. The average radius of curvature is centered at the bend apex for a distance of approximately a sixth of the channel meander length.

Most reaches of stable meandering rivers have radius of curvature-to-width ratios between 1.5 and 4.5. Of the 438 sites used to derive the wavelength-width relationship in figure 12–3, radius of curvature is recorded for 263 of the sites. This subset was used to develop a cumulative distribution curve of radius of curvature-to width ratios (fig. 12–8). This figure shows that 33.5 percent, 52.9 percent, and 71.2 percent of the sites have radius of curvature-to-width ratios between 2 and 3, 2 and 4, and 1.5 and 4.5, respectively. The final planform layout should have ratios within the normal range.

If the calculated meander length is too large or if the required meander belt width is unavailable, grade control structures may be required to reduce the channel slope and stabilize the bed elevations.

Figure 12–8 Cumulative distribution of radius of curvature-to-width ratio derived from a composite data set of 263 sites



654.1203 Natural variability

Natural streams and rivers are rarely of uniform depth and width. Variability in channel width and depth can either be allowed to develop naturally or can be part of the project design. Sand-bed streams have the ability to create natural variability in channel form rather quickly because they are characterized by significant bed-material sediment transport. Gravel-bed streams typically adjust much more slowly. Streams with very little bed-material movement may not adjust at all. If variability is to be included in the project design, dimensions for cross sections in riffles and pools can be obtained from stable reaches of the existing stream or from reference reaches.

(a) Natural variability in width for gravel-bed rivers

Gravel-bed rivers are typically characterized by riffles and pools which correspond to bends and crossings in sand-bed rivers. In stable gravel-bed rivers, riffles are wider and shallower than the average channel width, and the pools tend to be deeper and somewhat narrower. In meandering gravel-bed rivers, the pools tend to be in the bends and the riffles at the inflection points. In the design of gravel-bed channels, the natural variability in cross-sectional width can be estimated using hydraulic geometry relationships or reference reaches. As with all hydraulic geometry and analogy methods, the design tools should be developed from physiographically similar watersheds.

Hey and Thorne (1986) developed hydraulic geometry relationships for meandering gravel-bed rivers in the United Kingdom. Their regression equations were based on surveys from 62 stable self-formed channels in erodible material with well-defined flood plains. At most sites, the banks were either cohesive or composite. Composite banks are defined as noncohesive sand and gravel layers overlain by a cohesive layer. These sites include the range of data used in developing the regression equations that are described in more detail in NEH654.09. A typical example of one of the Hey and Thorne rivers is shown in figure 12–9.

Riffle spacing and riffle width are determined from regression equations as a function of the mean channel width. The mean channel width is determined from one of three hydraulic geometry relationships described in NEH654.09. The Hey and Thorne hydraulic geometry relations for mean width consider the density of vegetation along the channel banks. The equations for riffle spacing are applicable for all bank conditions. The riffle spacing is given as a function of mean width:

$$Z = 6.31W \qquad \text{(eq. 12–7)}$$

where:

Z = the riffle spacing

W = the mean channel top width

Most of the data fell between the equations as shown in figure 12–10.

$$Z = 10W \qquad \text{(eq. 12–8)}$$

$$Z = 4W \qquad \text{(eq. 12–9)}$$

Riffle spacing tends to be nearer 4 channel widths on steeper gradients, increasing to 10 channel widths with more gradual slopes.

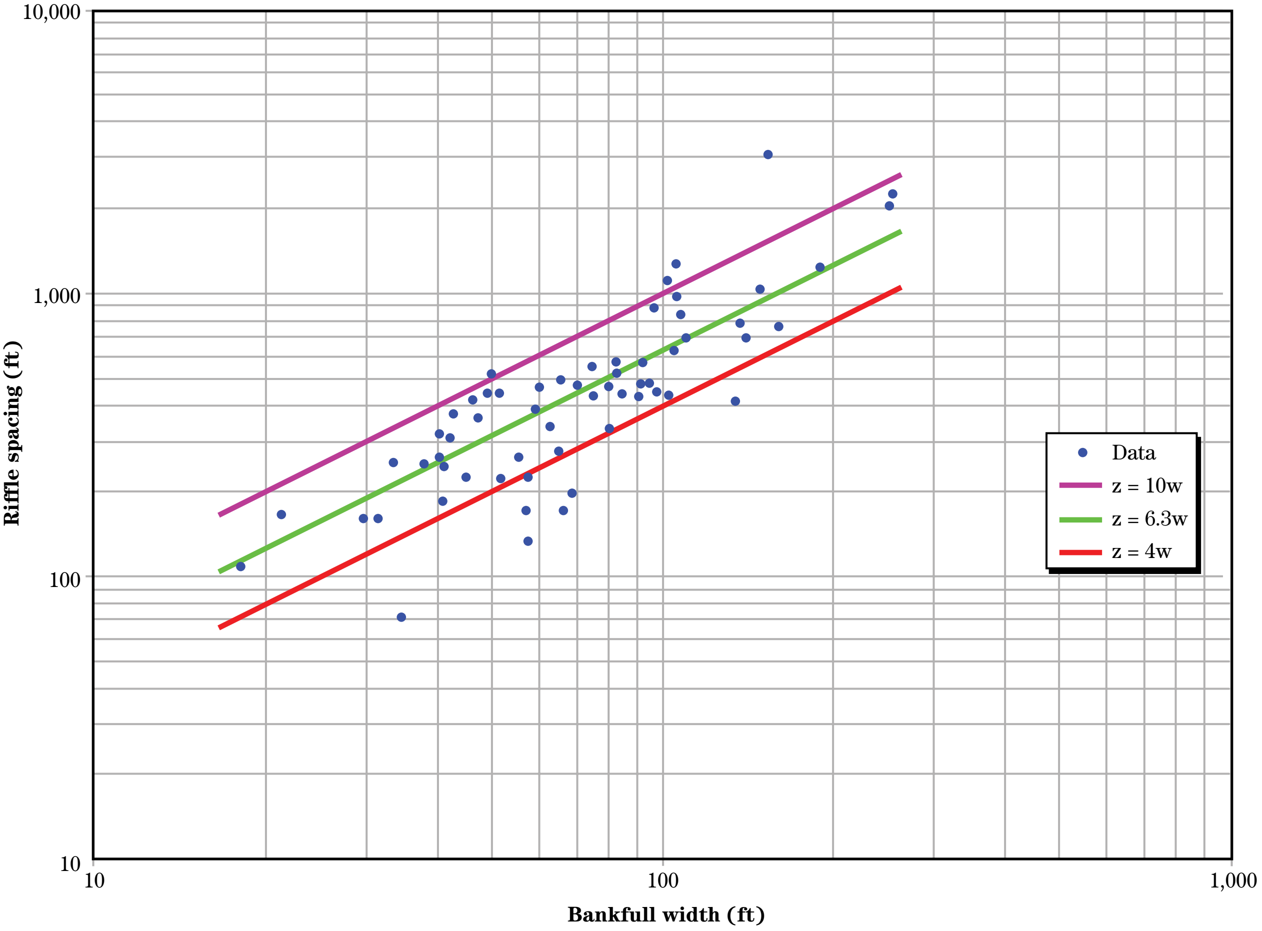
The riffle mean width, RW, was given as:

$$RW = 1.034W \qquad \text{(eq. 12–10)}$$

Hey and Thorne's riffle widths varied between 1.5W and 0.75 W.

Figure 12–9 Typical British gravel-bed river used in Hey and Thorne (1986) study

Figure 12–10 Relation between riffle spacing, Z, and bankfull channel width, W



(b) Riffle and pool spacing in nearly straight rivers

In rivers that are nearly straight (sinuosity less than 1.2), riffle and pool spacing may be set as a function of channel width. The empirical guide of 5 to 7 channel widths applies here (Knighton 1984). Two times this riffle spacing gives the total channel length through one meander pattern.

(c) Natural variability around meander bendways

Thorne (1988) and Thorne and Soar (2001) compiled empirical data sets of cross-sectional and planform dimensions from meander bends in the Red River between Index, Arkansas, and Shreveport, Louisiana. The Red River in this reach is typical of relatively large meandering rivers, with a wide variety of both bend geometries and bank materials. These studies provided a useful baseline database for examining the variability of width around meander bends, location of pools, and maximum pool depths. Equations were developed to define natural variability around the meander bends. Of course, if applied elsewhere, these equations should be used with caution.

The bends in the Red River data set were classified as one of three types based on the Brice (1975) classification system: equiwidth meanders, denoted as Type e (T_e) meanders (fig. 12–11); meanders with point bars, denoted as Type b (T_b) meanders (fig. 12–12); and meanders with point bars and chute channels, denoted as Type c (T_c) meanders (fig. 12–13). The Red River meander bend geometry data set is shown in table 12–4.

- **Equiwidth meandering**—Equiwidth indicates that there is only minor variability in channel width around meander bends. These channels are generally characterized by low width-to-depth ratios, erosion resistant banks, fine-grain bed material (sand or silt), low bed-material load, low velocities, and low stream power. Channel migration rates are relatively low because the banks are naturally stable.
- **Meandering with point bars**—Meandering with point bars refers to channels that are significantly wider at bendways than crossings, with well-developed point bars, but few chute channels. These channels are generally

Figure 12–11 Equiwidth meandering river, Type e (T_e)

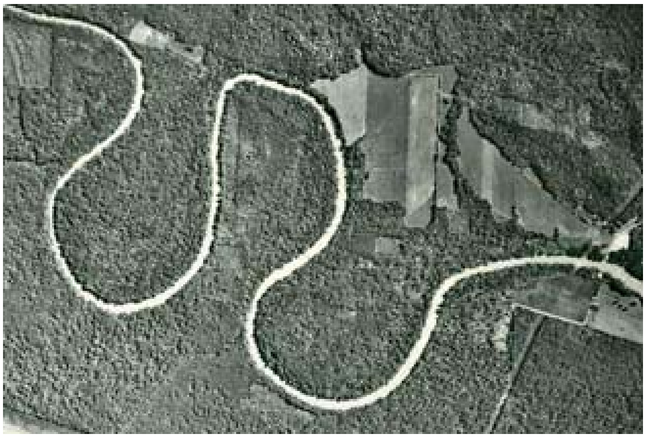


Figure 12–12 Meandering with point bars, Type b (T_b)

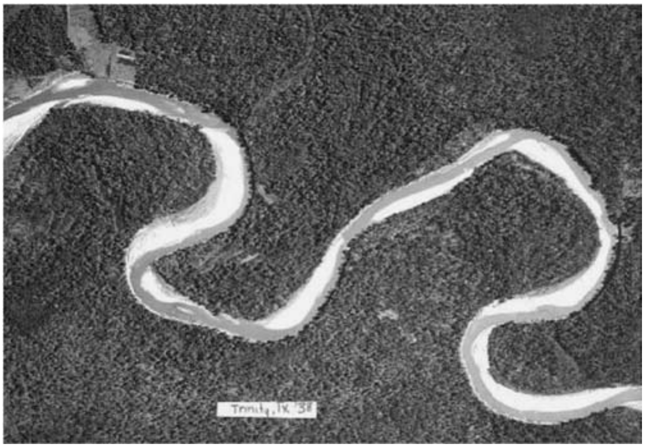


Figure 12–13 Meandering with point bars and chute channels, Type c (T_c)

characterized by intermediate width-to-depth ratios, moderately erosion-resistant banks, medium-grained bed material (sand or gravel), medium bed-material load, medium velocities, and medium stream power. Channel migration rates are likely to be moderate unless banks are stabilized.

- **Meandering with point bars and chute channels**—Meandering with point bars and chute channels refers to channels that are much wider at bendways than crossings, with well-developed point bars and frequent chute channels. These channels are generally characterized by moderate to high width-to-depth ratios, highly erodible banks, medium to coarse-grained bed material (sand, gravel and/or cobbles), heavy bed-material load, moderate to high velocities, and moderate to high stream power. Channel migration rates are likely to be moderate to high unless banks are stabilized.

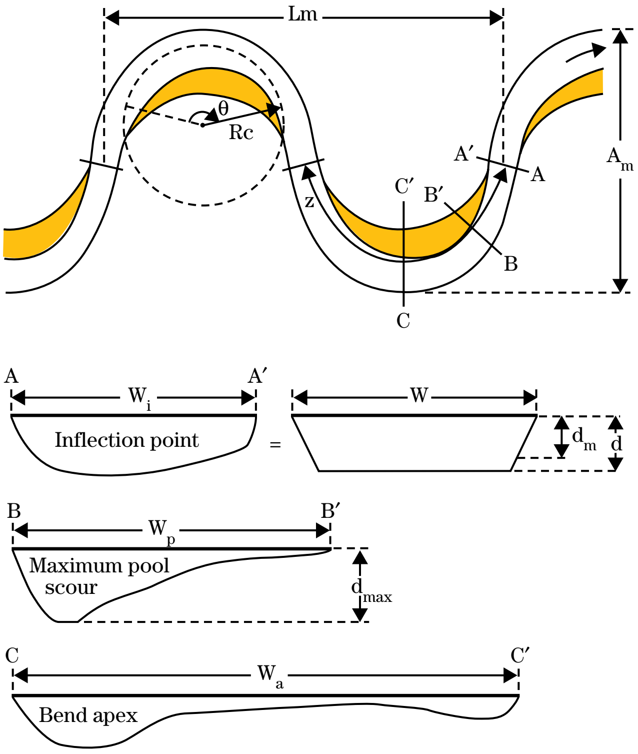
Ranges of physical characteristics pertaining to each of the meander bend types are addressed in more detail in NEH654.09. Figure 12–14 provides a definition sketch for channel cross-sectional geometries and dimensions through a meander.

Table 12–4 Ranges of physical characteristics found in different meander bend types identified from the 1981 Red River hydrographic survey between Index, AR, and Shreveport, LA

	n	**S (10^6)**	**P**	**W_i / d_m**	**d_{max} / d_i**	**Rc / W_i**
Type e	20	65 to 268	1.0 to 2.1	34.2 to 74.1	1.6 to 2.4	0.9 to 9.3
	(8)	(133 to 268)	(1.2 to 2.1)	(38.3 to 74.1)	(1.7 to 2.4)	(0.9 to 5.2)
Type b	34	76 to 294	1.0 to 2.0	36.8 to 121.0	1.5 to 2.6	1.5 to 9.1
	(19)	(105 to 294)	(1.1 to 2.0)	(36.8 to 102.4)	(1.7 to 2.6)	(1.5 to 6.1)
Type c	13	91 to 201	1.1 to 2.3	33.5 to 88.2	1.6 to 2.4	2.2 to 6.8
	(10)	(91 to 201)	(1.2 to 2.3)	(33.5 to 88.2)	(1.6 to 2.4)	(2.2 to 5.2)

Note:
n = number of meander bends studied
S = water surface slope
P = sinuosity
W_i / d_m = inflection point width-to-mean depth ratio
d_{max} / d_i = maximum scour depth in pool-to-mean depth at inflection point
Rc / W_i = radius of curvature-to-inflection point width ratio
Values in parentheses refer to meander bends with sinuosity 1.2 or greater.

Figure 12–14 Meander cross-sectional dimensions for variability design



Note: Point bars defined by shaded regions

Lm = meander wavelength

A_m = meander belt width

θ = meander arc angle

d = depth of trapezoidal cross section

d_{max} = maximum scour depth in bendway pool

W_p = width at maximum scour location

Z = meander arc length (riffle spacing)

Rc = radius of curvature

W = reach average bankfull width

d_m = mean depth (cross-sectional area / W)

W_i = width at meander inflection point

W_a = width at meander bend apex

(d) Width variability around meander bends

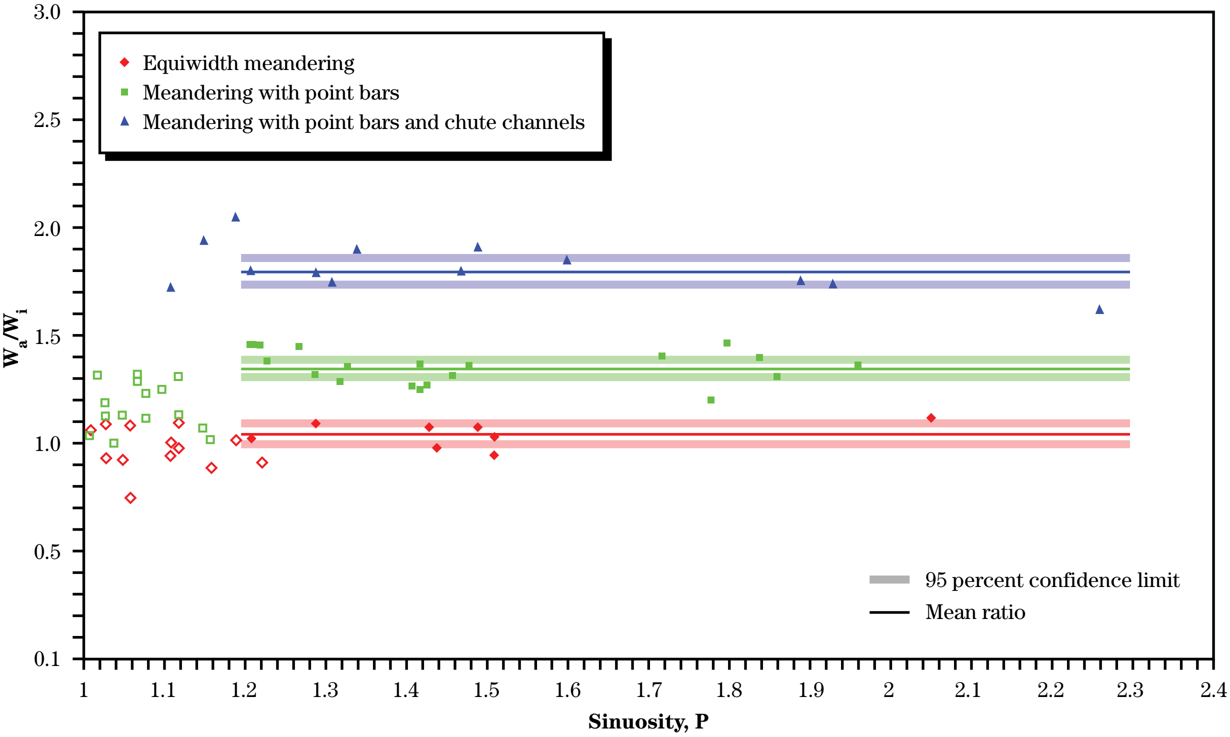
Two dimensionless parameters can be used to describe the width variability around meander bends, based on the enhanced Red River data set. These are the ratio of bend apex width to inflection point width, W_a/W_i, and the ratio of width at the location of maximum bend pool scour to inflection point width, W_p/W_i. Theoretically, these parameters adjust according to the degree of curvature and the type of meander bend. To derive new morphological relationships, sinuosity, P, was preferred as the independent variable, rather than the radius of curvature-to-width ratio. The latter would have resulted in width appearing on both sides of the regression equations.

Morphologic relationships for the width ratios as a function of meander type were developed for channels with sinuosities greater than 1.2. This is a commonly accepted threshold between nearly straight channels with only slight sinuosity and meandering channels with moderate to high sinuosity. The bed apex width to the inflection point width ratio, W_a/W_i, was found to be independent of sinuosity. Data are plotted with confidence limits in figure 12–15. Values for the ratios for each type of meander bend can be determined from table 12–5 and the following equation, where p denotes the level of significance and corresponds to the 100(1–p) percent confidence level.

Morphologic relationships for the width ratios as a function of meander type were developed for the ratio of pool width at the location of maximum scour to inflection point width (W_p/W_i) for channels with sinuosities greater than 1.2. This ratio was also found to be independent of sinuosity. Data and confidence limits are plotted in figure 12–16 (source data: 1981 Red River hydrographic survey). Values for the ratios for each type of meandering river can be determined from the following equation and table 12–6.

$$\left(\frac{W_a}{W_i}\right)_p = a + u_p \qquad \text{(eq. 12–11)}$$

Figure 12–15 Ratio of bend apex width to inflection point width, W_a/W_i as a function of meander bend type only, for sinuosities of at least 1.2. Confidence limits of a mean response are shown at the 95 percent level. (Source data: 1981 Red River hydrographic survey)



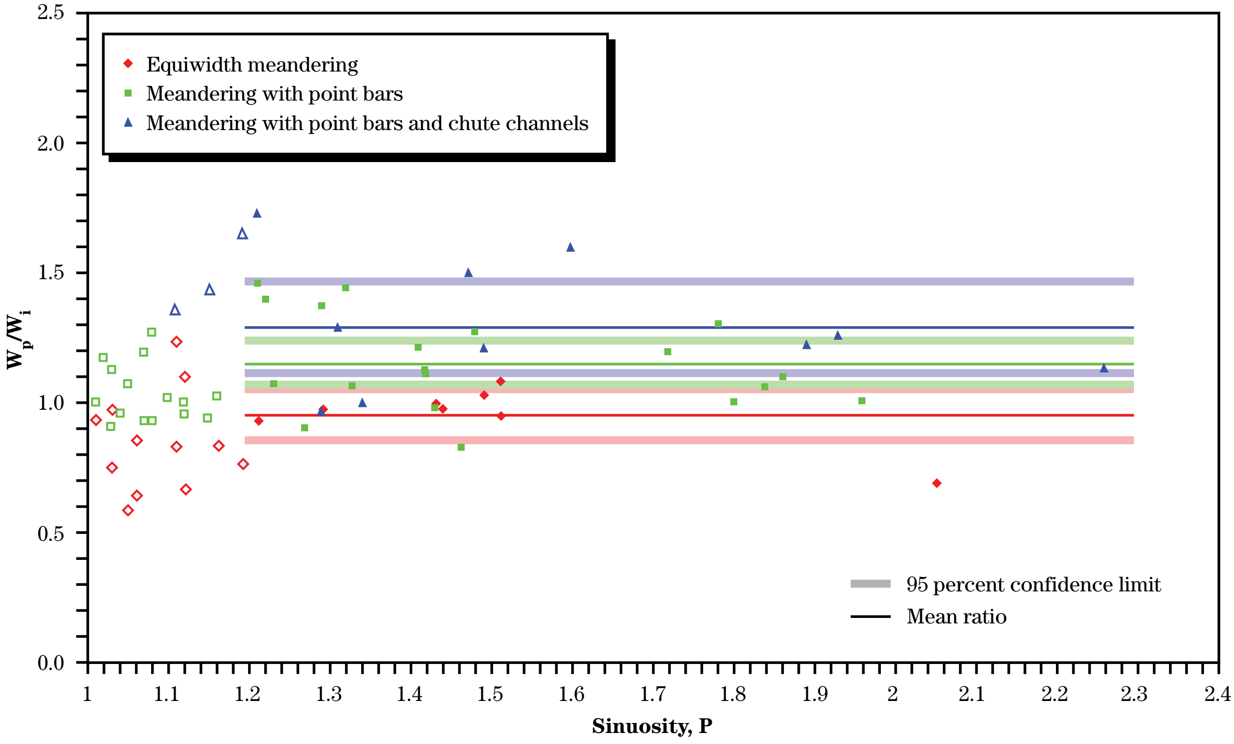
Note: Filled symbols = sinuosity of at least 1.2; empty symbols = sinuosity less than 1.2

Table 12–5 Constant values used to estimate the mean ratio of bend apex width to inflection point width, W_a/W_i, within confidence bands for different types of meander bends and for sites with sinuosity of at least 1.2. Coefficients pertaining to the 99, 95, and 90 percent confidence limits are given.

	a	$u_{0.01}$	$u_{0.05}$	$u_{0.1}$
Type e	1.05	0.08 (0.29)	0.05 (0.20)	0.04 (0.16)
Type b	1.35	0.05 (0.27)	0.04 (0.20)	0.03 (0.16)
Type c	1.79	0.09 (0.36)	0.06 (0.25)	0.05 (0.20)

Note: Values given refer to mean response confidence limits. Values in parentheses are used to calculate single response confidence limits.

Figure 12–16 Ratio of pool width (at maximum scour location) to inflection point width, W_p/W_i as a function of meander bend type only, for sinuosities of at least 1.2. Confidence limits of a mean response are shown at the 95 percent level.



Note: Filled symbols = sinuosity of at least 1.2 empty symbols = sinuosity less than 1.2

Table 12–6 Constant values used to estimate the mean ratio of pool width (at maximum scour location) to inflection point width, W_p/W_i, within confidence bands for different types of meander bends and for sites with sinuosity of at least 1.2. Coefficients pertaining to the 99, 95, and 90 percent confidence limits are given.

	a	$u_{0.01}$	$u_{0.05}$	$u_{0.1}$
Type e	0.95	0.15 (0.56)	0.10 (0.38)	0.08 (0.30)
Type b	1.15	0.12 (0.64)	0.09 (0.47)	0.07 (0.39)
Type c	1.29	0.26 (1.07)	0.18 (0.74)	0.14 (0.60)

Note: Values given refer to mean response confidence limits. Values in parentheses is used to calculate single response confidence limits.

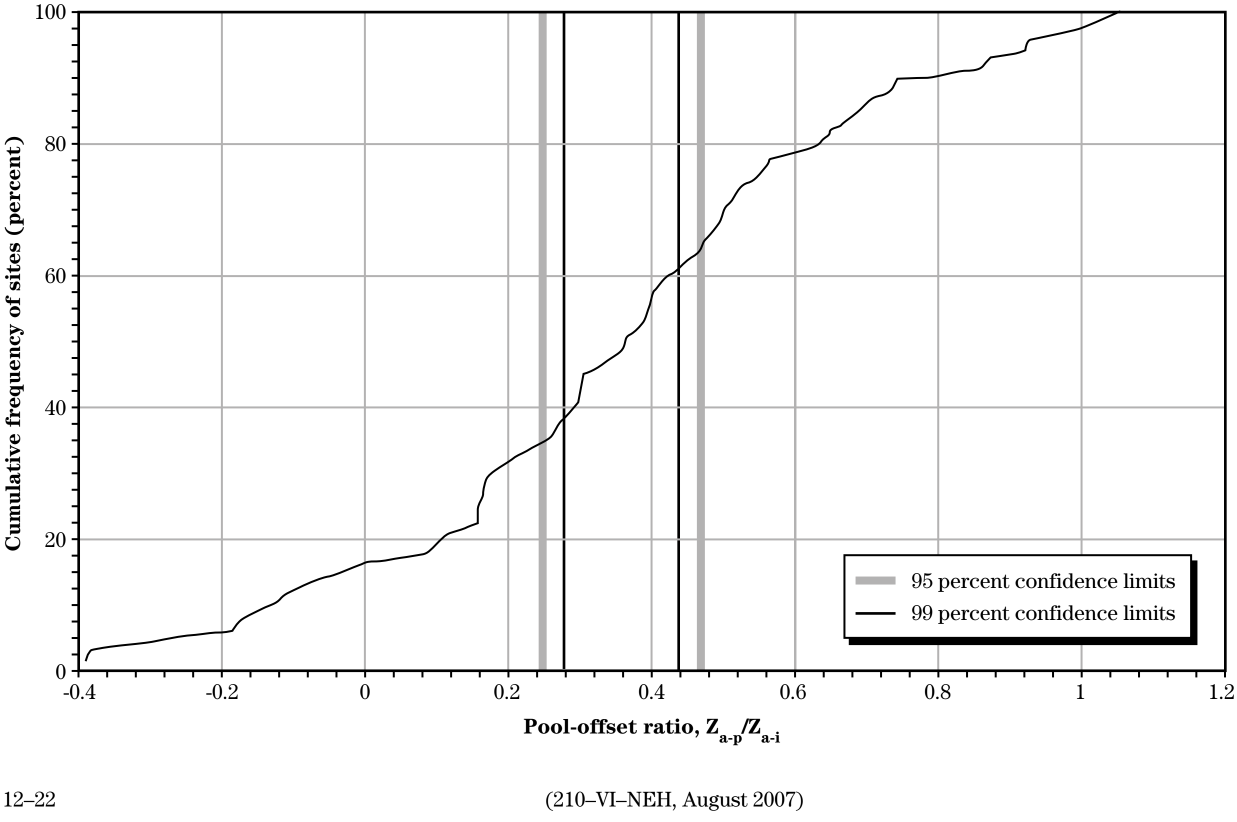
(e) Location of the pool in a meander bend

While the location of meander inflection points and bend apexes are geometrically defined, the location of pools, defined by the position of maximum bend scour, is variable. Pool location is controlled by the meander configuration, complex velocity distribution, and large-scale coherent flow structures which pulse sediment along the channel to form alternate zones of scour and fill. In natural meanders, the deepest pool is usually located downstream from the bend apex. The pool location in a meander bend can be represented empirically by a pool-offset ratio, defined as the ratio of the channel distance between bend apex and maximum scour location to the channel distance between bend apex and downstream inflection point, Z_{a-p} / Z_{a-i}. The pool–offset ratio was found to be independent of sinuosity. Neither was a distinct relationship found for the different meander types. The range and cumulative distribution function for the pool-offset ratio is shown in figure 12–17 (source data: 1981 Red River hydrographic survey). The mean value for the ratio was 0.36 and the range was –0.4 to 1.08.

(f) Maximum scour in bendways

Maximum scour depth is calculated to incorporate deep pools in constructed channels and to estimate required toe depths for bank protection. Data from a wide range of rivers (Thorne and Abt 1993; Maynord 1996) were used to develop morphological equations for the maximum scour depth in pools. These maximum scour depths are based on the surveyed maximum local depth at the bend. The data were divided into two subsets using a width-to-depth threshold value of 60, which is an approximate modal value.

Figure 12–17 Cumulative distribution of the pool-offset ratio, Z_{a-p}/Z_{a-i}, for all types of meander bends studied. Confidence limits on the mean response are shown.



The best-fit morphological relationships are given by Thorne and Soar (2001) as:

$$\frac{W_i}{d_m} < 60 \qquad \text{(eq. 12–12)}$$

$$\frac{d_{max}}{d_m} = 2.14 - 0.19\ln\left(\frac{Rc}{W_i}\right) \qquad \text{(eq. 12–13)}$$

$$\frac{W_i}{d_m} \geq 60 \qquad \text{(eq. 12–14)}$$

$$\frac{Rc}{W_i} < 10 \qquad \text{(eq. 12–15)}$$

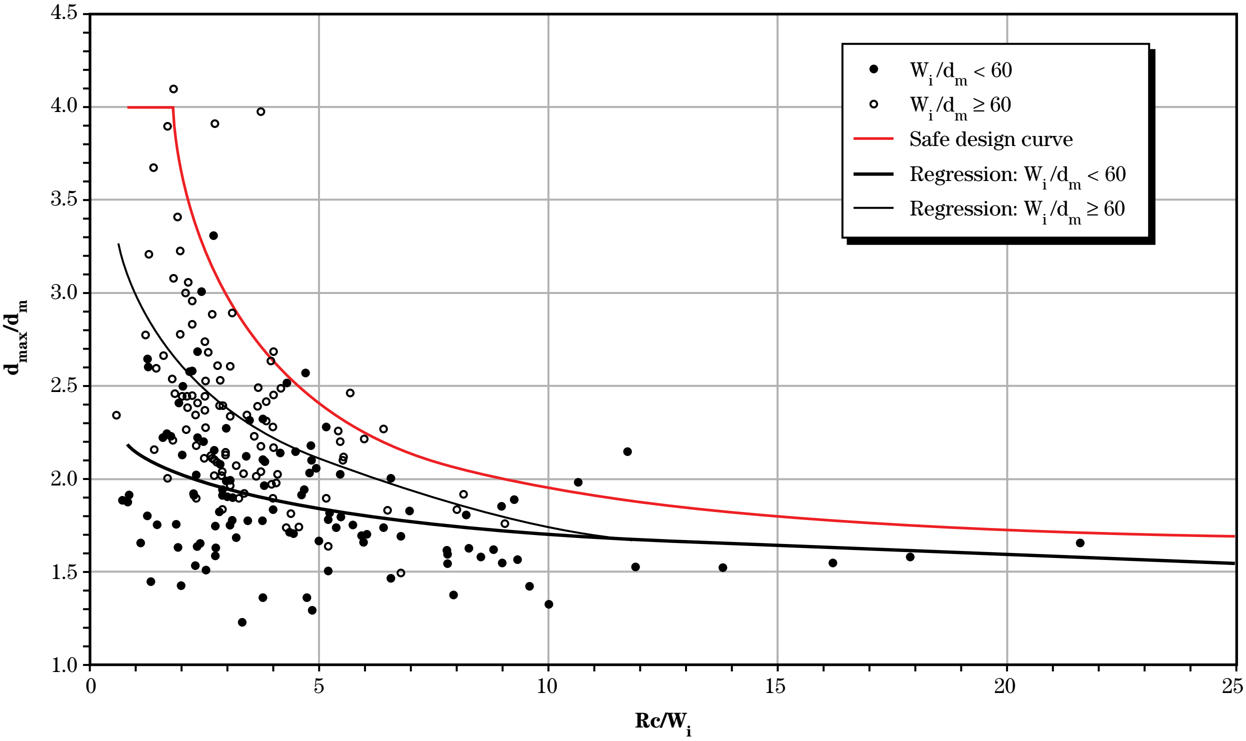
$$\frac{d_{max}}{d_m} = 2.98 - 0.54\ln\left(\frac{Rc}{W_i}\right) \qquad \text{(eq. 12–16)}$$

A practical, safe design curve may then be defined by considering both equations as:

$$\frac{d_{max}}{d_m} = 1.5 + 4.5\left(\frac{Rc}{W_i}\right)^{-1} \qquad \text{(eq. 12–17)}$$

This equation is an asymptotic relationship with a theoretical minimum d_{max}/d_m of 1.5, representing pool scour depths expected in a straight channel with a pool-riffle bed topography. From this upper-bound relationship, d_{max}/d_m ranges from 4 to 3 for Rc/W_i between 1.8 and 3. For channels with an Rc/W_i less than 1.8, pool depth is independent of bend curvature. The recommended dimensionless scour depth should be 4. All three relationships are portrayed in figure 12–18 (Thorne and Abt 1993; Maynord 1996), which show that this equation is a safe curve for both classes of W_i/d_m. More information on scour and how it relates to specific project features is provided in NEH654.14.

Figure 12–18 Dimensionless maximum scour depth in meander pools as a function of radius of curvature-to-width ratio



654.1204 Practical channel design equations for meander bend geometry

It is possible to derive a mean band of uncertainty, u, suitable for all three types of meander bends and to provide a set of practical design equations. The cumulative effects of Type e, Type b, and Type c bends are represented by the binary parameters, T_e, T_b and T_c, respectively. The value of T_e has a value of 1 for all three types of bend and represents the smallest planform width ratio. If point bars are present, but chute channels are rare, T_b is assigned a value of 1, and T_c is assigned a value of 0. If point bars are present and chute channels are common, both T_b and T_c are assigned values of 1. Obviously T_c can only be given a value of 1 when T_b has a value of 1.

Bend apex ($P \geq 1.2$)

$$\frac{W_a}{W_i} = 1.05T_e + 0.30T_b + 0.44T_c \pm u \qquad \text{(eq. 12–18)}$$

Pool width ($P \geq 1.2$)

$$\frac{W_p}{W_i} = 0.95T_e + 0.20T_b + 0.14T_c \pm u \qquad \text{(eq. 12–19)}$$

For all three bend types and sinuosities greater than 1, the pool offset ratio is given by:

Pool-offset ($P>1.0$)

$$\frac{Z_{a-p}}{Z_{a-i}} = 0.36 \pm u \qquad \text{(eq. 12–20)}$$

Values of u refer to confidence limits on the mean response as given in table 12–7.

A practical design equation for predicting or constructing maximum scour depths at bends is the upper-bound curve in figure 12–17, given by the following equation:

$$\frac{d_{max}}{d_m} = 1.5 + 4.5\left(\frac{R_c}{W_i}\right)^{-1} \qquad \text{(eq. 12–21)}$$

For sites where active meandering is not permitted, bank protection will be required along the outer bank to prevent erosion. In addition, this equation should be used together with bank stability charts to establish whether bank stabilization against mass failure is also necessary.

Table 12–7 Uncertainty, u, in estimates of width variability around meander bends and location of pools. Values refer to confidence limits on the mean response.

Confidence limits %	W_a / W_i	W_p / W_i	Z_{a-p} / Z_{a-i}
99	0.07	0.17	0.11
95	0.05	0.12	0.08
90	0.04	0.10	0.07

654.1205 Bankline migration

Bankline migration is a natural process associated with natural meandering channels. Meander loops tend to move downstream as river processes erode the outside of bends and deposit sediment on point bars. The ability to forecast adjustments in planform is important to the planning and design of any project where highways or structures could be damaged. The rate of bank migration at a given site is a function of erosional forces and resisting forces. The variables affecting erosional forces include discharge, cross-sectional geometry, sediment load, bed roughness, bedforms and bars, and the geometry of the bend itself. The variables affecting resistance forces include bank geometry, the composition of the bank, bank vegetation, pore water pressure, freezing and thawing, and wetting and drying. Due to the wide variability in significant variables, it is difficult to develop an algorithm that can reliably predict bankline migration rates.

Nanson and Hickin (1986) compiled data for 18 gravel-bed rivers in western Canada and reported maximum bankline migration rates at the bend apex (fig. 12–19). Cherry, Wilcock, and Wolman (1996) used 133 data sets from meandering sand-bed rivers collected by James Brice of the USGS to develop an empirical relationship to estimate bankline migration. They related mean annual flow and channel width to the mean erosion rate along the entire length of channel (fig. 12–20). They concluded that the simple correlation was inadequate. However, it does provide an order of magnitude estimate for the mean erosion rate and can be used to estimate a range of probable erosion rates.

Figure 12–19 Bankline migration rates in gravel-bed rivers

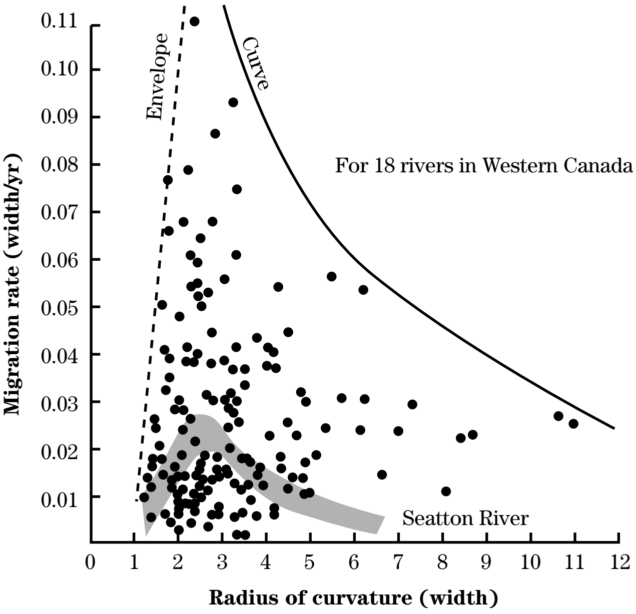


Figure 12–20 Average bank erosion rate

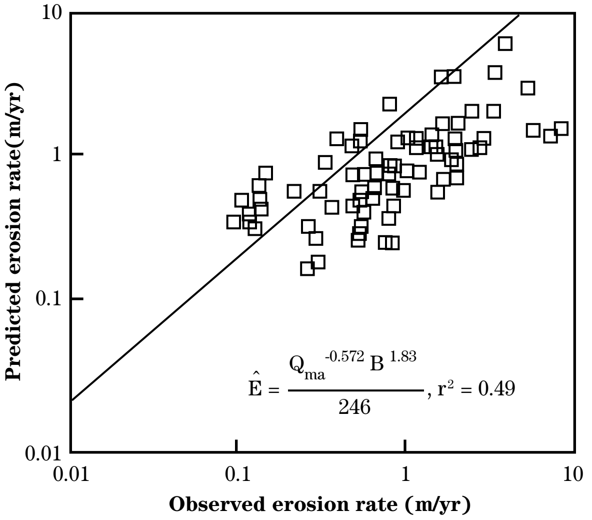
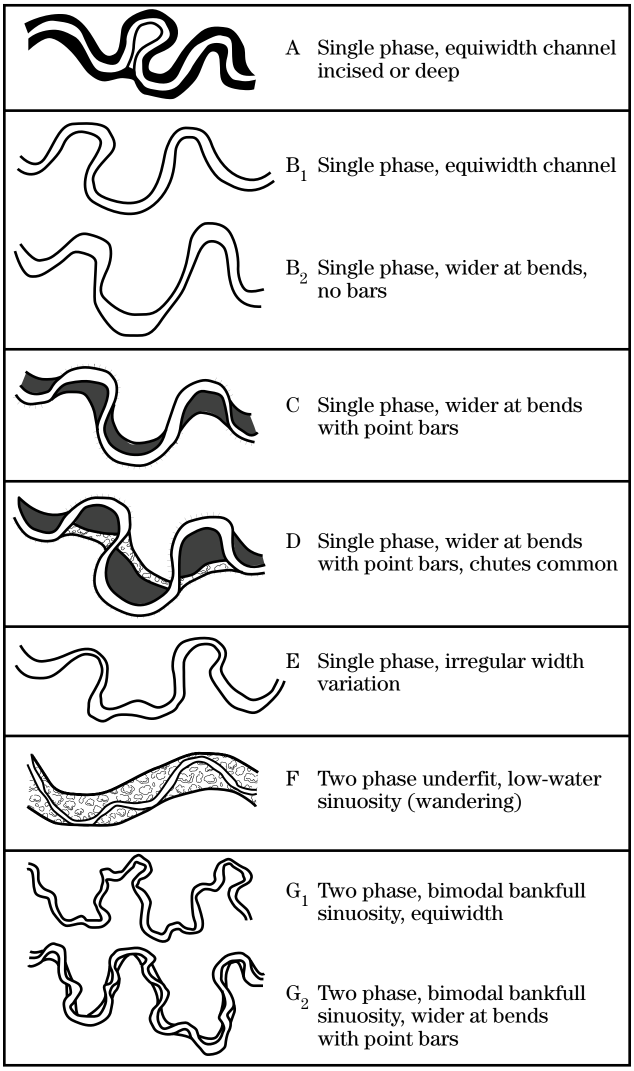


Figure 12–21 Modified Brice classification system for estimating bankline migration



Ayres Associates (2004) used the same data set as Cherry, Wilcock, and Wolman (1996), relating the maximum rate of apex movement to the channel width at the apex. They segregated the data for four channel types: B1–single phase equiwidth, B2–single phase wider at bends, C–single phase with point bars, and A–single phase incised or deep. Their classification is a modification of the Brice (1975) classification system shown in figure 12–21 (Ayers Associates 2004). The scatter in the Ayres data (fig. 12–22 is about the same. Note that the Cherry, Wilcock, and Wolman (1996) data and bank migration rates can only be estimated in an approximate sense. Ayres Associates plotted a cumulative percentage of apex movement curve (fig. 12–23) which provides a useful tool for predicting bankline migration in terms of risk and uncertainty.

Several researchers have developed two-dimensional, depth-averaged numerical models to predict bankline migration. These models are data intensive and should be considered research tools. Garcia, Bittner, and Nino (1994) related the local erosion rate to the difference in the average velocity and the near-bank velocity. Odgaard (1986) related erosion to the difference in average depth and near-bank depth. The models produce relatively accurate velocity distributions in the meandering channel; however, bank resistance coefficients must be empirically determined or calibrated to existing conditions at specific sites. The high degree of variability in bank composition in meandering alluvial systems makes application of these models difficult.

The most reliable method for predicting bankline migration rate is to estimate historical rates from aerial photos of the project river. It must be recognized that rates at a specific site will change as the planform changes. In addition, erosion rates change with cyclic climate changes and changes in the watershed.

Figure 12–22 Bankline migration—apex movement versus channel width

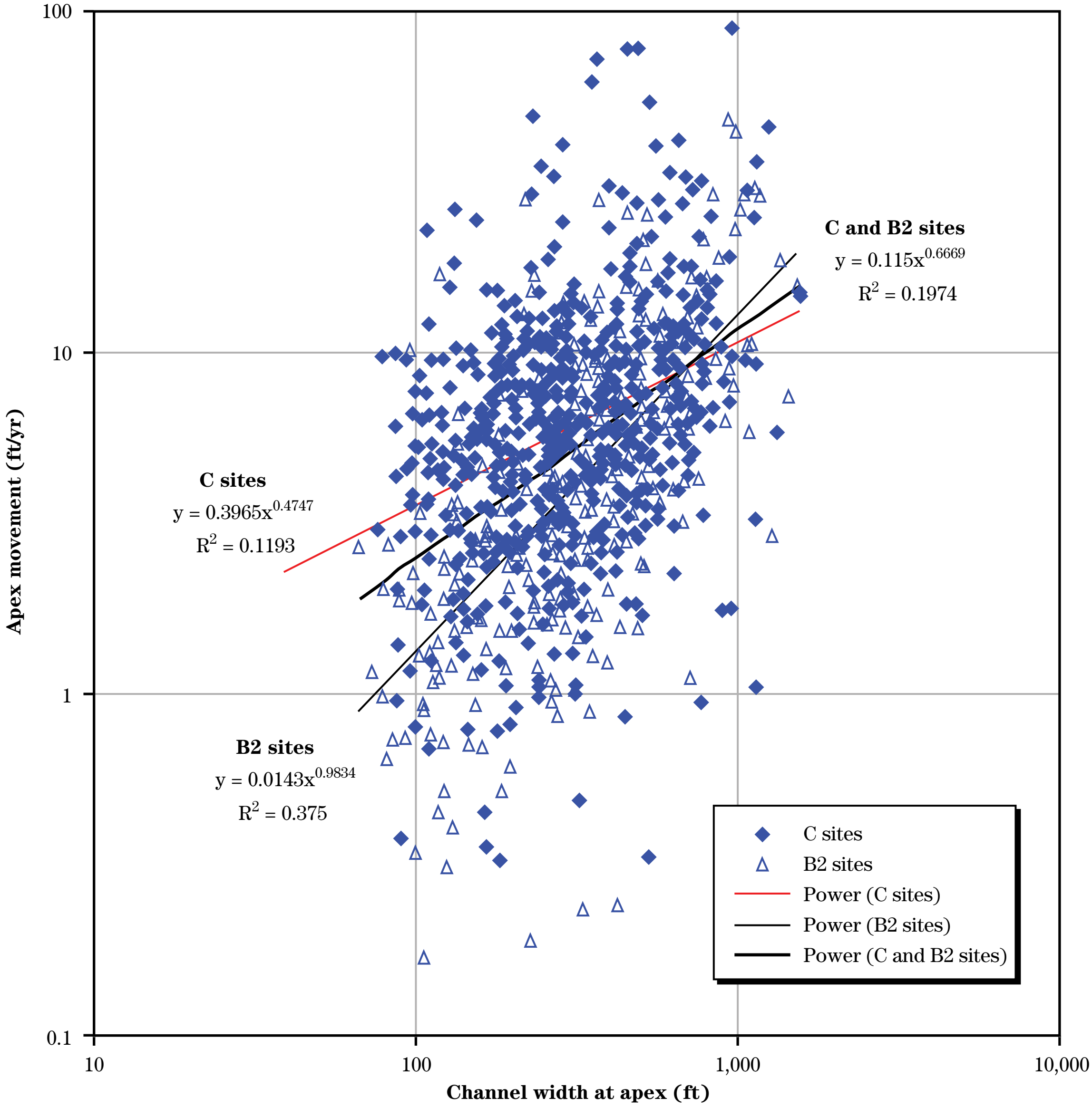
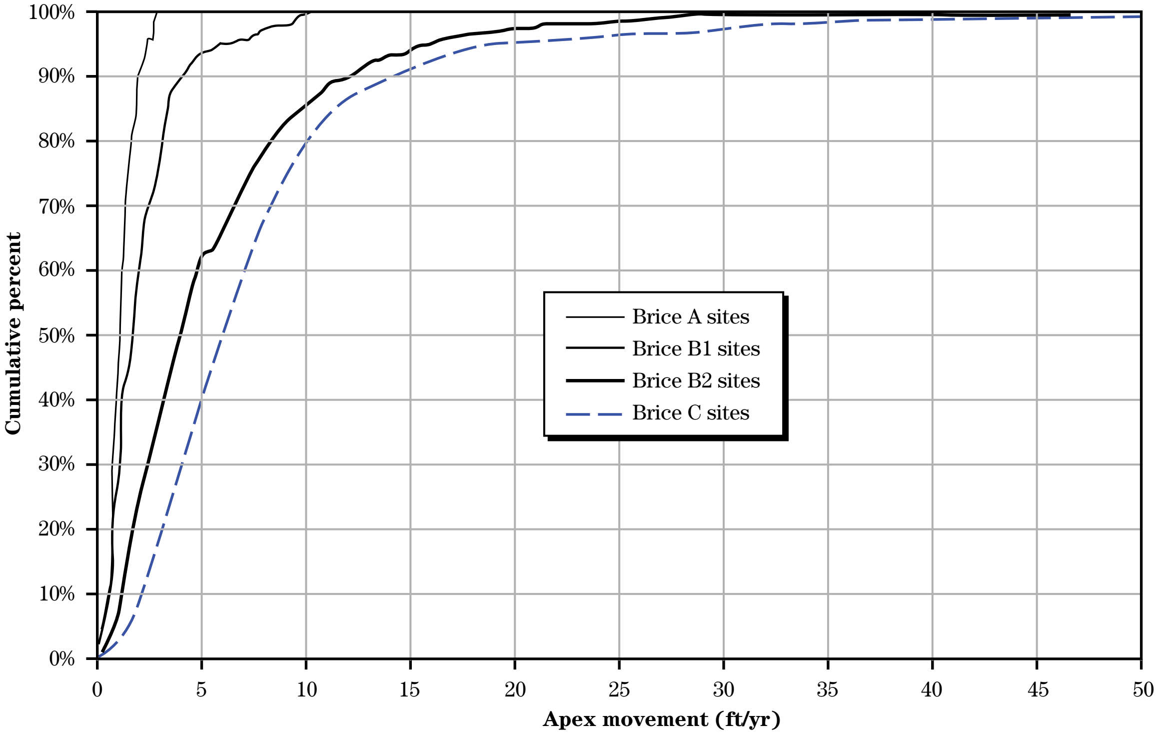


Figure 12–23 Cumulative percentage of apex bend movement



Example problem: Variability in channel planform geometry

Objective: Average channel dimensions for a new meandering sand-bed channel with point bars have been determined. Provide for channel geometry variability so that the new channel will not have excessive adjustments to make as it seeks its new equilibrium condition. Determine the channel width at the bend apex and at the location of the maximum scour. Also, estimate the most probable maximum scour depth and its most probable location. Determine the design depth of the bank protection if it is needed. Estimate the bankline migration rate that might occur if the bank is not protected.

Given: Average channel dimensions at the crossing and the general planform alignment are:

Width = 450 ft
Depth = 25 ft
Channel slope = 0.00030
Valley slope = 0.00049
Meander wavelength = 5,000 ft
Radius of curvature = 2,000 ft
Channel-forming discharge = 50,000 ft^3/s
Mean annual flow = 8,000 ft^3/s

Step 1 Calculate sinuosity

$$P = \frac{\text{Valley slope}}{\text{Channel slope}}$$

$$P = \frac{0.00049}{0.00030} = 1.63$$

Step 2 Calculate the channel distance through one meander wavelength

$$M = P \times \text{ meander wave length}$$

$$M = 1.63 \times 5{,}000 = 8{,}150 \text{ ft}$$

Step 3 Calculate the channel width at the bend apex and at the pool using tables 12–5 and 12–6.

This is a type b channel (meandering with point bars)

Width at apex = 1.35 × average channel width

Width at apex = 1.35 × 450 ft

Width at apex = 608 ft

With 90 percent confidence that the width should be between

$$\text{Width at apex} = (1.35 + 0.16)$$
$$\text{and } (1.35 - 0.16) \times 450 = 680 \text{ and } 536 \text{ ft}$$

Width at pool = 1.15 × average channel width

Width at pool = 1.15 × 450 ft

Width at pool = 518 ft

With 90 percent confidence that the width should be between

$$\text{Width at pool} = (1.15 + 0.39)$$
$$\text{and } (1.15 - 0.39) \times 450 = 693 \text{ and } 356 \text{ ft}$$

Step 4 Determine the most probable location of the pool in bend using figure 12–17.

At a cumulative frequency of 50 percent (most probable) the pool-offset ratio is 0.36

$$\frac{Z_{a-p}}{Z_{a-i}} = 0.36$$

The distance to the bend apex from the crossing (inflection point) is one half the channel distance through a meander wavelength.

$$Z_{a-i} = \frac{M}{2} = \frac{8{,}150}{2} = 4{,}075 \text{ ft}$$

$$Z_{a-p} = 0.36 \times 4{,}075 = 1{,}467 \text{ ft}$$

The location of the pool is then 5,542 feet downstream from the inflection point.

$$4{,}075 + 1{,}467 = 5{,}542 \text{ ft}$$

Step 5 Determine the most probable scour depth and the safe design depth for bank protection using figure 12–18.

$$\frac{\text{Radius of curvature}}{\text{Average width}} = \frac{2{,}000 \text{ ft}}{450 \text{ ft}} = 4.44$$

$$\frac{\text{Average width}}{\text{Mean depth}} = \frac{450 \text{ ft}}{25 \text{ ft}} = 18$$

Calculate the average depth of scour at the pool.

$$\frac{d_{max}}{d_m} = 2.14 - 0.19\ln\left(\frac{Rc}{W_i}\right)$$

$$d_{max} = 25\left[2.14 - 0.19\ln\left(\frac{2{,}000\text{ ft}}{460\text{ ft}}\right)\right]$$

$$d_{max} = 46\text{ ft}$$

Calculate the safe design depth for bank protection.

The mean depth should represent the depth at channel-forming discharge to set an average pool depth for the initial channel geometry, but should represent depth at a design frequency flood peak to set a design depth for bank protection. In this example, a wide flood plain is assumed so that channel-forming and flood depths are similar.

$$\frac{d_{max}}{d_m} = 1.5 + 4.5\left(\frac{Rc}{W_i}\right)^{-1}$$

$$d_{max} = 25\text{ ft}\left[.5 + 4.5\left(\frac{450\text{ ft}}{2{,}000\text{ ft}}\right)\right]$$

$$d_{max} = 63\text{ ft}$$

Step 6 Estimate bankline migration rate using the Cherry, Wilcock, and Wolman equation (fig. 12–20) and the Ayres Associates graph for a type C channel (fig. 12–21).

$$E = \frac{Q_{ma}^{-0.572}B^{1.83}}{246},\ r^2 = 0.49$$

$$Q_{ma} = \frac{8{,}000}{35.3} = 227\text{ m}^3/\text{s}$$

$$B = \frac{450\text{ ft}}{3.28\text{ ft/m}} = 137\text{ m}$$

$$E\text{ m/yr} = \frac{\left(227^{-0.572} \times 137^{1.83}\right)}{246} = 1.5\text{ m/yr} = 4.9\text{ ft/yr}$$

$$\text{Apex movement (ft/yr)} = 0.3965W^{0.4747}\text{ ft}$$

$$\text{Apex movement} = 0.3965(450)^{0.4747}$$

$$\text{Apex movement} = 7.2\text{ ft/yr}$$

It is not surprising that this analysis indicates such a difference in these estimates, considering the large number of variables that have been ignored. However, this analysis provides an idea of the probable magnitude of the meander migration. It can also be used with additional analysis to assess if bank protection is necessary.

654.1206 Conclusion

In the natural system, there are rarely perfectly linear or straight systems. Natural systems that appear linear typically have some slight sinuosity to them.

Natural channel work requires that the proposed design fits into the natural system within the physical constraints imposed by other project objectives and riparian conditions. Design requires not only channel planform design but also an assessment of natural variability, as well as potential channel movement.

Planform design parameters include sinuosity, meander wavelength, an appropriate channel length for one meander wavelength, and trace of the channel. The approach used to perform this design should be appropriate to the stream conditions. In a threshold channel, planform relates to establishing a maximum slope based on critical stability of the boundary material. In an alluvial channel, planform is a separate dependent variable that must be determined within natural geomorphic limits.

Channel sinuosity is determined from the calculated channel slope and valley slope. To determine other parameters, analogy, hydraulic geometry, and/or analytical methods are employed. To apply the analogy method, a reference reach is located on either the study stream or another suitable stream. From the reference reach a template for the meander planform is developed for the project reach. This may often be problematic due to the nonavailability of a reference reach or subtle, but important fluvial, sedimentary, or morphological differences between it and the study reach.

Alternatively, meander wavelength can be determined using hydraulic geometry techniques. The most reliable hydraulic geometry relationship is wavelength versus width. As with the determination of channel width, preference is given to wavelength predictors from stable reaches of the existing stream either in the project reach or in reference reaches. The channel trace may also be determined analytically using the sine-generated curve. Finally, a string cut to the appropriate length can be laid on a map and fit to existing constraints and to the proper wavelength to form a meandering planform.

The methods used to estimate variability in cross section, as well as potential bank migration, are dependent on site-specific conditions. Some guidance developed for regionally specific studies has been presented. While this material provides a guideline, it should only be used with caution if applied elsewhere.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 13 Sediment Impact Assessments

Issued August 2007

Cover photo: Sediment moved in suspension and as bed load may have impacts on the restoration design. Watershed conditions that produce sediment (either naturally or in excess) should be well understood.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 13 Sediment Impact Assessments

Contents

Tables

Figures

Chapter 13 Sediment Impact Assessments

654. 1300 Purpose

Sedimentation analysis is a key aspect of design since many projects fail due to excessive erosion or sediment deposition. A sediment impact assessment is conducted to assess the effect that a full range of natural flows will have on possible significant aggradation or degradation within a project area. This chapter provides a brief overview of several types of sediment impact assessments, along with their rigor and level of uncertainty. The focus of this chapter is primarily on techniques appropriate for the analysis of alluvial channels. However, sediment assessments for threshold channels are also described. There are variants in each of the presented techniques, and more information may be needed to perform the assessments. It is the intent of this chapter to provide an introduction to sediment impact assessments sufficient to select the approach that is most appropriate for most projects. Note that although sediment impact assessment is presented following channel design chapters of this handbook, much of this analysis described should also be done in the sediment assessment phase of the design process that precedes and supports channel design. However, a sediment impact assessment is an important closure loop on any proposed design.

654.1301 Introduction

The success of any restoration that includes channel reconstruction is based on the designed channel's ability to transport the inflowing water and sediment load without excessive sediment deposition or scouring on the channel bed. Therefore, a critical step in any channel design project is a sediment impact assessment. Also, since any bank protection measures may fail if the bed is unstable, an assessment of bed stability is also critical for any bank stabilization project.

Sediment impact assessments can range widely in effort and output. These assessments can be accomplished using visual or qualitative techniques for relatively simple projects or by using a numerical model that incorporates solution of the sediment continuity equation for more complex projects. Several types of sediment impact assessments are described in this chapter. While the focus of this document is primarily on techniques appropriate for the analysis of alluvial channels, threshold channels are also described.

The first step in understanding and implementing a sediment impact assessment is to define the anticipated channel bed response. This is an assessment of bed stability to determine if the channel bed is aggrading, degrading, or is relatively stable. Other aspects of a stability assessment may include bank stability or planform stability. The sediment impact assessment is primarily concerned with the stability of the channel bed.

654.1302 Bed stability

Aggradation and degradation are potential major adjustments of an individual channel or a fluvial system. Since a sediment impact assessment is concerned with predicting these responses, it is important to define what these adjustments are and how they can affect a channel.

(a) Aggrading channel

A channel is considered to be aggrading when long-term sediment deposition occurs on the bed. The channel cross section is filling up or becoming shallower. Channel widening, avulsions, and a reduction in flood capacity are characteristic of an aggrading channel. A channel may experience aggradation due to localized watershed processes such as landsliding or construction activities, or it may be due to natural processes, watershed characteristics, and geology. A constructed channel may aggrade if it is deepened and widened for flood conveyance and does not maintain flows and depths sufficient to transport inflowing sediments under more frequent lower discharges.

(b) Degrading channel

A channel is considered to be degrading when long-term sediment removal occurs from the channel bed. The channel cross section becomes deeper. Bank failure, lowering of water tables, and restriction of a stream's connection to its flood plain can occur in a degrading channel. A channel may experience degradation due to a reduction in sediment supply (as may occur in the stream reach below a dam), an increase in flow (as may occur with development in the watershed), or as a result of a lowering of the base level at the mouth of the reach, triggering headcutting, nickpoints, and degradation. A constructed channel may degrade if bed shear stresses are increased in excess of what the channel boundary was designed to withstand. This can occur due to channel straightening or elimination of flood plain access at high flow.

(c) Stable channel

For the purposes of this chapter, a channel is considered stable (or in dynamic equilibrium) when the prevailing flow and sediment regimes do not lead to long-term aggradation or degradation. A stable channel does not experience changes in its cross-sectional geometry over the medium to long term. Short-term changes in sediment storage, channel shape, and planform are both inevitable and acceptable in natural channels. For example, aggradation or degradation may occur on a streambed over the course of a storm hydrograph, but does not necessarily indicate overall instability. While short-term adjustment may damage bank stabilization or bank habitat structures, these assessments are usually performed in a scour analysis as described in NEH654.14. The focus of the analysis described in this chapter is on long-term, progressive changes.

654.1303 Threshold versus alluvial channels

The choice of the appropriate type of sediment impact assessment depends, in part, on whether the channel at the project location is an alluvial channel or a threshold channel. Therefore, it is important for the practitioner to be able to distinguish between these channel types. In general, the geomorphology of a threshold channel is a product of a process that is no longer at work or not regularly at work. Sediment passes through a threshold channel with very little impact on the channel boundary. In an alluvial channel, there is an exchange of sediment between the channel boundary and the flow. An alluvial channel is more active, and its geomorphology is a product of more frequent events. It is important to note that there is not always a sharp demarcation between threshold and alluvial channels. A channel may behave as a threshold channel under low to moderate flow events, yet behave as an alluvial channel under larger flow events. More information about threshold and alluvial channels is provided in NEH654.09.

A sediment impact assessment is particularly important in alluvial channel design. As described in NEH654.09, stability design for alluvial channels begins by determining the channel dimensions for the channel-forming discharge, using analogy, hydraulic geometry, and/or analytical methods. While a single flow and associated sediment load may have a strong effect on the geomorphology of the stream over the long term, other flows and sediment loads may adversely impact the project. Therefore, once these preliminary dimensions are determined, the next step is to assess how well that channel will maintain sediment continuity for the full range of natural flows. This becomes even more important in cases where the desired channel dimensions cannot be achieved due to project constraints or conflicting project objectives. Alluvial channels typically require more in-depth analyses to assess the potential impacts of sediment, but qualitative techniques can be used in low risk situations.

While the focus of this chapter is primarily on alluvial channels, sediment impact assessment should also be considered for threshold channels. Where the design channel is threshold in nature, the sediment impact assessment may be more qualitative, or it may be integral to the design process itself. For example, the identification of the flow condition that would mobilize the boundary of a threshold channel can be sufficient as a check for potential degradation. In this case, the sediment impact assessment is often referred to as a stability assessment. Many of the approaches for stability assessment of threshold channels are presented in NEH654.08. However, it may also be appropriate to perform a check to assure that any suspended sediment will remain in suspension and not be deposited in the design threshold channel. This analysis can be accomplished by comparing the channel shear velocity to the settling velocity of the sediment, under a variety of expected flow conditions. Finally, the designer should consider possible impacts that may occur if the threshold channel were to transition to an alluvial channel.

654.1304 Types of sediment impact assessments

A variety of techniques may be used to assess the impact of sediment on a project area. The approaches described here are not exhaustive, nor are they applicable in all situations. However, a final sediment impact assessment should be viewed as a closure loop at the end of the design process to:

- validate the efficacy of the design channel geometry
- identify flows which may cause aggradation or degradation over the short term (these changes are inevitable and acceptable in a dynamic channel)
- recommend minor adjustments to the channel design to ensure dynamic stability over the medium to long term

The type of sediment impact assessment used will determine the certainty of the result, as well as the precision of a conclusion that the channel will aggrade, degrade, or remain stable. The selection of the appropriate methodology should be done with a firm understanding of the assumptions, accuracy, data requirements, and limitations of the approach. This chapter outlines some of the most common techniques and offers general guidelines regarding selection criteria. For more details regarding the assumptions and limitations of these methodologies or approaches, the original documentation associated with each should be reviewed. Final decisions regarding the suitability of a particular approach must be determined using engineering judgment on a case-by-case basis.

Most of the following approaches were developed for application with the analysis and design of alluvial channels. However, they can also be used with threshold channels, as well. The following approaches are listed in general increasing level of difficulty.

654.1305 Visual geomorphic assessment

A visual geomorphic assessment is primarily a qualitative check that should be done for both threshold and alluvial streams. This may be the only assessment needed for a potential project, or it may be the first step of a more detailed sediment impact assessment, if required. Visual geomorphic assessments of sediment impacts are generally sufficient where:

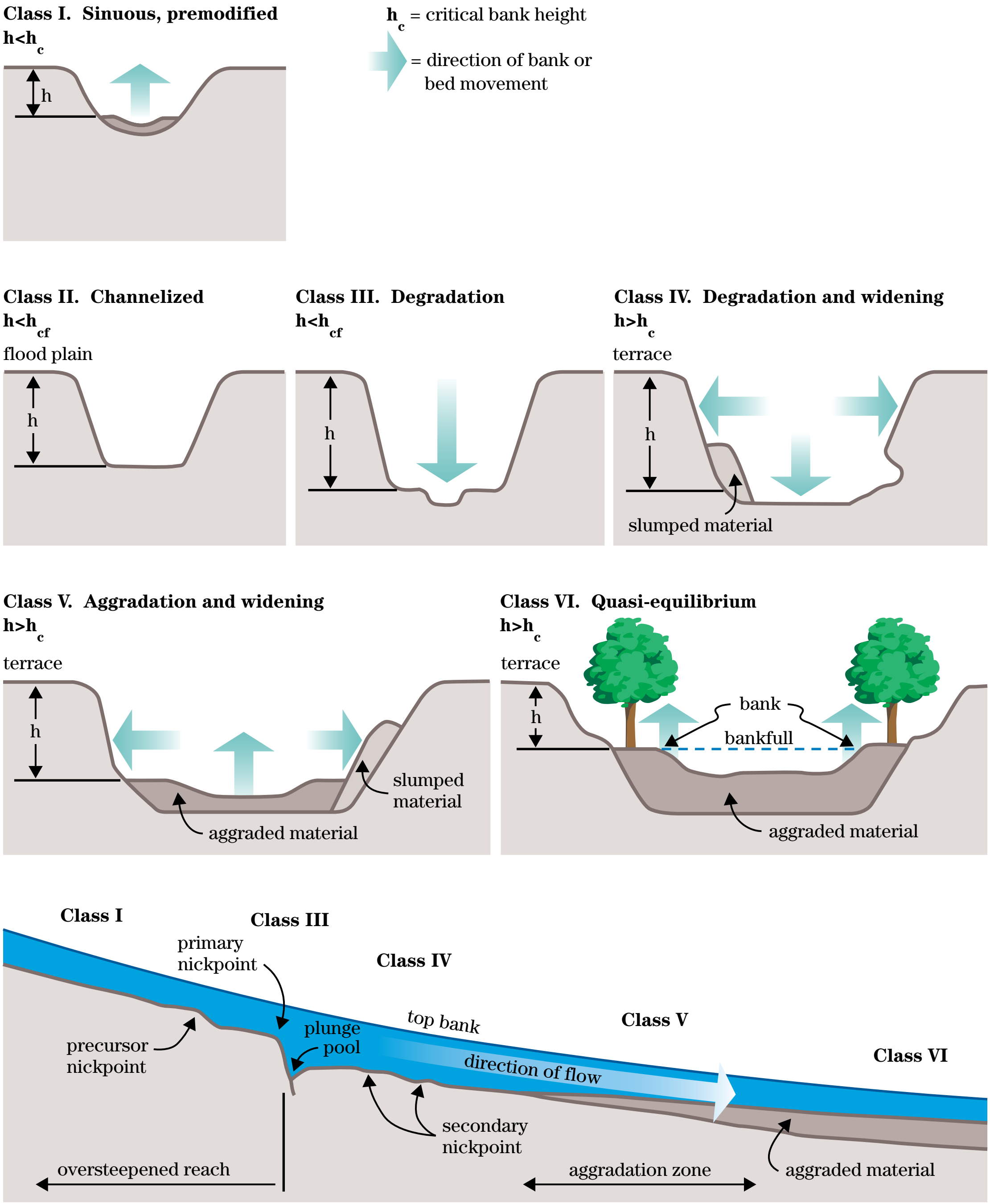
- project failure will have minimal adverse effects
- minimal change to the channel shape is proposed
- the watershed land use and cover and erosion processes are relatively stable

The visual geomorphic assessment includes judgment of current conditions, expected future conditions, and the river's anticipated response to the designed project. It includes the identification of potentially destabilizing processes of erosion, sediment storage, and deposition. A visual assessment can involve the use of channel evolution stage, the use of Lane's stream balance relationship (described in NEH654.1305(c)), and assessments of dominant channel processes. It is critical that experienced personnel conduct this effort. In all cases, the reasoning, judgment, and estimates that support the assessment should be clearly documented and discussed by the stakeholders.

(a) Assessments of channel processes and evolution

The existing shape or morphology of a stream is an indication of ongoing channel evolution processes and has long been recognized as a diagnostic tool in evaluating fluvial landforms. The appropriate channel evolution model can be applied to identify current stream condition, subsequent stages and direction of evolution, and the ultimate expected stable channel form that will evolve, as well as qualitatively estimate the time scale of channel recovery. An assessment of the existing channel evolution stage, as well as the stage that will exist with the proposed project, can be an aid in assessing channel responses. The channel evolution model (CEM) (fig. 13–1 (modified from Simon and Hupp 1986; Simon

Figure 13–1 Six-stage model of channel evolution



Class I. Sinuous, premodified
$h<h_c$

Class II. Channelized
$h<h_{cf}$

Class III. Degradation
$h<h_{cf}$

Class IV. Degradation and widening
$h>h_c$

Class V. Aggradation and widening
$h>h_c$

Class VI. Quasi-equilibrium
$h>h_c$

1989)) was developed by Schumn, Harvey and Watson (1981, 1984), and modified by Simon and Hupp (1986) and Simon (1989, 1994).

Using space-for-time substitution, the authors developed a conceptual model with reach types that are divided into the following six stages. In a space-for-time substitution, downstream conditions are interpreted as preceding (in time) the immediate location of interest, and upstream conditions are interpreted as following (in time) the immediate location of interest. A reach in the middle of the watershed that previously looked like the channel upstream will, therefore, evolve to look like the channel downstream.

- Stage 1 is a U-shaped channel. It has no sediment storage in the channel as would occur in a newly constructed channel. This stage has also been used to represent a sinuous, premodified, nonincised channel. One of the key features of this stage is the frequent access of the channel flows to the flood plain.
- Stage 2 is a modified or channelized stage. This has also been used to represent the relatively instantaneous change which initiates the following sequence of changes:
    - newly straightened or a steepened slope stage 1
    - reduction in sediment supply
    - increase in discharge
    - lowering of the tailwater
    - advancing headcut
- Stage 3 is a downcutting stage. Rapid degradation is occurring as the channel slope flattens in response to the perturbation imposed on the system in stage 2. A lowering of ground water and undermining of bridge piers may occur in this stage. Stage 3 evolves into stage 4 when the channel bank height exceeds the critical bank height and the banks begin to fail.
- A stage 4 channel is evidenced by a widening channel. The toes of the bank slopes are subject to lateral erosion and undercutting. Usually, both sides of the channel show erosion, not just the outer banks. Stage 4 evolves into stage 5 when the channel widens to a point where it is no longer able to transport the incoming supply of sediment and deposition begins to occur.
- Stage 5 is an aggrading channel. The overwidened channel cannot maintain the velocities necessary to move the sediment that is being supplied from the upper watershed.
- Stage 6 is the quasi-equilibrium stage. The toes of the banks are stabilized with accumulated sediment and vegetation. Alternate bars with perennial vegetation may be evident. Simon (1994) observed that the deposition will likely not be sufficient to return the channel to its preimpacted stage.

These evolutionary stages are linked to rates of sediment transport (Simon 1989), bank stability, sediment accretion, and ecologic recovery (Hupp 1992; Simon and Hupp 1992). The model has been widely used to rapidly identify dominant, systemwide channel processes in watersheds impacted by various human and natural disturbances. Identification of channel process and forms is often accomplished concurrent with the geomorphic assessment and site investigations conducted at the beginning of a project. The CEM was developed from streams responding to straightening and base-level lowering. Specific assessment techniques, including this model, are addressed further in NEH654.03.

While this channel evolution model has been applied in a variety of watersheds throughout the United States, it is most applicable in the Southeast, with its abundant precipitation and deep soils. The use of a channel evolution model may be supported by a study of the watershed and channel history, future land use and development patterns, and appropriate classification of the existing and proposed stream.

(b) Regional hydraulic geometry relationships

Regional hydraulic geometry relationships may also be useful in performing a visual geomorphic assessment. Morphological measurements of width, cross-sectional area, and depth at the project site can be compared to regionally developed relationships or equations and their associated bands of uncertainty. This comparison can provide semiquantitative information on channel stability and sensitivity to change. However, this method only provides an indication of stability, because data points that lie far from the best-fit regression line could be influenced by other factors that are not common to the rest of the data set such as reach history, land use, or vegetation. Be aware that while observations and hydraulic geometry relations may be used to identify possible stability problems, analytical methods are often required to determine the magnitude of an identified stability problem. More information on the use and limitations of regional hydraulic geometry is provided in NEH654.03 and NEH654.09.

(c) Lane's alluvial channel balance relationship

Lane's balance or Lane's relationship is a qualitative conceptual model that can be used as an aid to visually assess stream responses to changes in flow, slope, and sediment. The model is based on the general theory that if force applied by the flowing water on an alluvial channel boundary is balanced with strength of the channel boundary and the delivered sediment load, the channel will be stable and neither aggrade nor degrade. This equilibrium condition in the channel can be expressed as a balance of four basic factors (Lane 1955b):

- sediment discharge, Q_s
- median grain size of bed material, D_{50}
- dominant discharge or streamflow, Q_w
- thalweg slope or energy slope, S

This balance can be expressed in the proportional relationship (eq. 13–1) or figuratively (fig. 13–2).

$$(Q_s)(D_{50})\alpha(Q_w)(S) \qquad \text{(eq. 13–1)}$$

Lane's relationship suggests that a stream will remain in equilibrium as along as these four variables are kept in balance. If one variable changes significantly, the stream will respond by aggrading or degrading, and another variable must adjust to restore balance. For example, a decrease in discharge could result in aggradation (as may occur downstream of a flood control dam or due to flow diversion). In contrast, a straightening of a stable channel (which would increase slope) may result in degradation. The increased slope of a straightened channel creates a disequilibrium condition where an increased sediment supply or a larger particle size is needed. Therefore, erosion of the streambed and streambanks will return the reach to an equilibrium condition. Since sediment yield varies over a long time in establishing the equilibrium condition, Lane's (1955a) conceptual relationship fits the concept of dynamic equilibrium established by Schumm (1977) and is, therefore, applicable to most streams and rivers.

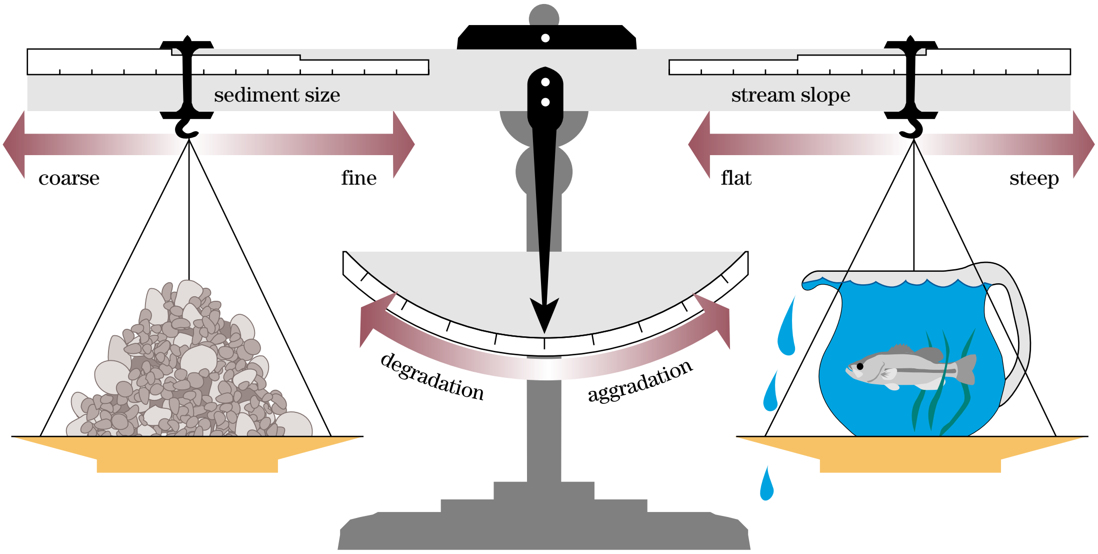
A limitation of this conceptual model is that it does not indicate which variable will adjust, the magnitude of the adjustment, or the timeframe that will be involved. While it may be used to identify possible stability problems, analytical methods are often required to predict, in quantifiable terms, their magnitude. In addition, even while in balance, the stream is free to migrate laterally, maintaining its cross-sectional area. This lateral movement may be unacceptable due to land use or boundary constraints. More detail on Lane's relationship, as well as other qualitative relationships is provided in NEH654.03 and also available in Stream Corridor Restoration: Principles, Processes and Practices (FISRWG 1998).

(d) Assessments of dominant channel processes

Dominant channel processes are the forces at work in the watershed that cause and limit channel change. They are the causal factors, direct and indirect, and controls likely to be present in the study watershed and at a study site. An understanding of these dominant channel forces or processes can assist the designer with the prediction of the proposed project's impact on channel morphology, ecology, and stability. The assessment and evaluation of dominant channel and watershed processes is often accomplished early in the planning and design stages as part of data collection. NEH654.03 addresses this in detail. However, the assessment of dominant processes should be revisited as the project is finalized, to ensure that the design fits the context of the watershed and is consistent with the sediment impact assessment.

Of particular interest should be the characterization of sediment sources based on their relative contribution to the project reach's bed load, suspended load, and wash load. The with-project conditions should be assessed within the context of this overall sediment balance. The designer should focus on significant sediment sources and sinks within the study reach and how they may be affected by the proposed project. The broad elements that should be examined are:

Figure 13–2 Lane's balance as represented in Federal Interagency Stream Restoration Working Group (FISRWG) (1998)



$$Q_s \bullet D_{50} \propto Q_w \bullet S$$

From Rosgen (1996), from Lane, Proceedings, 1955.
Published with the permission of American Society of Civil Engineers.

- spatial and temporal patterns of watershed sediment production
- sediment storage within the channel and in adjacent tributaries
- patterns and behavior of sediment movement through the system
- rates of sediment transport
- sediment deposition rates on the flood plain
- changes in sediment load due to changes in watershed land use

Much of the assessment of dominant processes can be accomplished by an examination and review of geological information, local historical accounts, historical thalweg and cross-sectional information, gage data, Federal Emergency Management Agency (FEMA) maps, biological monitoring, hydrologic modeling, and watershed development and land use patterns. Aerial photographs, maps, and old reports can also be useful in this assessment. Recent gage data can be analyzed and reviewed to determine if current conditions might be the result of a recent extreme event, rather than long-term and systemic instabilities.

Historical analysis can provide meaningful information. Well-documented stream history may provide a reasonably accurate assessment of future stream trends: will it aggrade or degrade? Historical data can be used to identify trends, provide information on rates of landform change in the watershed, and help determine land use impacts on current conditions. These effects can be due to watershed development that has altered streamflows, stream morphology, and sediment yields. Effects could have occurred gradually over a long period of time, such as changes in land use, population, or agricultural crops and farming practices. Streams in these watersheds may be adjusting naturally to an aggraded condition by slowly downcutting. Landslides and gravel nourishment, as well as gravel mining activities, can also have short-term, but profound impacts on reach dynamics and project performance. Finally, geologic aspects of the watershed should be considered. For example, as streams and rivers migrate laterally within their valleys in glaciated regions, they can encounter glacial till and coarse-grained glacial outwash, altering sediment loads and sediment particle sizes. A slug of sediment that enters the stream and moves downstream in pulses during high runoff is also common along streams where sediment load is dominated by landslides and debris flow torrents.

Onsite field assessments are needed to augment analysis and existing information sources. Observe conditions in tributaries and abandoned channels in the project reach, and identify indications of channel behavior and geomorphic conditions. Anthropogenic features, such as bridge abutments and piers, grade control structures, low-flow crossings, and bank protection can also provide an indication of possible channel responses to the project. Finally, determine whether the channel bed is aggrading, degrading, or stable.

Evidence of degradation will be different, depending on the project's location within a watershed, whether it is in the upland, middle, or lowland zone. Some field indicators of river stability/instability are given in table 13–1 (modified after Sear and Newson 1994) for each of these zones in a watershed. These are not absolutes, and exceptions and additions will be encountered.

While an assessment of the dominant processes and the application of engineering judgment are valuable and necessary for any design, the limitations of what is essentially a qualitative approach must be recognized. Issues that should be considered in weighing the impact of these assessments include observer experience and bias, temporal limitations, and spatial limitations. Issues related to observer bias can be partially overcome with the consistent use of trained personnel and consistent inventory procedures. This will minimize relative differences between observations. Temporal bias can be minimized with an examination of historical records, but these may be incomplete. While an assessment of the dominant processes may be used to identify possible stability problems, analytical methods are often required to determine the magnitude and direction of change in the instability.

Table 13–1 Field indicators of river stability/instability

	Location within watershed		
Condition	**Upland**	**Middle**	**Lowland**
Degradation	• Perched boulder berms • Terraces • Old channels • Old slope failures • Exposed pipe crossings • Suspended culvert outfalls and ditches • Undercut bridge piers • Exposed or 'air' tree roots • Leaning trees • Narrow/deep channel • Bank failures, both banks armored/ compacted bed • Deep gravel exposure in banks that are topped with fines	• Terraces • Old channels • Exposed pipe crossings • Suspended culvert outfalls and ditches • Undercut bridge piers • Exposed or 'air' tree roots • Leaning trees • Bank failures, both banks • Vertical banks • Compacted/compacted bed • Deep gravel exposure in banks that are topped with fines • Undercut stone and concrete walls • Abandoned streambeds that appear to be a deposition bar	• Old channels • Exposed pipe crossings • Suspended culvert outfalls and ditches • Undercut bridge piers • Exposed or 'air' tree roots • Leaning trees • Narrow/deep channel • Vertical banks • Bank failures, both banks • Deep gravel exposure in banks that are topped with fines • Undercut stone and concrete walls • Abandoned streambeds that appear to be a deposition bar
Aggradation	• Buried structures such as culverts and outfalls • Buried soils • Large uncompacted point bars • Eroding banks at shallows • Contracting or reduced bridge space • Deep, fine sediment over coarse gravels in bank • Many unvegetated point bars • Outlet of tributaries buried in sediment • Rills or remnant channels in riparian areas	• Buried structures such as culverts and outfalls • Buried soils • Large uncompacted point bars • Eroding banks at shallows • Contracting or reduced bridge space • Deep, fine sediment over coarse gravels in bank • Many unvegetated point bars • Angular bed material in an environment where rounded is expected • Outlet of tributaries buried in sediment • Rills or remnant channels in riparian areas	• Buried structures such as culverts and outfalls • Buried soils • Large silt/clay banks • Eroding banks at shallows • Contracting or reduced bridge space • Deep, fine sediment over coarse gravels in bank • Many unvegetated point bars • Angular bed material in an environment where rounded is expected • Outlet of tributaries buried in sediment • Rills or remnant channels in riparian areas
Stability	• Vegetated bars and banks • Compacted weed covered bed • Bank erosion rare • Old structures in position • Armoring of sediment • Older culverts and outfalls exiting at or near grade • Mouth of tributaries at or near existing main stem stream grade • Vegetated banks • Roots of large trees anchored in soil • Evidence of frequent overbank flows • Algae growth on substrate	• Vegetated bars and banks • Compacted weed covered bed • Bank erosion rare • Old structures in position • Older culverts and outfalls exiting at or near grade • Armoring of sediment • Mouth of tributaries at or near existing main stem stream grade • Vegetated banks • Roots of large trees anchored in soil • Evidence of frequent overbank flows • Algae growth on substrate	• Vegetated bars and banks • Weed covered bed • Bank erosion rare • Old structures in position • Older culverts and outfalls exiting at or near grade • Armoring of sediment • Mouth of tributaries at or near existing main stem stream grade • Vegetated banks • Roots of large trees anchored in soil • Evidence of frequent overbank flows • Algae growth on substrate

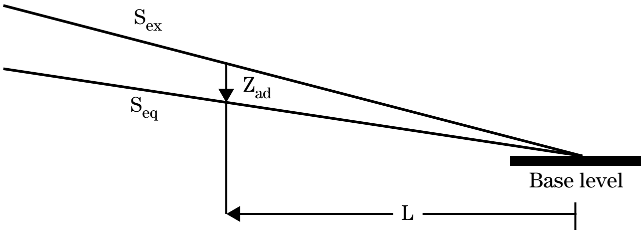
654.1306 Equilibrium slope calculations

Equilibrium or stable slope calculations are often used to support or refine visual assessments. The calculation of a stable or equilibrium slope may also serve as a form of sediment impact assessment, as well as being an integral part of the restoration design.

The equilibrium slope of a channel is defined as the slope at which the sediment transport capacity of the reach is in balance with the sediment transported into it. If the sediment transport capacity were to exceed the sediment supply, channel bed degradation will occur until the channel bed slope is reduced to the extent that the boundary shear stress is less than what is needed to mobilize the bed material. This new, lower slope is the equilibrium slope, S_{eq}. Possible causes of the sediment transport capacity exceeding sediment supply could include an upstream reduction in sediment yield (such as in a stream reach below a dam), an increase in sediment transport capacity during high discharges, or construction of a straight channel, resulting in increased stream gradient. This lowered, degraded bed may result in undermining or collapse of riparian structures or bank instability.

Equilibrium slope calculations are typically used for threshold streams. In the context of a sediment impact assessment, they are applied to a range of design flows. As illustrated in figure 13–3, slope adjustment in a threshold reach occurs by degradation proceeding from the upstream end to the downstream, and the downstream extent of degradation is often limited by a base level control. The z_{ad} is often referred to as the general scour depth.

Figure 13–3 Definition of equilibrium slope, S_{eq}. Relationship between existing slope, S_{ex}, equilibrium slope and the potential bed reduction, z_{ad}, for a reach of length L with base-level control



A variety of techniques can be used to calculate the limiting or equilibrium slope. One approach that is suitable for gravel-bed streams is the Meyer-Peter and Müller bed load transport equation, rearranged as follows:

$$S_L = \frac{K_1 \times D_{50} \times \left(\frac{n}{D_{90}^{\frac{1}{6}}} \right)^{\frac{3}{2}}}{d} \qquad \text{(eq. 13–2)}$$

where:
S_L = limiting slope
n = Manning's n
K_1 = conversion constant
D_S = particle size
d = flow depth

Similar equations, based on range in sediment particle size application, should be applied for other channel types. Note that the calculated equilibrium bed slope may be limited by resistant layers in the bed (such as bedrock) or by the formation of an armor layer. The overall depth of scour required to leave a stable armor layer can be assessed with the following equation:

$$\Delta Z = \frac{2 \times D_a}{P_c} \qquad \text{(eq. 13–3)}$$

where:
ΔZ = scour depth
D_a = size of armoring material (threshold grain size for incipient motion)
P_c = percent of material coarser than armoring size

The threshold particle size for incipient motion, the largest particle that can be lifted and transported by the flow, can be calculated as follows:

$$D_a = \frac{\tau_c}{0.047(\gamma_s - \gamma)} \qquad \text{(eq. 13–4)}$$

where:
D_a = particle size
τ_c = grain resistance boundary shear stress ($\frac{1}{8} f \rho \upsilon^2$)
γ_s = 165.4 lb/ft^3
f = friction factor ($= 8\frac{g}{C^2}$)
C = $\frac{1.49}{n} R^{\frac{1}{6}}$
R = hydraulic radius
ρ = 1. 94 slugs
υ = velocity (designer should account for bends)
n = near-field Manning's n (0. 025)

The assessment of this potential degradation for different flow levels is often used to determine the appropriate spacing and size of grade control structures. Further information about these analytical techniques and equations is provided in NEH654.08 and in NEH654 TS14C.

654.1307 Sediment rating curve analysis

The sediment rating curve analysis is a relatively simple technique that can be used to assess the sediment transport characteristics of an existing or proposed stream project. The approach is to use sediment rating curves to compare the sediment transport capacity of the supply reach to the existing and proposed project reach conditions. This approach relies on the technique of analogy. If the existing channel is stable, then sediment transport capacity in the project channel may be compared to that in the existing channel. If the supply reach is not fully alluvial, a carefully chosen reference reach may be used as a surrogate for the supply reach. This analysis is suitable for streams where the sediment supply is not limited in either the upstream (supply) or project reaches; that is, where the stream is certainly alluvial in nature. It is generally not suitable for threshold streams.

This qualitative technique does not require stream gage data or sediment gage data. It does require an estimate of the sediment grain size distribution from the supply reach, an estimated range of peak flows, and a description of hydraulic characteristics of both the study and supply reaches. By comparing the sediment rating curves of the two reaches, an estimate can be made of the sediment transport capacity of the study reach, relative to the capacity of the sediment supply reach. The basic steps are:

Step 1 Collect hydraulic information for the upstream, existing, and proposed project reaches. Hydraulic information can come from normal depth calculations, hydraulic modeling (such as the U.S. Army Corps of Engineers (USACE) HEC–RAS) based on new surveys, or with the use of existing flood plain information, such FEMA's flood plain maps.

Step 2 Collect sediment gradation for upstream, existing, and proposed project reaches. Guidance for sediment sampling is provided in NEH654 TS13A.

Step 3 Estimate a range of peak flows for the project reach. Peak flows can be estimated using regional regression curves or hydrologic modeling.

Step 4 Calculate sediment transport capacity for the range of peak flows in the upstream, existing, and proposed reaches. Information useful for the selection of appropriate sediment transport relationships is provided in NEH654.09.

Step 5 Create a sediment rating curve for the upstream, existing, and proposed reaches.

Step 6 Compare the sediment rating curves for these conditions to assess project performance.

By comparing the sediment rating curves of the two reaches, an estimate can be made of the sediment transport capacity, relative to the capacity of the sediment supply (fig. 13–4).

The comparison of the two sediment rating curves shown in figure 13–4 indicates that there is a strong possibility that the existing study reach is depositional for flows above Q_1. The proposed project conditions can be assessed in a similar manner as illustrated in figure 13–5.

A comparison of the two sediment rating curves in figure 13–5 indicates that the project reach should be able to transport the incoming sediment load through a discharge of Q_2. Above this discharge, deposition is possible, for example, at Q_3. These discharges can be compared to the peak discharges of estimated storm frequencies to provide a qualitative estimate of project life. This estimated condition should be checked by field observations to detect evidence of an aggradational trend, as well as the assessment of dominant channel processes. To improve channel stability, the sediment rating curve for the project channel should be as close as possible to the sediment rating curve for the supply reach.

Since there is no calibration of gage data or use of flow-duration data, the actual quantity of sediment deposition cannot be estimated. In addition, this approach does not account for changes in sediment transport capacity that may occur as sediment is deposited in the section and changes its geometry. However, this technique does provide the designer with a qualitative appraisal of anticipated project performance.

Figure 13–4 Sediment rating curve analysis for existing conditions

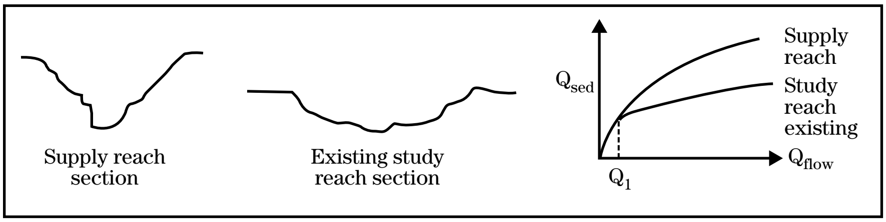
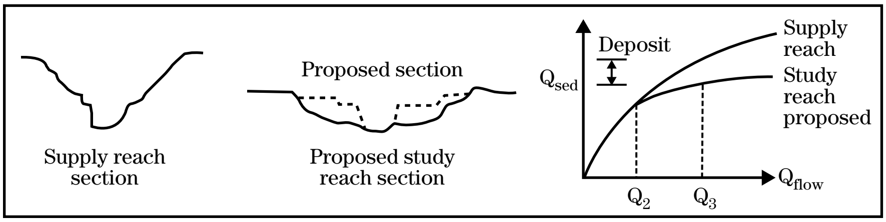


Figure 13–5 Sediment rating curve analysis for proposed conditions



654.1308 Sediment budget analysis

A sediment budget analysis is a quantitative assessment of channel stability using the magnitude and frequency of all sediment-transporting flows. A sediment budget analysis should be conducted for all realigned and constructed alluvial channels, after preliminary dimensions are determined, using the channel-forming discharge. Slight adjustments to the design may be required, after which another sediment budget analysis is conducted.

The stream's sediment budget is estimated by comparing the mean annual sediment load for the project channel with that of the supply reach(es). The mean annual sediment load from each reach is calculated by numerically integrating the annual flow-duration curve with a bed-material sediment rating curve. While the sediment load is typically calculated for annual conditions, it may also be assessed for a flow event of interest, depending on project conditions and purposes. If more sediment comes into the project area than can be passed, the excess will likely be deposited in the reach. If more sediment can be transported than what is coming into the reach, then erosion or degradation can be anticipated.

The following steps are recommended for conducting a sediment budget analysis.

Step 1 Assemble information about the stream. Collect data from the supply reach(es) upstream, the project reach, and downstream from the project reach. This includes geometric, sediment, and hydrologic information. Much of this information may have been collected during initial assessments and data collection. It may be necessary to construct flow-duration curves from 15-minute data (rather than daily) in areas where a large amount of sediment transport can occur during storms of duration much less than 24 hours. All sediment sources should be quantified, especially nonalluvial sources such as mass failures, landslides, debris flows, and soil creep. Additionally, the rates and volumes of sediment stored in the landscape should be estimated including in the channel, in wetlands, in lakes and ponds, on the flood plain, and on alluvial fans.

Step 2 Calculate hydraulic parameters for a typical or average reach for a range of discharges. This range should extend from the average annual low flow to the peak of the design flood. Average hydraulic parameters can be determined from normal depth calculations for a typical cross-sectional geometry, or from a backwater computer program such as HEC–RAS.

Step 3 Select an appropriate sediment transport function for the study reach. This can be achieved by comparing calculated sediment transport to measured data, taking care to ensure that bed-material load is being compared. When no data are available, one may rely on experience with similar streams in the region. Data ranges used in the development of various sediment transport functions are provided in NEH654.09. A review of this information may serve as guidance in selecting the appropriate function. However, if there are no available data for calibration, this analysis becomes more qualitative in nature.

Step 4 Calculate sediment transport rating curves. Apply calculated hydraulic parameters to the selected sediment transport functions for a range of flows. Curves should be developed for the existing channel in the assessment reach, upstream of the assessment reach (the supply reach), and downstream. Sediment transport rating curves should also be determined for any tributaries that might be affected by the assessment reach.

Step 5 Calculate sediment yield. Sediment yield should be calculated using the flow-duration sediment discharge rating curve method for the supply reach, assessment reach, and downstream reach. Use a flow-duration curve to obtain average annual sediment yield and a flood hydrograph to obtain sediment yield during a flood event. The calculation of average annual sediment yield is typically accomplished with the flow-duration sediment discharge method (USACE 1995a). This method requires sufficient gage data to develop the flow-duration curve and requires either measured bed-material load data or calculation of a sediment discharge rating curve, using an appropriate sediment transport relationship.

Often, sufficient gage data are not available to calculate a flow-duration curve for the project reach. If so, two approaches can be used to compute average annual sediment yield. The first is to synthesize a flow-duration curve using either the drainage area flow-duration curve method or the regionalized duration method (Biedenharn et al. 2000). Then use standard methods to compute sediment yield.

If information is available for calibration, this technique can be used to estimate the actual quantity of deposition. Even without calibration information, this technique can provide relative comparisons of stability for various alternatives. Note that this approach typically uses average reach conditions. It does not account for changes in sediment transport capacity that may occur as sediment is deposited in the section and changes its geometry. The level of confidence that can be assigned to the sediment budget approach is a function of the reliability of the available data about the stream and the project. Specific techniques are addressed in more detail in NEH654 TS13A and TS13B, Thomas et al. (1994), and EM 1110–2–4000 (USACE 1995a).

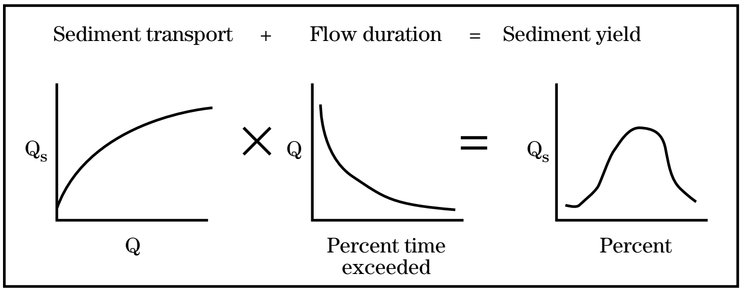
Step 6 Calculate trap efficiency by comparing the supply reach and assessment reach sediment yields. A positive trap efficiency indicates deposition and a negative value indicates erosion. If the assessment reach is stable, the trap efficiency is near zero.

An example sediment budget analysis conducted as part of the reconnaissance level planning study for a flood damage reduction project is provided in NEH654 TS13B.

654.1309 Computer models

Sediment budget analysis is typically accomplished using a computer program such as the USACE SAM or HEC–RAS program. However, a sediment budget can be analyzed with a spreadsheet program, as well. Where bed-material sediment transport is significant and highly variable, it may be necessary to use a numerical model that incorporates solution of the sediment continuity equation. Most computer models involve integrating a sediment transport function to a flow-duration relationship to estimate sediment yield —either by event, annually, or for multiple years (fig. 13–6).

Figure 13–6 Sediment budget



654.1310 Nonequilibrium sediment transport

A sediment impact assessment should include a nonequilibrium sediment transport model for high risk or high cost projects. River systems are governed by complicated dependency relationships, where changing one significant geometric feature or boundary condition affects other geometric features and flow characteristics, both temporally and spatially. Changes at any given location in a stream system are directly related to the inflow of sediment from upstream.

HEC–6 (USACE 1993c) is a one-dimensional, moveable boundary, open channel flow numerical model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods (typically years, although applications to single flood events are possible). This model simulates the sediment transport capacity of a reach by mathematically modeling the interaction between the sediment inflow and the hydraulic properties of the reach. In this model, a continuous discharge record is partitioned into a series of steady flows of variable discharge and duration. For each discharge, a water surface profile is calculated, providing energy slope, velocity, depth, and other variables at each cross section. Potential sediment transport rates are then computed at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each reach. The amount of scour or deposition at each section is then computed, and the cross-sectional geometry is adjusted for the changing sediment volume. Computations then proceed to the next flow in the sequence, and the cycle is repeated using the updated cross-sectional geometry. Sediment calculations are performed by grain-size fractions, allowing the simulation of hydraulic sorting and armoring.

HEC–6 is a powerful tool that allows the designer to estimate long-term response of the channel to a predicted series of water and sediment inflows. The use of a complex program such as HEC–6 involves a significant investment of engineering skill and time. The time required to perform a HEC–6 analysis can be upwards of 10 times that of the USACE SAM type analysis (Fripp, Webb, and Bhamidipaty 1996). However, it is often more advantageous to invest in this effort than to deal with the consequences of project failure. The critical decision to use a numerical model should be based on whether significant changes are expected to occur in the system as a result of the proposed design work.

The primary limitation of HEC–6 is that it is one-dimensional; that is, geometry is adjusted only in the vertical direction, and average hydraulic parameters are assumed in the computations. Changes in channel width or planform cannot be simulated. This analysis is typically based on one-dimensional, steady-flow models, while natural flows are three-dimensional and unsteady. In most cases, the three-dimensional effects of meander bends are accounted for with empirical geomorphic approaches and professional judgment (Copeland et al. 2001). For more complete information on details regarding the assumptions and limitations of specific models, the original documentation associated with each of them should be reviewed.

Finally, while a computer model such as USACE SAM or HEC–6 might provide a more precise answer, there is no reason to suppose that it gives a more certain answer. Computed answers might be highly precise, but are tied to original assumptions, which may not be accurate. Complicated models do not necessarily provide more accurate answers by themselves. If too little information is available as input to the models and no verification data are collected, it is unlikely that a detailed model will provide a more accurate answer than a simpler model. In all cases, field measurements and local experience should be used to complement the use of computer models.

654.1311 Choosing the appropriate technique

The choice of the appropriate technique to estimate the sediment impact of a proposed project includes not only an assessment of the project goals and watershed condition, but also the potential impacts of project failure. Visual and qualitative assessments are appropriate for sites where there is low risk and minimal change to an otherwise stable system. These can be accomplished with the aid of primarily judgment-based tools. As a project becomes more complex, and where there is a higher risk to life and property, more analytical approaches are used. Many analytical techniques are available that typically require the calculation of hydraulic parameters for the range of natural discharges, such as velocity and shear stress. All of these techniques require data determined from field observations and measurements, as well as calculations. Table 13–2 illustrates typical assessment techniques for estimating the impacts of sediment on different project types and watershed conditions.

As the risk and uncertainty increase, the use of more detailed models is recommended. Table 13–2 shows increasing complexity, from Lane's stream balance approach, to USACE SAM, to HEC–6. However, the use of increasingly complicated models is not necessarily recommended. On its own, a more complicated analysis will not necessarily be sufficient or more accurate. Any model is dependent on the skill and experience of the practitioner, as well as the input data. Engineering judgment becomes more critical with increasing risk, and the required field work and data collection become more labor intensive. Therefore, the suitable assessment column should be regarded as a cumulative recommendation that increases with increasing risk.

Since each stream system and project is unique, practitioners should review the assumptions and data requirements and consider their own experiences when determining the appropriate technique to use.

Table 13–2 Selection guidance for sediment impact assessment technique

Project type	Site/watershed assessment	Risk to life, property, or project investment	Suitable sediment impact assessment
Bank stabilization No significant change to cross section, slope, or planform	Relatively stable watershed and site	Low	Confirm that there is no significant change in the local hydraulic conditions from pre- to post project and note watershed stability
Bank stabilization No significant change to cross section, slope, or planform	Moderately active watershed and site	Moderate	Assess stable channel grade at design flows. Field check indications of future channel evolutionary change
Bank stabilization No significant change to cross section, slope, or planform	Moderately active watershed and site	High	Rating curve comparison of above and through site
Channel modification Small change to cross section, slope, or planform	Moderately active watershed and site	Low	Rating curve comparison of above and through site, as well as pre- and post project
Channel modification Significant change to cross section, slope, or planform	Moderately active watershed and site	Moderate	Sediment budget analysis with USACE SAM* type analysis
Channel modification Significant change to cross section, slope, or planform	Active watershed and site	High	Long-term numerical modeling with HEC–6* type analysis

* SAM and HEC–6 are now incorporated into HEC–RAS.

654.1312 Conclusion

It is strongly recommended that a sediment budget analysis be conducted for all projects that will involve a significant change to the existing stream channel. Sediment impact assessments can range widely in effort and output, but assess the stability of the project based on conditions of flow, coupled with sediment yield and transport. Visual or qualitative techniques may be used for relatively simple projects, analytical techniques for more complex projects. While no model or assessment eliminates all possibility of a project not performing as intended, the use of the appropriate tool as described in this chapter reduces the possibility of poor project performance.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654 Stream Restoration Design National Engineering Handbook

Chapter 14 Treatment Technique Design

Issued August 2007

Cover photos: *Top*—Treatment techniques for streambank stabilization and stream restoration require specific design tools. Management and removal of disturbance factors should be balanced with structural approaches.

Bottom—Treatments range from simple to complex. Design tools assist the user in properly installing a treatment.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 14 Treatment Technique Design

Contents

Tables

Chapter 14 Treatment Technique Design

654.1400 Purpose

Stream design and restoration often include specific treatments in the riparian area, on the bank, and in the bed of a stream. Treatments can include techniques that provide ecological enhancement, as well as protection of these areas. This chapter provides an overview of some of the frequently used treatment techniques for bank protection, grade protection, and habitat enhancement using a wide range of plant materials, earth materials, and other inert materials. In addition, analysis techniques that are needed for successful designs are provided. This chapter contains a brief overview of each analysis approach or treatment technique. Refer to the section in the listing of technical supplements for performance criteria, specific analysis, and design guidelines for each technique. Where information is available, the benefits, flexibility, risk, and cost of each technique are presented from a physical, as well as an ecological perspective.

The reader should not interpret the listed techniques as an endorsement of any particular product mentioned and should not infer that one treatment or approach is superior to another. The list of approaches is not exhaustive. There are other techniques, as well as variants of each of those described, that may be appropriate and applicable. Finally, while this chapter provides techniques that focus on the treatment of local problems, the use of several of these techniques, as well as other design elements, often can provide a more holistic approach to complex restoration projects.

654.1401 Introduction

A wide variety of analysis techniques can be applied to channel design and stream restoration. The selection and design of the different techniques depends upon the project goals, watershed conditions, and consequences of failure. All techniques contain some inherent flexibility and inherent risk. The tolerance for risk by the landowner and the public must be considered as the designer selects not only the technique to use but also the level of design analysis to apply. Finally, a selection of an appropriate treatment technique and level of analysis must consider cost. Cost effectiveness includes both the initial project costs, as well as operation, maintenance, and replacement costs. Much of the information presented in NEH654.02 and NEH654.04 should be reviewed and be included in these important decisions.

The design and restoration of a stream often requires the application of a combination of technologies. Techniques that are part of a traditional engineering approach can be altered or enhanced to provide habitat benefits. Many of the treatment techniques described herein are used in conjunction with other techniques to achieve project goals. For example, systems composed of living plant materials are often used in association with inert materials such as wood or rock, as well as manufactured products. In addition, the use of several design analysis techniques may be required for the successful application of a single treatment technique. Information on the reach and watershed that was assessed and calculated, as described in earlier chapters, may provide the required input for the designs and assessments.

Many of the treatment techniques described have been implemented by themselves to address small, local issues. This approach has sometimes been unjustly referred to as applying a band-aid solution. However, the band-aid approach may be completely justifiable in a scenario where there is only localized instability. It only becomes a band-aid when there is an attempt to address systemwide instability with a localized solution.

Some of the techniques described are sequential. For example, the installation of habitat features on an unstable stream must be done after the stream has been stabilized. Techniques such as the channel evolution model, addressed in NEH654.03 and NEH654.13, may be useful in making this assessment.

Some of the treatments described in this chapter should be implemented concurrently. For example, while it is often simpler to plant vegetation into a conventional bank protection project after construction, better results are achieved if the vegetation is incorporated directly into the treatment during construction. To adequately do so, provisions for vegetating should be addressed during the planning and design stages of the project.

654.1402 Design analysis

Design analysis, using sound physical principles and well-established engineering formulae, are used in the implementation of both soft and hard treatments. This section contains some of the techniques that have broad applicability to many treatment approaches described in this chapter.

The level of design analysis needed to employ these treatment techniques depends on both the treatment technique employed, as well as site conditions. The level of analysis should also match the cost of the project under consideration and level of risk associated with the project.

(a) Do Nothing option

The Do Nothing option is also sometimes referred to as the No Action alternative. This option is placed as the first entry under the design analysis section of this chapter to emphasize the importance of this consideration. It is covered briefly, but it is an important analysis. While it may seem self-evident that the planners and designers have discarded the Do Nothing approach if treatment options are being investigated, it is strongly suggested that this decision be continually revisited. This is also known as the Future, Without-action alternative, since the primary objective is to describe not only the problems as they exist today but also to predict a direction or magnitude of change in conditions. Natural stabilization may be occurring, but not quick enough to satisfy goals and objectives. Conversely, problems may be accelerating or affecting more area in the future, which brings the need for development of other restoration alternatives into focus.

Any treatment approach carries with it some level of both known and potential impact. These impacts can be both ecological and physical. Impacts that should be considered include:

- how the treatment interacts with the local environment
- how the treatment may alter, accelerate, or limit natural processes on a reach or watershed scale

- how the treatment may affect the social dynamics on a local or watershed scale
- alteration to the natural environment that is required for the construction of the treatment
- aesthetics—how the treatment interacts with the visual scene
- scale of impact on a temporal basis—is the cost of treatment justified based on sustainability of impact over time

These potential impacts should be weighed against the intended benefits of the treatment. These assessments often require a strong and well-coordinated interdisciplinary approach.

The Do Nothing option should constantly remain as a possibility. The resources, both physical and ecological, that may be lost by not implementing the project must be weighed against the impacts and costs of the project. By continually assessing this option, the designer can gain confidence that the selected design is appropriate and needed.

(b) Soil properties and special geotechnical problems related to stream stabilization projects

Many channel bank stability problems have a sizable geotechnical component. Although streambanks may be protected from erosive forces of flowing water, forces acting on soils in the bank can induce slope failures. Problems that are geotechnical in nature require a solution that is geotechnically based.

Analyzing bank slopes for geotechnical stability requires an understanding of a complex system of forces. The forces involved in bank instability problems include:

- gravity acting on the soils in the slope
- internal resistance of soils in the slope
- seepage forces in the soils in the slope
- tractive stresses imposed on the soils by flowing water

Knowledge of the site-specific soil characteristics and strength properties is required to understand, predict performance, and design stream restorations and stabilization. Soil characteristics and shear strength parameters are required for various stream stabilization techniques such as bank sloping, retaining wall design, sheet pile design, and pile foundation design.

NEH654 TS14A contains a descriptions of soil characteristics and special geotechnical problems, with a particular focus on bank protection. Guidance on recognizing these problems in the field is presented, along with a description of typical measures for solving them. A particular focus of NEH654 TS14A includes:

- stabilizing very steep slopes caused by erosion at the toe of the slope
- piping/sapping of streambanks, together with sloughing of saturated zones of sands and silts with low clay content
- shallow slope failures in blocky-structured, highly plastic clays
- severe erosion on dispersive clays

(c) Scour calculation

Scour is one of the major causes of failure for stream and river projects. It is important to adequately assess and predict scour in the course of any stream or river design. Designers of treatments such as barbs, revetments, or weirs that are placed on or adjacent to streambeds must estimate the probable maximum scour during the design life of the structure to ensure that the structure will either adjust to or account for this potential change. NEH654 TS14B provides guidance useful in performing scour depth computations.

Although the term scour includes both bed and bank erosion, the emphasis in NEH654 TS14B is on erosion that acts mainly downward or vertically such as bed erosion at the toe of a revetment or adjacent to a bank barb. Scour can be classified as one of three types, as shown in table 14–1.

A treatment may experience one or combinations of these scour types.

Many Federal and state agencies, as well as academic institutions, have developed methods and approaches for estimating these types of scour, and several of those techniques are briefly described in

NEH654 TS14B. Each of these techniques is developed for different types of conditions. The successful use of these techniques requires an understanding of both their inherent limitations, as well as their advantages.

(d) Stone sizing criteria

Many channel protection techniques involve rock or stone as a stand-alone treatment or as a component of an integrated system. Rock is often used where long-term durability is needed, velocities are high, periods of inundation are long, and there is a significant threat to life and property. NEH654 TS14C contains information useful in determining the required particle size to resist fluvial forces, regardless of the application of the stone.

The design of stone or riprap requires engineering analysis. Stone sizing should be approached with care because rock treatments can be expensive and can give a false sense of security if not applied appropriately. Since stone sizing methods are normally developed for a specific application, care should be exercised matching the selected method with the intended use. For example, a design technique developed for conventional riprap revetment may contain inherent assumptions that limit its applicability to a stone barb. The forces that are acting on the barb may be outside the range that were considered for the revetment and may lead to the barb being damaged during less than design flows.

Table 14–1 Scour types

Type of scour	Definition
General	Commonly affects the entire channel cross section, but general scour may affect one side or reach more than another
Bedform	Usually found in sand-bed streams, this is the troughs between crests of bedforms
Local	Commonly affects the streambed immediately adjacent to some obstruction to flow

Many Federal and state agencies have developed methods and approaches for sizing riprap, and several of those techniques are briefly described in NEH654 TS14C. NEH654 TS14C also describes some of the typical applications of both integrated systems and stand alone riprap treatments.

(e) Use of geosynthetics in stream restoration and stabilization projects

A variety of geosynthetic materials may be used for various function and applications in stream restoration and stabilization projects. A geosynthetic is defined as a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering-related material as part of a manmade project structure or system (American Society for Testing and Materials International (ASTM D4439). Geosynthetics used in stream restoration and stabilization include geotextiles, geogrids, geonets, geocells, and rolled erosion control products. NEH654 TS14D addresses the design of these products.

(f) Use and design of soil anchors

Many treatments do not rely solely on their weight or positioning for their stability. Some external anchoring is needed to resist the fluvial forces of the stream or river. If the treatment relies on an anchor for stability, proper design and installation is essential for project success. NEH654 TS14E covers three of the more common anchoring methods that are in use.

- driven soil anchors
- screw-in soil anchors
- cabling to boulders

These approaches have been used on structures such as rootwads, large woody debris structures, and brush barbs. Depending on the site conditions and design of the treatment, these methods may provide either temporary or permanent anchoring.

The focus of NEH654 TS14E is primarily on driven soil anchors. It provides guidance for estimating the pull-out capacity required of the anchor, given expected streamflows, soil characteristics, and the nature of the object that is to be anchored. Installation guidance is also provided.

(g) Pile foundations

Piles are also used to transfer foundation forces through relatively weak soil to stronger strata to minimize settlement and provide strength. The most likely applications for pile foundations in stream restoration and stabilization projects are as support for bank stabilization (retaining wall) structures and as anchors for large woody material. Piles may be used to support ancillary structures such as culverts, structural channels, bridges, and pumping station structures. NEH654 TS14F addresses the design and analysis required for pile foundation design. Installation issues are also addressed.

654.1403 Treatment techniques

Treatment techniques address a variety of stream stabilization and habitat enhancement techniques. While these treatments are addressed in separate sections, environmentally sensitive stream design will often require combining techniques. There are well-established techniques that are not listed here, including variants of some of the ones that are addressed. Depending on site conditions and project goals, these other treatments may be appropriate, as well.

(a) Grade stabilization

One of the most challenging problems facing river engineers today is the stabilization of degrading channels. Channel degradation leads to damage of both riparian infrastructure, as well as the environment. Bank protection is generally ineffective over the long term if the channel continues to degrade. When systemwide channel degradation exists, a comprehensive treatment plan is usually required. This usually involves the implementation of one or more grade control structures to arrest the degradation process. Another more involved approach would be to change the channel gradient through a reconstruction of the channel, incorporating suitable meander bend geometry.

While grade control can be applied to any alteration in the watershed that provides stability to the streambed, the most common method for establishing grade control is the construction of inchannel structures. A wide variety of structures have been employed to provide grade control in channel systems. These range from simple loose rock structures to reinforced concrete weirs and vary in scale from small streams to large rivers. NEH654 TS14G provides a description of some of the more common types of grade control structures and describes the various design factors that should be considered when selecting and siting grade control structures.

(b) Flow changing techniques

Flow changing devices are a broad category of treatments that can be used to divert flows away from eroding banks. These include devices known as deflectors, bendway weirs, vanes, spurs, kickers, and barbs. While there are variants in their design and behavior and names, they are basically structures that:

- project from a streambank
- are oriented upstream
- redirect streamflow away from an eroding bank
- alter secondary currents
- promote deposition at the toe of the bank

These treatments are typically constructed of large boulders and stone, but timber and brush have also been successfully used as part of stream design and restoration. NEH654 TS14H describes the attributes and design criteria for many flow-changing techniques. However, the primary focus of NEH654 TS14H is on the analysis, design, and installation of stream barbs. NEH654 TS14H draws on recent field evaluations that focus on areas where these structures have performed well, as well as areas where their performance has been less than satisfactory. A design description includes cautions and warnings related to specific design features. A step-by-step design procedure is also provided.

(c) Soil bioengineering

Stabilizing streambanks with natural vegetation has many advantages over hard armor linings. Compared to streams without vegetated banks, streams with well-stabilized vegetation on their banks have better water quality and fish and wildlife habitats. Vegetation is an extremely important component of biological and chemical health, as well as the stability of the system.

Streambank soil bioengineering is defined as the use of live and dead plant materials in combination with natural and synthetic support materials for slope stabilization, erosion reduction, and vegetative establishment (Allen and Leech 1997). Streambank soil bioengineering uses plants as primary structural components to stabilize and reduce erosion on streambanks, rather than just for aesthetics. As a result of increased public appreciation of the environment, many Federal, state, and local governments, as well as grass roots organizations, are actively engaged in implementing soil bioengineering treatments to stabilize streambanks.

NEH654 TS14I provides guidance for the analysis, design, and installation of many commonly used soil bioengineering techniques. Integrated approaches are addressed, as well as techniques that solely use plants to provide stabilization. Installation guidelines and materials requirements are described in detail. NEH654 TS14I addresses many of the regional concerns and issues that should be considered for the successful application of these techniques.

(d) Large woody material for habitat and bank protection

Large woody materials (LWM) structures are intended to provide habitat and stabilization, until woody riparian vegetation and stable bank slopes can be established. LWM normally decays within a few years, unless it is continuously submerged, but this decay depends on climatic conditions, wood type, and density. Therefore, structures made entirely or partially of woody materials are not suited for long-term stabilization, unless wood is preserved by continuous wetting or chemicals. Woody structures are best applied to channels that are at least moderately stable, have gravel or finer bed material, and that have a deficit of habitats created by wood. NEH654 TS14J addresses the analysis, design and installation of LWM structures.

(e) Streambank armor protection with riprap structures

Structural measures for streambank protection, particularly rock riprap, have been used extensively and with great success for many years. Many situations still require rock riprap to some degree. It is one of the most effective protection measures at the toe of an eroding or unstable slope. Rock is a fairly common commodity in most areas of the country and readily available to most sites. Rock riprap measures have a great attraction as a material of choice for emergency type programs, where quick response and immediate effectiveness are critical.

NEH654 TS14K describes some of the basic principles and techniques used to treat streambank erosion with the more traditional structural measures such as rock riprap and rock-filled gabions. These design basics are applicable to any structure that involves the use of stone. This section also describes the challenges inherent in integrating more vegetatively oriented solutions into these techniques without materially increasing the exposure time and risks involved with failures. This combined approach is desirable to produce a better long-term solution that will be complementary to the natural environment and more self-sustaining. NEH654 TS14K also addresses where stone can be used to provide habitat enhancement, either as part of a traditional bank stabilization structure or as instream habitat boulders.

(f) Articulating concrete block revetment systems for stream restoration and stabilization projects

A variety of natural and constructed materials are available to provide erosion protection in stream restoration and stabilization projects. One of these products is an articulating concrete block (ACB) revetment system. An ACB revetment system is a matrix of interconnected concrete block units installed to provide an erosion resistant revetment with specific hydraulic characteristics. The individual units are connected by geometric interlock, cables, ropes, geotextiles, geogrids, or a combination thereof and typically overlay a geotextile for subsoil retention. An ACB revetment system may be used to provide permanent erosion protection where vegetation and other soil bioengineering practices are not stable for the design event. Typical applications may include entire channel cross-sectional protection, toe and lower side slope protection, stream crossings, grade stabilization structures, and other high energy environments.

NEH654 TS14L describes the ACBs currently available and some of the benefits of their use. A summary of hydraulic performance testing is presented along with design procedure for open channel flow. Critical features are described for typical installations, including subgrade preparation, ancillary components (such as drainage layers), filter placement, ACB placement, system termination, and anchors and penetrations.

(g) Vegetated rock walls

A vegetated rock wall is a mixed-construction biotechnical slope protection. They are primarily used in urban and suburban applications where limited area is available and where there is a need for static bank stabilization. They may be considered to be an alternative to a conventional concrete channel. While vegetated rock walls are expensive, they provide more habitat benefits and are generally considered to be more aesthetically pleasing.

NEH654 TS14M describes the analysis, design, and installation requirements for these structures. Both structural, mechanical and vegetative elements work together to prevent surface erosion and shallow mass movement by stabilizing and protecting the toe of steep slopes. These walls differ from conventional retaining structures because they are placed against relatively undisturbed earth and are not designed to resist large earth pressures.

(h) Fish passage and screening design

Fish passage and screen design is often an important component in stream restoration and water resource management. A wide variety of design issues depend on the project region and species of interest. NEH654 TS14N provides an overview of fish passage and screen design including biological considerations. This section includes a generalized assessment and design approach. Additional references for more information regarding design of fish passage and screen structures are provided.

(i) Stream habitat enhancement using LUNKERS

Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids (LUNKERS) are structures that are designed to provide both stability and edge cover for aquatic habitat. While their use has primarily focused on providing trout habitat, they are applicable to other species, as well. LUNKERS have also been used in many projects to enhance the integrity of stream channel geomorphology and bank stability. Where flood volumes and velocities are to be mitigated, LUNKERS can contribute to bank stability and establishment of a secure riparian corridor.

NEH654 TS14O provides step-by-step guidance for the analysis, design, and installation of these structures. A particular focus is on the placement, anchoring, and finished grading for LUNKER structures to result in stream channels that function efficiently without lateral scour.

(j) Gully stabilization

Gullies develop in response to concentrated flow. Basically, the forces created by flowing water exceed the resisting soil forces. Unchecked, the gullies erode and deliver sediment through a variety of processes that cause loss in soil productivity, channel entrenchment and headward advance, and expansion into the landscape. The processes increase the channel network, bank slope, bank height, and streambank instability resulting from the headward migration of nickpoints. NEH654 TS14P describes the major elements involved with gully formation processes and problem assessment. Alternate approaches to treatment may be considered, depending on gully specifics and landowner desire for effectiveness, cost, and reliability. The information and examples provided in NEH654 TS14P should help in the determination of the approach that may be most suitable for the circumstances.

(k) Abutment design for small bridges

Bridges are installed in a variety of NRCS applications including farm and rural access roads, livestock crossings, emergency watershed protection work, and recreation facilities. They may also be used to replace existing culverts that act as barriers to fish passage. NEH654 TS14Q presents a procedure for determining the ultimate and allowable bearing capacity for shallow strip footings adjacent to slopes. The procedure is appropriate for the design of abutments for the relatively small bridges typically involved in NRCS work.

(l) Design and use of sheet pile walls in stream restoration and stabilization

Sheet pile may be used in a variety of applications for stream restoration and stabilization. It is typically used to provide stability to a stream, stream slopes, or other manmade structures in high-risk situations. Typical applications of sheet pile include toe walls, flanking and undermining protection, grade stabilization, slope stabilization, and earth retaining walls. While sheet pile can be combined with soil bioengineering techniques, it does have some ecologic and geomorphic disadvantages.

NEH654 TS14R describes typical applications for cantilever sheet pile walls in stream restoration and stabilization projects. It also describes the types of sheet pile material, loads applied to the sheet pile, failure modes, design for cantilever wall stability, structural design of the piles, and some construction considerations.

(m) Sizing stream setbacks to help maintain stream stability

Many local communities, watershed groups, counties, and states are developing setback ordinances to help protect stream systems. NEH654 TS14S briefly outlines several guidelines and presents an empirically based equation that predicts the streamway width required to allow a stream to self-adjust its meander pattern. NEH654 TS14S does not cover stream setbacks that are required due to local or state laws or cost-sharing program rules.

654.1404 Conclusion

Treatment technique design contains an overview of some of the frequently used treatment techniques for bank protection, grade protection, and habitat enhancement, as well as analysis techniques for their design. Specifics related to each of the presented treatment and analysis approaches are included in the technical supplements of this handbook.

Many of these treatment techniques have been used and are applicable for small, local issues. While they have been considered to be band-aid solutions, in many cases, a band-aid is all that is needed or justified. In addition, many of the techniques described in this chapter have been used as components of larger, more extensive restoration and design projects.

The reader should not interpret descriptions herein as an endorsement of any product that is mentioned, nor should one treatment or approach be inferred as superior to another. The choice of a particular treatment or combination of treatments should be based on the stakeholders' goals and objectives, watershed conditions, and site condition.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 15 Project Implementation

Issued August 2007

Cover photo: Appropriate designs will enable elements of the restoration plan to be implemented and meet the restoration goals, while minimizing disturbance. Rushed implementation without proper designs can result in failure.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 15 Project Implementation

Contents

Tables

Chapter 15 Project Implementation

654.1500 Purpose

This chapter addresses general project implementation issues with an emphasis on U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) programs, requirements, and guidance. The three phases involved in project implementation are design, contracts and agreements, and installation. This chapter describes how the phases are interrelated, how each phase requires knowledge of the limitations or restrictions of the other phases, and provides a general overview of the process of project implementation with appropriate references to other NRCS and government contracting documents. For the purposes of this document, the planning phase, including determination of the nature and source of problems, as well as the desired objectives and future conditions, is presented in detail in National Engineering Handbook (NEH) 654.01, 654.02, and 654.03.

654.1501 Introduction

Project implementation is divided into three phases:

- design
- contracts and agreements
- installation

All stream restoration projects should follow these three phases. The level of effort required for implementation may vary substantially from project to project. The level of effort depends on the complexity of the project, tolerance for risk, and the available resources. As described in NEH654.02, the design phase may trigger cycling back through the planning process if preliminary designs cannot meet the planned project objectives.

Stream restoration projects may include design elements that specifically focus on removing perturbations or sources of impairment of ecosystem functions. Critical design elements may include nonstructural approaches requiring changed management, altered access, or possibly changes in institutional regulations. This chapter focuses on the design elements of a stream restoration plan that require construction and how to implement them. Restoration plans can, however, range from simple changes in resource management to largely structural alternatives. The design elements of a restoration plan to be implemented depend heavily on the results of a planning process that adequately identifies the nature of the stream's problems, their sources, and realistic goals and expectations for the implemented project actions.

Specific aspects of the other phases must be considered when working on a single phase in the implementation process. This requires a general understanding of all three phases. For example, the completeness of the design package depends on the type of construction contract or agreement that will be used. The type of construction contract or agreement depends on the staff available to direct the work and/or provide quality assurance (QA).

Direction throughout the implementation process is provided by NRCS policies, technical guidance, and program guidelines. Any project involving the NRCS is required to follow these established policies and guidelines. The division of responsibilities between the NRCS and a program sponsor is detailed in a project agreement of which there are several different types. These agreements detail the responsibilities of both parties. Sponsors using NRCS program funds are required to follow many of the same implementation policies and guidelines as are required of the NRCS.

The NRCS has been implementing projects for many years, and over that time many technical resources have been developed. Although stream restoration projects may be a complex blend of ecology and engineering, the general process of project implementation is the same as for other types of NRCS projects.

654.1502 Planning

(a) Importance

Planning is the foundation of any successful stream restoration project. The planning process provides an opportunity to investigate, discuss opportunities, and formulate realistic goals and feasible and constructible alternatives. Proper planning provides direction for design, procurement, and installation. During the planning phase, potential problems and/or restrictions are identified. The earlier potential project problems are identified, the easier it is to make changes to the plan without requiring additional time, effort, and funding. See NEH654.02 for a thorough description of the planning process.

654.1503 Design

The planning process defines the purpose for the design, defines realistic goals for the restoration, formulates alternatives to achieve these goals, and determines the level of detail in the design package. The design process requires a more in-depth look at the processes causing the problems and acting on the design features. The design follows NRCS policy in the NRCS National Engineering Manual (NEM) 511, Design.

Problems, objectives, and selected alternatives from the planning process are used by the designer as the basis for the design. The designer will also need other information such as potential permitting requirements, funding, material availability, site or reach limitations, and expected construction period. This information should be collected during the planning process.

(a) Design package

The level of detail of the design package depends on the type of contract or agreement chosen during planning. For example, a firm, fixed-price contract requires a complete design package that will allow contractors to understand in detail what is to be constructed; whereas, a time and material contract may only require minimal drawings and no specifications. The level of detail for design is decided during planning based on available resources and complexity of the project. A complete design package typically contains the following:

- design report
- construction drawings
- material specifications
- design specifications
- engineer's cost estimate
- bid schedule
- estimated construction schedule

(b) Design scheduling

Stream restoration projects may have short periods of time during the year when construction activities can take place. These limited construction periods may be due to harvesting and planting seasons, varying flow levels, fish migration and spawning, or other limitations related to sediment concentrations and limitations on ingress and egress. In addition, the plant materials used in many soil bioengineering support practices for the design require specific harvesting, storage and handling requirements, and planting times. When setting design completion dates and scheduling design staff, consideration must be given to the time required by the contracting process to meet construction scheduling needs.

Funding thresholds and/or construction schedules may require the design to allow for phases of construction. If all of the design cannot be constructed at one time, additional work is generally required to protect what has been completed. Work required to protect each phase should be included in the drawings.

(c) Constructability

For structural alternatives, constructability always must be considered throughout the design. Examples of constructability issues include:

- material availability
- equipment availability
- site and equipment access
- labor requirements
- dewatering requirements
- special measures to protect riparian conditions

When considering constructability, the designers must consider not only if it can be built, but also how can it easily be built. The designers should always be thinking of alternative designs that would have equal or better results but are easier to construct.

(d) Design layout

The physical location of design elements in a stream restoration project can be critical to its success. Although there may be considerable flexibility in the location (dimensions, alignment, and slope of some design attributes), other design elements may require strict adherence to specific criteria or limitations. However, designers should resist placing unnecessarily restrictive tolerances, as this will increase construction and inspection costs. By providing sufficient information on the design drawings to locate these features in the field, as well as the appropriate tolerances, the responsibility for accurate placement can be placed on the contractor. The design elements can also be checked for accurate placement by someone other than the designer.

It is important for a designer to consider how the design will be transferred from the plans into the field, or fitting the design into the landscape. Only in rare circumstances should a designer direct the construction of major projects without laying out the design in the field. The most common methods used to locate features on a drawing include referencing to a baseline or centerline, creating a grid, or using a global positioning system (GPS). Table 15–1 lists these methods and outlines some of the advantages and disadvantages of each.

Regardless of which method is used, benchmarks must be established and identified on the plans. Benchmarks are objects in the field of known location that will not be disturbed throughout the construction of the project. The location of baselines, centerlines, and local coordinate systems are referenced to benchmarks. When using GPS coordinates, benchmarks are useful as a means of checking the accuracy of the GPS system.

(e) Quality assurance and quality control

When a complete design package is not required, the level of design detail on the plans and specifications depends on the experience and availability of QA and quality control (QC) staff and the experience and reliability of the contractor. For example, minimal drawings and no specifications may be sufficient if a time and material or a labor-hour contract is employed, experienced construction personnel familiar with the design will be onsite, and the contractor is experienced and reliable. Precautions with this method include limited information to perform a review and reliance on the availability of experienced construction oversight.

Table 15–1 Advantages and disadvantages of commonly used layout methods

	Advantages	**Disadvantages**
Baseline	• Only two points required to locate baseline	• Difficult to reference when features are along a curve
Centerline	• Easy to reference feature locations using stations • Follows the direction of the stream	• Can be difficult or impossible to stake out in the middle of a stream • Curve data required to locate in the field
Grid	• Easy to reference features using CAD	• Difficult to use on large sites • Time consuming to layout grid
Global positioning system (GPS)	• No referencing to other control points • Points can be located quickly in the field • Easy to reference features using CAD	• Satellite reception can be a problem in heavily wooded areas

654.1504 Contracts and agreements

Stream restoration projects may be accomplished using contracts and/or certain types of agreements. There are several factors to consider when choosing the type of contract or agreement best suited for a specific stream restoration project. These factors include:

- program requirements
- project agreement requirements
- extent of design
- complexity of design
- human and equipment resources
- schedule or timeframe
- cost of installation

Stream restoration projects constructed under a specific NRCS program must be installed in conformance with those program's guidelines. Program guidelines often restrict the type of contract or agreement that may be used for installing the practices.

Project agreements include any agreement entered into by the NRCS and sponsors in which detailed working arrangements are established for the installation of cost-shared measures. The responsibilities of all parties involved and details of the actual implementation procedures for the specific project are detailed in the project agreement.

The type of contract depends on the time frame for starting and completing the work. When work must begin and be completed quickly, equipment rental may be more appropriate due to the limited time to obtain or design detailed plans and specifications. This is also contingent upon the availability of qualified NRCS or sponsor representatives needed to direct the work, as noted above.

(a) Contracting

When describing the various methods of contracting for the installation of practices for NRCS projects, it is necessary to divide contracts into two main categories: Federal contracts and non-Federal contracts. These contracts can be further divided into formal or informal, depending on the value of the contract. Under the Federal Acquisition Regulations (FAR) as of 2005, formal contracts must be used for projects with a value greater than $100,000, and informal contracts and contracting procedures can be used for projects with a value of $100,000 or less. Informal contracts are those put in place using simplified acquisition procedures. The advantages of using simplified acquisition procedures are:

- simplicity and ease of buying
- purchases can be made more expeditiously
- usually less paperwork
- usually lower administration costs

There are several types of Federal and non-Federal contracts, each having specific advantages and disadvantages.

It is important to understand the advantages and disadvantages of the types of contracts available for use in the installation of stream restoration measures to complement the planning, design, and construction efforts required for a successful project. Some advantages might be minimal administrative burden, minimal construction oversight, and maximum incentive for the contractor to control cost. Conversely, some types of contracts require maximum administrative burden, maximum construction oversight, and no incentive for the contractor to control costs. Table 15–2 summarizes the various items to consider when selecting the type of contract best suited for a specific situation.

Federal contracts

Federal contracts are governed by the FAR. Information can be found at the following Web site:

http://www.arnet.gov/far

NRCS contracting regulations also include the Agriculture Acquisition Regulation and the NRCS Acquisition Regulations. Federal contracts that might be applicable to stream restoration work include fixed-price, cost-reimbursement, incentive, time-and-materials, labor-hour, equipment rental, and letter contracts. These contracts can be formal or informal (simplified procedures), depending on the value of the contract.

Federal contracts are normally used when project sponsors do not have the capacity to solicit, award, and/or administer a locally awarded contract and/or have the necessary resources to accomplish the work with their own forces under certain types of agreement actions. A warranted NRCS contracting officer can provide pertinent information and guidance for Federal contracting procedures. A wide variety of Federal contract types may be used under the acquisition regulations. The selection of the appropriate type of contract, as well as the method of solicitation, is situation driven. NRCS Federal contract actions must comply with all applicable acquisition regulations and policy.

Fixed-price contracts—Place the maximum risk and full responsibility on the contractor for all costs and resulting profit or loss associated with the work. This type of contract provides the maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden on NRCS and/or sponsors. A fixed-price contract requires the contractor to understand, in detail, what is to be constructed before bidding to do the work. This requires a design that includes detailed drawings, specifications, and a bid schedule containing a bid item for each major item of work. The designer must provide a cost estimate by bid item so that the cost of the work can be estimated and the contracting officer can ac-

Table 15–2 Contract comparisons

Contract type	**Federal contract**	**Non-Federal contract**	**Administrative burden**	**Construction oversight**	**Incentive for cost control**	**Required design effort**	**NRCS/sponsor's risk**	**Contractor's risk**	**Comments**
Fixed-price	√	√	low	low	high	high	low	high	Most preferable type of construction contract. Must have accurate cost estimate and construction details
Cost reimbursement	√	√	high	high	low	low	high	low	Use only when uncertainties in contract performance do not permit use of any type of fixed-price contract
Incentive	√	√	—	—	high	—	—	—	Rarely used for construction. May be fixed-price or cost-reimbursement contract
Time-and-materials	√	√	high	high	low	low	high	low	Use only when accurate cost estimate, extent or duration of work cannot be established. See limitations at FAR 16.601(c)
Labor-hour	√	√	high	high	low	low	high	low	Same as time-and-materials contract, but without materials being supplied by contractor
Letter	√	√	high	high	low	low	high	low	Requires national level approval. Only use when the head of the contracting activity determines in writing that no other contract type is suitable. FAR 16.603–3
Equipment rental	√	√	high	high	low	low	high	low	Similar to time-and-materials or labor-hour contracts and is use when nature of work and limited design details preclude using a fixed-price construction contract

Note: — indicates the rating could be either high or low cess the reasonableness of the bids. Most fixed-price contracts are awarded after contractors have submitted a sealed bid in response to an Invitation for Bids (IFB). The IFB includes the drawings and specifications for the work and specific contract requirements. This is the most preferred type of contract and should be used to the maximum extent practicable. Fixed-price contracts can be accomplished using either simplified or formal acquisition procedures, depending on the value of the project. The design effort and level of detail may be the same for simplified fixed-price contracts as it is for formal fixed-price contracts.

Cost-reimbursement contracts—Suitable for use only when the cost of the work cannot be estimated with sufficient accuracy to use a fixed-price contract. The cost of the work is estimated for the purpose of obligating funds; however, a detailed cost analysis is not required. The contractor must have an accounting system adequate for determining incurred costs that are reimbursable. This type of contract requires significantly more government oversight during the construction phase to document that efficient construction methods and efficient cost controls are being used. It provides little incentive for the contractor to control costs and perform effectively and imposes a much larger administrative burden on the contractor, NRCS, and/or the sponsors.

Incentive contracts—Link the contractor's profit to performance by establishing reasonable and attainable targets that are clearly communicated to the contractor. These contracts are designed to motivate the contractor in specific areas that might not otherwise be emphasized, such as motivation for early completion. Incentive contracts discourage inefficiency and waste. Incentive contracts can be fixed-price incentive contracts or cost-reimbursable incentive contracts. These types of contracts are normally used for performance-based service contracts and rarely, if ever, are used for construction work.

Time-and-materials contracts—Used to procure supplies or services on the basis of direct labor and materials costs. Time-and-materials contracts should be used only when it is not possible to accurately estimate the extent or duration of work or to anticipate costs with any degree of confidence. With this type of contract, there is no incentive to the contractor to control costs, significant government oversight is required, and a much larger administrative burden is imposed on NRCS and/or the sponsor.

Labor-hour contracts—A variation of the time-and-materials contract, differing only in that materials are not supplied by the contractor.

Equipment rental contracts—Used in instances where a fixed-price construction contract would be impractical because of the nature of the work and when it would not be feasible to prepare detailed drawings and specifications. It requires substantial construction oversight and imposes an additional administrative burden on NRCS.

Letter contracts—Written preliminary contractual instruments that authorize the contractor to begin work immediately. A letter contract should be as complete and definite as feasible under the circumstances, and there are requirements for scheduling price negotiations and establishing set prices as soon as feasible. A letter contract may be used only after the head of the contracting activity or a designee at the national level determines in writing that no other contract is suitable.

Non-Federal contracts

Non-Federal contracts, like Federal contracts, can be categorized as formal or informal (using simplified procedures). They can also take the form of fixed-price, cost-reimbursement, or incentive type contracts in accordance with the Contracting Local Organization's (CLO) procurement regulations and the Federal requirements imposed on the CLO as provided in the Code of Federal Regulations (CFR) at 7 CFR 3016.36. CLO contracts are those administered by a non-Federal entity such as state government, county government, or other local sponsor. The contract language, including general and special contract clauses, will likely differ from one entity to another. The CLO, NRCS, or both, will provide a QA inspector to verify that work is performed according to design and contract requirements. In other instances, the CLO may require substantial NRCS assistance to develop and administer the contract and may incorporate NRCS general and special provisions in the contract.

The amount of NRCS involvement in non-Federal contracts may depend on the capabilities of the contracting organization.

Fixed-price CLO contracts—Can include both construction contracts and vegetative contracts. A fixed-price CLO contract is similar to a fixed-price FAR contract in that it requires the same degree of detailed design, and it places the maximum responsibility on the contractor, with the maximum incentive to perform in an efficient cost-effective manner. Also, note that a CLO contract awarded under informal or simplified procedures can require the same degree of detailed design as a formal contract. As with fixed-price FAR contracts, the level of construction oversight and contract administration may be minimized with a fixed-price CLO contract. This is not to infer that no QA inspection is needed, only that the intensity of inspection may be less on this type of contract than on other contract types, such as equipment rental contracts where the inspector must verify the hours of equipment and personnel and must direct the work.

Time-and-materials CLO contracts—Non-Federal contracts used to procure supplies or services on the basis of direct labor and materials costs. Time-and-materials contracts should be used only when it is not possible to accurately estimate the extent or duration of work or to anticipate costs with any degree of confidence. With this type of contract, there is no incentive to the contractor to control costs, significant CLO oversight is required, and a much larger administrative burden is imposed on the CLO and perhaps the NRCS (depending on the NRCS level of involvement).

Labor-hour contracts—A variation of the time-and-materials contract, differing only in that materials are not supplied by the contractor.

Equipment rental contracts—Non-Federal contracts used in instances where a fixed-price CLO construction contract would be impractical because of the nature of the work, and it would not be feasible to prepare detailed drawings and specifications. It requires substantial construction oversight and imposes an administrative burden on the CLO and/or NRCS.

Contract value

The value of the contract dictates whether simplified or if formal contracting procedures must be used. As of 2005, simplified acquisition procedures under the FAR may be used for work that costs $100,000 or less, but more formal acquisition procedures are required for work in excess of $100,000. Fixed-price contracts, cost-reimbursement contracts, incentive contracts, time-and-materials contracts, labor-hour contracts, letter contracts, or equipment rental contracts may be used under both simplified and formal contracting procedures. Table 15–3 lists the various contracting procedures required for construction or service (equipment rental) contracts at each dollar threshold where changes in the procedural requirements are required by the FAR.

While it is most often the size of the procurement that determines whether to use simplified or formal procedures, there can be some apparent exceptions in practice. For example, exigency Emergency Watershed Protection (EWP) solicitations with estimated costs in excess of $100,000 require a formal bid opening and award of a formal contract. However, the advertising time and scope can be shortened because of the exigency. In some extreme cases, the NRCS would only notify 5 or 10 contractors, and only 2 or 3 days would be needed to develop the solicitation, hold the site showing, and award the contract. But, the result should be a formal contract for those actions exceeding the simplified acquisition threshold of $100,000.

(b) Project agreements and other assistance relationships

The NRCS and a sponsor can jointly install works of improvement using project (cooperative) agreements. The NRCS policy regarding project agreements is found in the National Contracts, Grants and Cooperative Agreement Manual (NCGCAM) GM 120–510 through 517. Project (cooperative) agreements must define the contracting, and/or use of the sponsor's forces, cost-sharing (as applicable), and administrative procedures that will be used to carry out the selected method of installation. The sponsor may choose to contract for or perform, using their own forces, engineering designs, cost estimates, installation of the stream restoration measures, and construction oversight and associated inspection services. The agreements must define the contracting, cost-sharing (as applicable), and administrative procedures needed to carry out the selected method.

The NRCS must assure the quality of the design, contracting, and any construction carried out by project sponsors through design quality reviews, construction oversight, or other means established by the state conservationist (STC) and in accordance with the NCGCAM and NEM.

Table 15–3 Dollar thresholds requiring changes in procedures by the FAR

	Construction				**Service (equipment rental)**				
Alternate methods of contracting	**Less than $2,000**	**More than $2,000**	**More than $25,000**	**More than $100,000**	**More than $2,500**	**Less than $10,000**	**More than $10,000**	**More than $25,000**	**More than $100,000**
Verbal quotes	x				x	x			
Written quotes (RFQ)		x	x				x	x	
Sealed bid (IFB)				x[2/]			*	*	*
Negotiated (RFP) (rarely used)							*	*	*
8(a) Set Aside	*	*	*	*	*	*	*	*	*
FedBizOpps—less than 30 days			x[1/]					x[1/]	
FedBizOpps—minimum 30 days				x[1/]					x[1/]
Davis Bacon		x	x	x					
Service Contract Act					x	x	x	x	x[1/]
Bid security				x[2/]					
Performance and payment security			x[3/]	x			x[3/]		

* if applicable
1/ Unless EWP Exigency or 8(a) Set Aside
2/ Unless 8(a) Set Aside
3/ Alternate payment protection
Can use one solicitation with multiple award contracts
Can use Indefinite Quantity Contract with minimum/maximum qualifies, rather than Fixed Price with quantity variations
EWP work can be done using Master Package

Structural practices designed by non-NRCS personnel will be done under the direction and supervision of a licensed professional engineer in the state where the measures will be installed. All design reviews will be in accordance with the NEM 501 and with any procedures established by the state conservation engineer (SCE). Predesign conferences for more complex measures must be held with appropriate representatives from the NRCS, the sponsor(s), and the architectural and engineering (A&E) firm, if used.

The cooperative agreement approach can extend the capacity of NRCS to provide assistance under NRCS programs. It can also provide the sponsor with primary control of the installation process, and it can match the level of cooperative work to the sponsor's capability and resources. For example, the sponsor may lack or be unable to obtain contract administration assistance, but may have personnel or be able to secure professional engineering and other technical services that can evaluate, design measures, and prepare contract documents. The NRCS could then provide contract administration and construction assistance after the sponsor prepares the drawings and specifications. The project (cooperative) agreement would list the division of responsibilities with explicit details of the tasks to be performed by the sponsor and the tasks to be performed by the NRCS.

Regardless of the type of agreement that will be used, all project (financial assistance cooperative) agreements must meet the applicable requirements in the NCGCAM GM 120–510 through 517, as well as the applicable Federal regulations in 7 CFR 3015 and 3016.

In addition, the NRCS must ensure that all required prerequisites to signing a project agreement for the installation of project measures are met in accordance with NCGCAM 514.35.

For projects installed using contracts, there must be a project agreement between the sponsor and the NRCS authorizing the implementation of the stream restoration measures using either a Federal contract or non-Federal contract.

Project agreement for a Federal contract

A project agreement for Federal contracting may be used for installation of stream restoration measures in accordance with the NCGCAM 510.10(b) and 510.11. This work is normally performed under a competitively awarded contract. The NCGCAM, sections 510 and 514, provides applicable guidance and detail for the use of this type of project agreement.

Project agreement for a non-Federal contract

A project agreement for non-Federal contracting may be used in accordance with the NCGCAM 510.10(b), 510.11, and 510.30 through 510.39. This work should also be performed under a competitively awarded contract. The NCGCAM, sections 510 and 514, provides applicable guidance and detail for the use of this type of project agreement.

In addition, project installation may be accomplished using contract and/or agreement actions. Project agreements can be used to install works of improvement as follows.

Project agreement for force account

Force account agreements may be used for project installation in accordance with the NCGCAM 510.15. This method is used when the sponsor performs the work using its own equipment and personnel. The sponsor may supplement their own equipment through rental of relatively minor amounts of equipment. However, force account agreements can offer the potential for additional costs and poor quality work. Because of these factors, the sponsors may install project measures by force account only under the conditions indicated in the NCGCAM 510.15(c). The NCGCAM, sections 510 and 514, provides applicable guidance and detail for the use of this type of project agreement. The Sponsoring Local Organization (SLO) must keep accurate records of cost of all work performed. It requires substantial construction oversight and imposes an administrative burden on the parties to the agreement. Difficulty may arise in coordinating the force account work with the ongoing duties and other work that is required of the SLO workforce.

Project agreement for division of work

Division of work agreements may be used for cost-sharing land treatment measures. These are measures that are authorized under Public Law 83–566 (PL 566) watershed work. This type of project agreement may be used for project installation in accordance with NCGCAM 510.16. The work is divided between NRCS and SLO with the details of each organization's responsibilities spelled out in the project agreement. If the work is to be shared on a division of work basis, it must be described in the watershed plan, and cost estimates must be included in the supporting tables. The SLO is not required to keep records of expenditures. Detailed NRCS cost estimates are maintained to document that PL 566 costs do not exceed the authorized rate.

Project agreement for performance of work
Performance of work agreements require that the value of work to be performed by the SLO be determined by negotiation between the SLO and NRCS and be included in the project agreement. The NRCS must estimate the cost of the work to establish the maximum value of work before signing the agreement. This type of project agreement may be used for project installation in accordance with NCGCAM 510.17. This is applicable if the works of improvement are to be cost shared on a percentage basis. The percentage rate of cost sharing is to be included in the watershed plan agreement. This work should normally be performed under a competitively awarded contract. However, the sponsors may be able to perform certain elements of the project work with their own forces or with contributed labor, equipment or materials in lieu of providing cash. The NCGCAM 510.17 and 514 provide applicable guidance and detail for the use of this type of project agreement.

Project agreement for average cost
A project agreement for average cost may be used for installation of land treatment measures in accordance with NCGCAM 510.18. This method cannot be used with units of government. Average cost land treatment contracts (financial assistance agreements) are authorized under PL 566 with the cost of the work being the average cost of similar work within a defined area over a set period of time. The average cost is usually set by county and is determined by averaging the cost of all similar work for which there are records for a 1-year period. For example, the per-unit cost of work, such as bank shaping, would be averaged for all of the bank shaping that falls within a specific level or category. Bank shaping might be categorized as light, medium, or heavy based on the effort required to shape an acre. An average cost of light, medium, or heavy bank shaping would then be established for a county based on previous year costs.

Long-term contracts (financial assistance agreements) are authorized under PL 566 for contracts between the SLO and a landowner or between the NRCS and a landowner. The contract period ranges from 3 to 10 years with all cost-shared measures being installed at least 2 years before the financial assistance agreement expires. The work items are scheduled according to a plan with the purpose of reducing erosion and sediment damages within a PL 566 watershed. The work includes items like shaping and vegetating eroded areas, building grade control structures, and other measures that are approved for the program. Stream restoration may be approved for this type of program.

(c) Personnel for administering contracts and agreements

Contracting is a team effort that relies on individual team members to perform specific tasks. The titles of team members are sometimes different for non-Federal contracts than for Federal contracts, but their tasks transcend from one to the other. The six principal responsible positions on a team are administrative officer, contracting officer (CO), contract specialist, SCE, GR/COR, and government inspector.

NRCS state administrative officer (SAO)
The SAO is responsible for all administrative matters for CLO contracts and most agreements. This includes making sure funds are available and that people and equipment needed to administer the agreement and any resulting contract will be available when needed. For Federal contracts, the NRCS-warranted contracting officer is responsible for contractual matters in accordance with FAR 1.602.

Contracting officer (CO)
The CO is responsible for administering the contract including ensuring that the proper type of contract is being used and funds are spent according to regulations. For CLO contracts, the NRCS contract specialist or SAO is there to lend guidance to the CO who is a CLO official or employee.

NRCS contract specialist
The NRCS contract specialist assists the administrative officer in contract matters for CLO contracts and agreements. The NRCS contract specialist is the CO on Federal contracts. The contract specialist works closely with the design engineer to ensure that the design package included in the solicitation package contains the information needed for the work to be contracted.

State conservation engineer (SCE)
The SCE is responsible for the design and ultimately responsible for ensuring proper construction of the works of improvement. The SCE or an assigned staff member works closely with the CO on Federal contracts or the NRCS administrative officer and NRCS contract specialist for CLO contracts to provide design information needed to define and contract the work. The SCE is also involved in making sure there is adequate inspection staff to provide the required level of construction oversight and QA.

Government representative (GR) on non-Federal contracts or contracting officer's representative (COR) on FAR contracts
The GR or COR is responsible to the SEC and the CO to see that the work is carried out as designed and in accordance with the contract requirements.

Construction inspector
The construction inspector is responsible for the day-to-day QA inspection required to ensure that the work is installed according to the design, industry standards, and contract requirements. The construction inspector is responsible to the GR/COR and CO to assure that the quality of the work is consistent with contract requirements.

The availability of personnel to perform specific tasks should be the first consideration when planning a project. For example, consider a stream restoration project that is planned to use volunteer labor under a force account agreement with the sponsor and rented equipment through a Federal or non-Federal equipment rental contract. The project will use live vegetation that must be planted during a specific planting season. This type of work would require contract personnel to prepare the equipment rental contract within a narrow timeframe and require significant construction oversight by trained field personnel. This normally requires much more oversight and administrative effort than would be the case with a firm fixed-price contract. A fixed-price contract would require a very detailed and thorough design package, but would likely require less contract administration and construction oversight. It might also be possible to do the work under a locally led CLO contract with relatively little burden on NRCS contracting personnel and minimal NRCS construction oversight.

654.1505 Installation

Installation of stream restoration projects in accordance with approved drawings and specifications is essential if the project is to serve its intended purpose and expected service life with normal operation and maintenance. The NRCS has standardized construction practices and procedures to ensure that stream restoration and other projects are installed according to design. These procedures provide uniformity in NRCS activities and result in common understanding between all parties involved with the design and installation of stream restoration and other projects. Policy concerning NRCS construction practices and procedures can be found in the NEM 512.

(a) Personnel required during installation

Installation of a stream restoration project is a team effort where each team member has specific responsibilities. The team is made up of the following members:

- owner or contracting officer
- engineer
- specialists for support of specific design elements
- government representative or contracting officer's representative
- construction inspector
- contractor

Owner
The owner is responsible for contracting for construction. For NRCS Federal contracts, the NRCS is considered the owner during construction and according to the FAR, the CO is responsible for ensuring performance of all necessary actions for effective contracting, ensuring compliance with the terms of the contract, and safeguarding the interest of the United States in its contractual relationship. On non-Federal contracts, the CLO is considered the owner during construction and an employee or CLO official serves as CO. A private individual or group is considered the owner on jobs that are administered by a private individual or group.

Engineer
The engineer is responsible for the technical requirements of project installation and represents the owner. The engineer is assigned technical and contract administration duties as outlined in the quality assurance plan (QAP) and in an appointment letter issued by the CO of Federal contracts or issued by the SAO for non-Federal contracts. The engineer may be an NRCS employee, an A&E firm employee, or an employee of the CLO or partnership agency.

Other specialists including biologist, ecologist, forester, fluvial geomorphologist, or others
Other specialists may be needed to support specific elements of the design, monitor specific site conditions for plants and animals, and assure that goals of the planned project are realized through the construction and implementation of the project's design elements. A specialist may be an NRCS employee, an A&E firm employee, or an employee of the CLO or partnership agency.

Government representative
The GR is an NRCS employee who has the responsibility to protect the government's interest and maintain close working relations with the CLO. The GR is an engineer if NRCS has QA responsibility for a construction project. The NRCS administrative officer will appoint a GR by letter for all construction contracts that are administered by others and that use Federal funds. This appointment is not normally provided for contracts handled by private individuals or informal groups.

Contracting officer's representative
The COR is an NRCS employee appointed by the CO and has the responsibility to protect the government's interest on Federal contracts. On NRCS construction projects, the COR is an engineer with responsibility for QA.

Construction inspector
The construction inspector is responsible for QA testing, engineering surveys, daily documentation of construction activities, coordination with the contractor's QC personnel, and maintaining the as-built plans. The NRCS CO or SAO appoints the inspector for Federal and non-Federal contracts respectively. The level of inspection required of the construction inspector is detailed in the QAP. For work other than that performed under formal and some informal contracts, formal appointment of an inspector is not required. However, an inspection staffing plan must be developed and approved in accordance with NCGCAM 516.3 for all project agreements in excess of $25,000 which results in either a non-Federal contract, force account agreement, or a performance of work agreement. The inspector should be made aware of the specific items that require QA inspection with sufficient guidance given to ensure that the inspection is adequate to achieve compliance with the design.

Contractor
The contractor is an individual or firm that installs the stream restoration measures. The contract or agreement with the owner may be formal, as in project installation, or informal, as with an individual landowner or informal group. As mentioned in the contracts and agreements section, provisions are available for the project sponsor(s) to perform work with their own forces under agreements that may include division of work, performance of work, or force account. Thus, the sponsor could also be the contractor.

(b) Preconstruction activities

Preconstruction activities include soliciting contractors, showing the site, selecting the contractor, and meeting with the contractor before construction. The time and effort devoted to preconstruction activities vary according to the complexity and value of the work. The objective in performing these activities is to ensure that the prospective bidders understand the work and contract requirements they must fulfill if they are selected to do the work and acquire the services of a responsible qualified contractor.

Soliciting contractors to bid the work
Solicitation marks the beginning of preconstruction activities. The solicitation package for both formal and informal fixed-price contracts consists of the drawings, specifications, bid schedule, and contract provisions with which the contractor must be familiar to bid the work. For informal work performed under a land treatment contract (financial assistance agreements), the contract used to delineate the work performed may be an agreement between an individual land user and a contractor. In this case, a minimal amount of written materials may be all the contractor needs to bid the work.

For formal contracts valued in excess of $100,000, the solicitation process generally takes 60 to 90 days. During this time, the CO compiles the solicitation package, advertises the work to prospective bidders, shows the site, opens bids, determines the responsive low bidder, and awards the contract. For Federal contracts, a solicitation notice must be posted for a minimum of 30 days on the Federal Business Opportunities (FedBizOpps) Web site so that it is available to all who wish to bid the work. The COR/GR reviews the solicitation package and provides comments to the CO before the solicitation package is issued. The COR/GR is normally responsible for staking the site for the site showing and assisting with the site showing. The construction inspector should also be involved at the earliest possible stage to provide review comments, assist in staking, and assist with the site showing.

When performing work under an Emergency Watershed Program (EWP) exigency, the time for the formal solicitation process may be greatly reduced if the emergency dictates this need and the action is in accordance with FAR 6.302–2. As an example, 5 to 10 contractors are notified and given an opportunity to bid the work, and the development of the solicitation, site showing, and contract award may be accomplished in as little as 2 or 3 days. For all other contracts exceeding the simplified acquisition threshold of $100,000, the work must be advertised on FedBizOpps with a solicitation notice posted a minimum of 30 days.

The amount of time needed to solicit contractors and award the contract may be much less than needed for formal contracts valued in excess of $100,000. Contracts valued at $100,000 or less may be accomplished using a simplified acquisition process with less stringent requirements. See table 15–2 for a list of the items to consider whenever selecting the type of contract and/or agreement best suited for a specific project situation.

The concept of advertising and bidding the work based on drawings and specifications that accurately depict the planned work also applies to informal contracts such as those between landowner and contractor. In some cases, the value of the work does not warrant taking the time to solicit bids from several contractors. The work may be depicted with sketches and/or a field review requiring minimal overall preconstruction activities.

Showing the site to potential bidders

Showing the site to the potential bidders is necessary so that they may inspect the area, determine the scope of the work, and receive answers to questions. Stakes and/or flagging shall be used to identify major items of work and their relationship to other elements of the proposed project. For formal contracts, the site showing is conducted by the CO with assistance from the COR/GR. The CO normally reviews contract items, and the COR/GR reviews the technical items. The inspector(s) should attend so that they have first hand knowledge of items discussed and contractor's concerns. The following items should be identified and discussed at the site showing, as appropriate:

- access roads and site entrance
- rights-of-way and construction limits
- clearing limits
- onsite vegetation or instream features that must be preserved
- location of known utilities
- proposed location of the design features of the project
- existing structures to be removed
- proposed borrow and waste areas
- location of geologic test holes/pits
- contractor's responsibility for pollution control and stormwater permit
- environmental issues
- construction safety
- other important features

Questions should be answered by referring to the solicitation package when the answer can be found in the package. When a question cannot be answered by referring to a specific part of the solicitation package, the question and answer should be recorded and included in an amendment to the solicitation package that is made available before the bid opening to all solicitation package holders. This process can also apply to solicitations using simplified acquisition procedures if site conditions or the complexity of the work warrants the need for a more formal site showing.

Conversely, if the work is relatively simple in nature and informal contracts are used, the items listed above should be reviewed with the contractor before the work begins. In most cases, these items have a bearing on the value of the work and should be reviewed with the contractor before bidding the work.

Awarding a contract

This comes after the CO determines that the low bidder is responsible. A responsible bidder must have the capacity, credit, integrity, tenacity, and perseverance to perform the work as specified. In making this determination, the CO may rely on the COR/GR to review submittals and perform a field review of the contractor's equipment and operations on previous or ongoing jobs. The CO will generally interview others who have dealt with the contractor to obtain their views of the contractor's capacity, integrity, tenacity, and perseverance.

Preconstruction conference

A preconstruction conference should be attended by the CO, COR/GR, inspector, and contractor before beginning construction. For Federal contracts, the term postaward conference is used. For informal work, the owner, engineer, inspector, and contractor should meet before construction to ensure that all have a thorough understanding of the work. The following items should be reviewed, as appropriate:

- drawings and specifications
- contract provisions
- invoicing procedures and progress payments
- contractor's construction schedule
- land rights and construction work limits
- permits
- easements
- work restrictions
- utilities in or near the work area
- construction safety, public safety, and safety plan
- sanitary facilities
- construction office space if provided by the contractor
- construction materials and material approval process
- staking and construction surveying
- contractor QC
- owner QA
- removal of water and dewatering plan(s)
- stream closures
- protected species of plant or animal
- weather and time extensions
- for intermittent inspection, a checklist of items to be inspected where the contractor or owner are required to notify the inspector
- any other item that could have an impact on the work

For formal contract work, the preconstruction conference minutes and all basic information of the conference should be recorded in the official job diary. This may also be applicable for informal contracts as needs dictate.

(c) Construction activities

Work begins

The work begins on formal contracts only after the contractor has received a notice-to-proceed (NTP). The engineer or construction inspector and the contractor schedule to meet onsite at the beginning of work to review last minute details before the start of work. For formal contracts, there are several items that must be in place before the start of the work including:

- contractor's safety plan, first-aid facilities (first-aid kit, stretcher)
- construction barriers as necessary
- sanitary facilities
- hard hat sign(s)
- bulletin board with specific items posted
- stormwater permit, associated posting requirements, and notice-of-intent
- stormwater pollution prevent plan (SWPPP) and associated best management practices

- contractor's quality control plan
- identification and CO approval of several key players on the contractor's staff including the superintendent, safety officer, surveyor, and QC manager
- other items as required by the contract

The first item of business is for the contractor and the construction inspector to hold a tool box safety meeting. In this meeting, the contractor's safety plan is reviewed and emphasis is placed on job-specific safety issues. Other items that may be covered in this meeting include site maintenance, pollution control, and utilities. NRCS places the safety of the public, the contractor's personnel, and NRCS personnel at the forefront of concerns on any construction job. NRCS policy related to safety can be found in the General Manual, Title 110, Part 402 (GM 110–402) and in the NEM 503.

Materials

The materials that are to be incorporated into the work must be approved by the CO or the individual assigned by the CO, such as the engineer. Materials must be evaluated in relation to applicable industry standards and/or specifications to determine that they meet design requirements. Material quality is evaluated by one or more of the following procedures:

- results of laboratory testing performed by the NRCS, consulting firm, and commercial lab
- written certification from the manufacturer with test results attached
- material markings and tags
- examination and/or testing onsite

Final approval of vegetative materials should not be given until immediately before installation to ensure that the materials are alive, have been stored and handled properly, were harvested or grown correctly, and are in the specified condition for the project application.

QA activities and specific contract administration tasks

QA tasks must be performed at the field level. QA activities vary in accordance with the complexity and hazard class of the stream restoration project. For the more complex projects, projects being constructed under formal contract, and any project that requires substantial QA, a QAP must be prepared and used in accordance with the Natural Resources Conservation Service Acquisition Regulations (NRCSAR) and the NCGCAM. The QAP will identify the individuals with the expertise to perform various QA tasks, outline the frequency and timing of testing, estimate the contract completion date, and be co-approved by all responsible supervisors, SCE, and CO (Federal contracts) or administrative officer (non-Federal contracts).

Although it is advisable to have a written QAP, a written QAP is not required for jobs administered by an individual or landowner. In some instances, the QA inspector need only inspect the work at various stages or times during construction. For these instances, a checklist should be provided to the contractor and landowner that would list specific parts or stages of construction that will require QA inspection. The contractor or landowner should notify the inspector in advance of the need for inspection of those items.

The QAP defines NRCS QA duties including the following quality, quantity, and timeliness requirements:

- general description of the work
- items requiring inspection
- timing of inspections
- skills needed by inspectors
- number of staff hours
- equipment and facilities needed
- names and qualifications of personnel
- supervisor's statement of availability

The contractor is responsible for QC to ensure that the work installed meets the minimum requirements of the contract. QC is a bid item for most formal contracts and NRCS Construction Specification 94, Contractor Quality Control is included in the contract. For less formal work, the contractor's QC duties should be defined in a manner that will ensure contractor QC is performed to attain the desired quality of work.

The owner (NRCS or CLO as applicable) is responsible for QA activities including observing construction methods and procedures, reviewing QC testing activities, conducting material testing to evaluate the QC program, and other measures to ensure compliance with contract provisions.

The performance of QA duties in an efficient economical manner requires:

- providing the proper number of qualified personnel with the knowledge, skills, and abilities necessary to conduct timely and effective inspection as outlined in the QAP
- continuous coordination with the contractor's QC representative to ensure NRCS QA activities are effective
- minimizing interference with the contractor's production activities

Under no circumstances will certification stating the work has been accomplished in compliance with the drawings, specifications, and other contract provisions occur without a physical review and documentation of the work performed. Continuous inspection is required for any activity the quality of which cannot be verified by intermittent inspection and for work that cannot be readily removed or replaced if it fails to meet the requirements of the contract. Intermittent or periodic inspection may be adequate for certain phases of project activities, depending on the complexity of the installation and potential impacts on the health and welfare of the public.

Documentation of construction activities and development of as-built plans is required for formal contract work and should be considered for other more informal work. The construction inspector maintains the official job diary, recording day to day activities and site and weather conditions. Written documentation should be supported by photo documentation. For more information on construction inspection, see NEH 645, and NCGCAM 517.5 through 517.13.

654.1506 Conclusion

Design, contracts and agreements, and installation are the three phases of project implementation. Consideration for specific aspects of the other phases must be given when working on a single phase in the installation process.

Quality planning is required for the efficient implementation of a project. A quality stream restoration planning effort requires an interdisciplinary team that can formulate a plan that is feasible, constructible, effectively addresses the identified problems, and meets the planned goals without adverse effects on the rest of the stream system. Planning provides the basis for the project implementation process.

The selected alternative plan that results from the planning process may range from simple actions to a complex of management and structural measures to achieve the goals of the project. Be aware that stream restoration design elements may include critical nonstructural approaches that may be integral to the success of the project.

Information that is gathered during the planning process and used to formulate a solution is analyzed in greater detail during design. The level of detail required in the design is dependent on the type of contract or agreement being used, complexity of the design, availability of experienced NRCS or CLO staff for QA activities or to direct the work if using equipment rental or similar types of contracts, and experience of potential contractors.

Designing a stream restoration project requires consideration of installation periods that can best be constructed in phases. Phases may require additional design to protect the work completed at each phase. Constructability should always be considered throughout the design. All of these considerations, as well as others, must be addressed since it is easier and often much less expensive to make changes during planning and design than during installation.

Various types of contracts and agreements are available for installing works of improvement that will permit accomplishing the work in the most beneficial manner to all concerned. In addition to formal contracts, informal contracts and agreements are used in much of the work that is accomplished with cost-shared funds. In selecting the contracts and/or agreements to be used, careful consideration must be given to the type of work, amount of work, desires and capabilities of the sponsors and/or land user, and the interests of the NRCS. Planning and design decisions should be made with installation procedures in mind and consideration given to the availability of qualified personnel needed for construction oversight and agreement during all phases of a project.

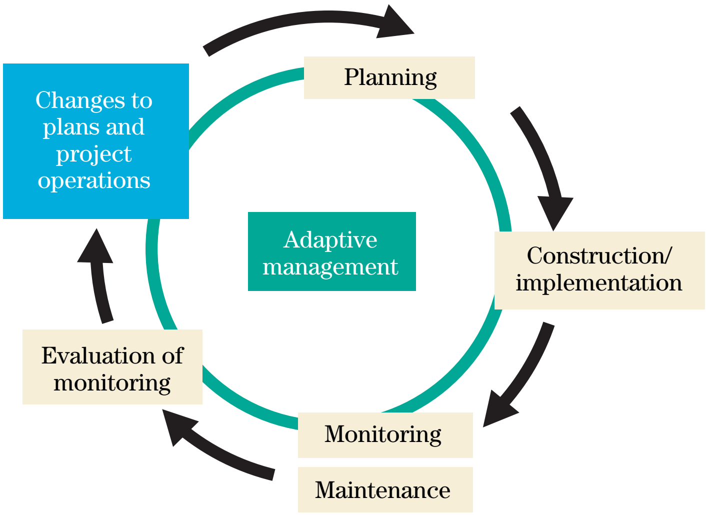
NRCS requires QA for all levels of construction to ensure that projects are installed in accordance with the design, industry standards, and contract requirements. The contractor is responsible for QC to ensure that the work installed meets the minimum requirements of the contract. The owner is responsible for QA activities including items related to safety of the public, the contractor's workforce, and NRCS personnel. NRCS has standardized construction practices and procedures to ensure that stream restoration and other projects are installed according to design.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 654 Stream Restoration Design
National Engineering Handbook

Chapter 16 Maintenance and Monitoring



Issued August 2007

Cover photo: Monitoring during and after implementation enables project managers to determine the level of success achieved and identifies when maintenance is needed.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 16 Maintenance and Monitoring

Contents

Tables

Figures

Chapter 16 Maintenance and Monitoring

654.1600 Purpose

Any stream restoration project, whether it is designed solely for habitat improvement or strictly to meet some human requirement, is implemented to achieve specific goals or objectives. Continued performance of the project features and health of the biotic resources depend on appropriate maintenance and monitoring of the system. Maintenance and monitoring are actions intended to ensure that the objectives of the stream restoration project are met over time. This chapter provides an overview of key issues in the development of monitoring and maintenance plans. Incorporation of adaptive management as a component of operations is included as a possible approach to maintenance and operation of the project. The user is also directed to the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) National Water Quality Monitoring Handbook for additional detailed information on setting up monitoring plans.

654.1601 Introduction

(a) Relationship of design and implementation to maintenance and monitoring

Maintenance and monitoring are the actions intended to ensure that the objectives of the stream restoration project are attained. Because project objectives, design criteria, and project site conditions determine the specifics of the actual project, maintenance and monitoring plans should follow from the opportunities, constraints, and requirements identified in the planning and design phase. Completion of the construction phase leads to the period of initial project operations when the stream restoration and streambank structures begin to function as designed.

Maintenance is the collection of actions taken to ensure that the stream restoration project performs as designed and to attain project objectives. It ensures the continued functioning of the structures and management measures once they are in place. While projects should be designed so they need a minimal amount of maintenance, some can be required especially in response to extreme flow events.

Monitoring is the process of measuring or assessing specific physical, chemical, and/or biological parameters of a project. Monitoring of any project, whether it is in the channel, streambank, riparian area, and/or adjacent lands, is necessary to ensure that the project is performing as intended. The parameters to be monitored should be directly related to the performance of the project and are linked to the goals and objectives of the project. This is also sometimes referred to as the hypothesis statement, or key questions to be answered.

The monitoring results may identify performance failures and inefficiencies requiring project modifications and changes to structures or operational practices. Performance objectives established for the project allow comparison of monitoring results to identify potential changes that may be needed in response to these performance problems.

(b) Maintenance and monitoring requirements resulting from project objectives

NEH654.02 describes the goals, objectives, and risks of project development. Maintenance and monitoring requirements can be identified initially from examining those actions required to meet the objectives of the project. Table 16–1 compiles different objectives identified in some typical NRCS stream projects. The objectives cited are taken from documentation on various projects. Some of the projects outlined in this table are described in more detail in the case studies of this handbook.

The terms goal and objective are sometimes used interchangeably. However, there are some distinct differences. Project goals are typically defined as the overall desired outcome, such as "restore channel to preflood conditions." Objectives are the more detailed, focused outputs or outcomes that achieve the project goals. The goal of restoring a channel to preflood conditions

Table 16–1 Project goals and objectives

Project	Goal	Objectives
Rose River, VA	Restore channel to preflood condition	Restore the hydrologic function [capacity] of the river by removing large cobble and debris bar that constricts the flood plain Stabilize streambanks Provide safe access for children to fish, stable cattle and tractor crossings
Little Blue River, KS	Remedy large-scale streambank erosion	Reduce excess stream sediment Improve stream channel dimension, pattern, and profile Establish a riparian ecosystem Improve terrestrial habitat Improve water quality Reduce nutrients and chemical pollutants
Rapidan River, VA	Restore the hydrologic function of the stream.	Get the water into one channel, not braided and shallow, that matched the preflood geomorphic dimensions
Goode Road/ Cottonwood Creek, Hutchins, TX	Stabilize banks	Reduce peak flows at lower elevation to protect bridge
Chalk Creek, Summit County, UT	Prevent erosion and reduce runoff of sediment	Protect water quality for cutthroat trout and overall health of the watershed
Red River Basin, ND	Restore riparian zones and stabilize stream channel and banks	
Big Bear Creek, PA	Stabilize channel and banks and improve aquatic habitat	Stabilize channel and banks using soil bioengineering and revegetation, stopping scour at a bridge Restore 3.7 miles of stream to a high-quality, cold-water fishery dominated by native brook trout

may have objectives such as increase hydraulic capacity by removing flood plain constrictions, stabilizing streambanks, and providing safe access for children to fish, and for stable cattle and tractor crossings (Rose River Restoration NRCS–VA). By attaining the project goal to restore the channel to preflood conditions, these objectives are achieved.

To obtain the goals and objectives of the project, potential maintenance and monitoring actions are suggested in table 16–2. This table lists two example projects showing the requirements that could be deduced from the objectives.

Distinctions between maintenance and monitoring requirements are not made in this section. The important point is to understand what parameters should be accounted for so that objectives are met.

Table 16–2 Project objectives and maintenance and monitoring actions

Project	Objectives	Maintenance or monitoring action or evaluation
Rose River, VA	Improve stream channel dimension, pattern, and profile	Channel profiles
	Stabilize streambanks	Channel planforms comparison to preflood conditions
Chalk Creek, Summit County, UT	Protect water quality for cutthroat trout	Survey of quantity/quality of rearing, spawning, and cover habitat
		Monitor habitat requirements, (stream water temperature, bed-material composition, water depth, and velocity)

654.1602 Development of monitoring plans

Monitoring helps determine whether the project is functioning as intended. Monitoring reveals the need for adjustments to design, construction procedures, and management actions. The information collected from monitoring should be made available to landowners and private interests who can make use of the information. Monitoring parameters are components of a project to be assessed that are evaluated to determine whether project objectives are being met (Washington Departments of Fish and Wildlife, Transportation, and Ecology 2003). Monitoring may be performed for a number of purposes such as (adapted from Federal Interagency Stream Restoration Working Group (FISRWG) 1998; North Carolina Stream Restoration Institute and North Carolina Sea Grant 2003):

- Performance evaluation: determine if the stream project design and management measures are functioning properly.
- Ecological or biological assessment: determine if biological resources are responding to altered conditions.
- Trend assessment: evaluate changing environmental conditions by long-term sampling at various spatial and temporal scales.
- Risk assessment: identify causes and sources of physical, chemical, or biological impairment or uncertainties that will affect operation of the project.

(a) Monitoring parameters

Physical, chemical, biological, and off-project parameters are identified to make up the monitoring plan. These parameters should be linked to the objectives, hypotheses, or key questions being tested with monitoring. Measurements of the selected parameters measure the performance and indicate the ecological functioning of the project.

Physical parameters

Physical parameters are the geomorphic and topographic features that compose the channel bed, streambank, and adjacent riparian areas. Table 16–3, adapted from FISRWG (1998), identifies the physical attributes (cross-sectional profiles and specific parameters for the attribute).

Chemical parameters

Improvements in water quality are a primary objective of many stream restoration projects. Stabilization of channels and streambanks results in reduction of sediment loading and movement. Land use changes in the stream corridor affect nutrient and chemical constituents in the water. Table 16–4 lists potential chemical parameters that could be affected by a project (adapted from FISRWG 1998).

Biological parameters

Aquatic and terrestrial communities change in character and abundance as the channel and streambank are stabilized. Streamside vegetation provides habitat and connectivity to other habitats or adjacent riparian areas. The biological attributes (table 16–5 (adapted from FISRWG 1998)) are the communities, structural components, and processes (primary production) that indicate the biological functioning of the stream system.

Off-project parameters

Project monitoring and maintenance focuses on the processes, systems, and impacts to the specific project and adjacent riparian areas. The watershed, upstream, and downstream processes and impacts were likely examined when formulating designs, accounting for the out-of-study area, or off-project constraints to design and construction. Monitoring and maintenance plans should consider off-project actions such as urbanization and other land use changes, sediment loading, and water control actions (detention structures). This investigation of off-project considerations could identify important parameters such as amount of urbanization or additional water users that should also be monitored.

Table 16–3 Physical parameters for consideration in monitoring

Physical attribute	Parameter
Plan view	Sinuosity, width, bars, riffles, pools, boulders, logs
Cross-sectional profile	Bank repose angle Depth bankfull Width Width-to-depth ratio
Longitudinal profile	Bed particle size distribution Water surface slope Bed slope Pool size/shape/profile Riffle size/shape/profile Bar features
Classification of existing streams	Varies with classification system
Assessment of hydrologic flow regimes through monitoring	2-, 5-, 10-year storm hydrographs Discharge and velocity of baseflow
Channel evolutionary track determination	Decreased or increased runoff, flash flood flows Incisement/degradation Overwidening/aggradation Sinuosity trend-evolutionary state, lateral migration Increasing or decreasing sinuosity Bank erosion patterns
Corresponding riparian conditions	Saturated or ponded riparian terraces Alluvium terraces and fluvial levees Upland/well drained/sloped or terraced geomorphology Riparian vegetation composition, community patterns and successional changes
Corresponding watershed trends—past 20 years and future 20 years	Land use/land cover Land management Soil types Topography Regional climate/weather

Table 16–4 Chemical parameters for consideration in monitoring

Chemical attribute	Parameter
Water clarity	Turbidity
Constituents	Dissolved and suspended solids Nutrients Toxins—natural and manufactured
Organic loading	Biological oxygen demand
Oxygen capacity	Dissolved oxygen
Water quality measures	Temperature pH Alkalinity/acidity Hardness

Table 16–5 Biological parameters for consideration in monitoring

Biological attribute	Parameter
Primary productivity	Periphyton Plankton Vascular and nonvascular plants
Zooplankton/diatoms	Species Numbers Diversity Biomass Macro/micro-organisms
Fish community	Anadromous and resident species Specific populations or life stages Number of out-migrating smolts Number of returning adults
Riparian wildlife/ terrestrial community	Amphibians Reptiles Mammals Birds Plants (invasive species)
Riparian vegetation	Structure Composition Function Changes in time (succession, colonization, extirpation)
Habitat structure	Spawning gravel Instream cover Shade Pool/riffle ratio Amount and size distribution of large woody debris

(b) Types of monitoring

The types of monitoring corresponding to the purposes of monitoring are:

- ecological or biological monitoring
- performance monitoring
- trends monitoring
- risk monitoring

For stream restoration projects, performance and ecological or biological monitoring are most important and are included here. While trends and risk monitoring may be very important, a complete discussion is beyond the scope of this chapter. More information is available in FISRWG (1998).

(c) Monitoring strategies

The strategy for collecting and using monitoring data is determined by:

- project type and constituent project structures and nonstructural features (Design documents for the project and restoration (Fischenich and Allen 2000; Johnson, Pittman, et al. 2001) provide information on potential project design features and parameters for monitoring.)
- monitoring parameters identified as important for the project's performance
- type and purpose of monitoring
- resources available (funding) for monitoring

Low effort monitoring
All stream restoration projects require some inspection and monitoring to ensure performance and identify problems and unexpected occurrences. Agency funding for projects often ends with construction, and postimplementation or operations funding is dedicated to maintenance costs. Several low-effort or low-tech monitoring strategies are possible:

- Site visits to future ongoing planning or construction projects can incorporate side trips to the project site. A simple windshield survey and walk-through observation trip can provide valuable monitoring information.
- Local volunteer watershed and conservation organizations are often willing to include monitoring as part their activities. Training of the groups to perform the monitoring and reporting is necessary, but these groups can become valuable eyes and ears for the project (U.S. Environmental Protection Agency (EPA) 1997).

Photographic record
Photographic documentation may provide the information needed for monitoring and is a cost-efficient strategy. For monitoring, repeat photography taken from the same location provides a visual record of changing conditions for soils and vegetation (Hall 2001). However, for a qualitative comparison, it is best to compare photos taken during the same season. This is especially important if vegetation is a major project component. Photographic monitoring is especially suited for documenting success of vegetative plantings, impacts of humans and livestock, and changes in channel gradient and bankline stability (Governor's Watershed Enhancement Board 1993). Monitoring for a project is determined by the objectives and parameters identified in the monitoring plan. Monitoring with photography requires:

- determining specific objectives
- using a repeatable technique
- choosing appropriate camera and media (digital and film)
- developing a filing system (Hall 2001)
- establishing fixed and permanent reference points so that photographs can be compared over time

The frequency for acquiring photography is determined by the parameters monitored. Videography and other remote sensing image acquisition may also be an efficient mode of collecting this information.

Monitoring programs and surveys
A monitoring plan establishes the details of the program for measurement of the selected parameters. The monitoring plan includes (adapted from Washington Departments of Fish and Wildlife, Transportation, and Ecology 2003):

- statement of monitoring objectives
- hypotheses or key questions to be answered

- monitoring parameters
- monitoring protocol
- analysis and use of the information

Statement of monitoring objectives—Identifies the purpose and type of monitoring (project performance) and the project objective (improvement in channel stability, bank stability, and improvement in natural conditions). The direct connection of project objectives to monitoring objectives enables monitoring results to be used for modifying designs and operations to better achieve project goals.

Monitoring parameters—Measurement of the parameters identified as being important for monitoring should be specified in the monitoring plan. Monitoring intensity and evaluation techniques are specified for each of the parameters.

Monitoring intensity—Refers to the level of detail required in the monitoring process; that is, the level of detail required for making decisions on the monitoring objectives (Washington Departments of Fish and Wildlife, Transportation, and Ecology 2003). In some cases, yes/no or good/fair/poor responses provide sufficient information. In other cases, quantitative measurements and modeling are needed to answer monitoring questions. Differences between qualitative and quantitative methods (time, analytic requirements) may determine the level of detail possible within project constraints.

Evaluation techniques—The types of analysis methods used (cross-sectional survey) to monitor the selected parameters. The field sampling methods may differ regionally and for species or habitats. Information for field sampling methods should be identified or developed by NRCS regional engineering and natural resources personnel and project design personnel. This approach ensures that the monitoring will reflect the study area conditions.

Monitoring protocols—For each parameter that has been selected to be monitored, a protocol for implementing the evaluation technique is described. As with evaluation techniques, protocols should be identified or developed by those experienced with local or regional conditions. Protocols normally include (Washington Departments of Fish and Wildlife, Transportation, and Ecology 2003):

- specification of methods and geographic extent of measurements
- identification of monitoring period and frequency
- design of monitoring forms for data collection
- description of data-analysis techniques

654.1603 Developing plans for maintenance

Maintenance of constructed projects ensures that the project operates or performs as intended. Maintenance requirements depend on the project type and level of risk, project goals, and level of effort or resources available for maintenance. The important categories of maintenance are (Martin and Fisher 2002):

- hydrology
- geomorphology
- vegetation
- domestic animals/livestock
- wildlife
- people

Types of maintenance are (FISRWG 1998)

- scheduled maintenance
- remedial maintenance
- emergency maintenance

(a) Project type requirements

Channels and flood plains
Projects establish or restore stability to channels and flood plains. The maintenance of design conditions for hydrology and streambank and flood plain stability often requires scheduled maintenance of project features. Project objectives often include sustainability of the system (FISRWG 1998). Establishment of a dynamic equilibrium requires less extensive maintenance efforts than objectives for maximum hydraulic capacity or other objectives requiring more extensive and frequent maintenance actions. The maintenance requirements specific to the structures, materials, and construction methods can be identified by examining the design documentation and local project conditions for the project. Table 16–6 contains lists of parameters in the stream corridor that could be considered for maintenance.

Protection/enhancement measures
Management measures (structures, vegetation, management actions) that protect streambanks, deflect flows, and improve habitat conditions require periodic maintenance. Failure of the measures after construction should be evaluated to determine if the design or construction method should be altered, rather than just repaired (FISRWG 1998).

Table 16–7 contains a list of possible maintenance actions that may be required for specific protection and enhancement features.

Boulders and other instream features should be maintained to ensure proper functioning. Revetments and heavy or hard protection features require inspection and potential repair and addition of materials. The vegetation of soft protection systems requires inspection to determine survival and level of protection from the vegetation. Hybrid measures, using vegetation in combination with geogrids, geotextiles, and cellular blocks, require maintenance of structural components such as loss of geotextile material and replacement or replanting of vegetation (Fischenich and Allen 2000). The intent of some streambank and channel features is to provide temporary stabilization until riparian vegetation develops and establishes more stable channel bank conditions, so that maintenance of protection/enhancement features will become less important over time (FISRWG 1998).

Vegetation
After construction, monitoring should be frequent enough to evaluate how vegetation establishment progresses (Winward 2000). Many projects that rely on soil bioengineering require that the vegetation become firmly established before experiencing a significant flow event. If a significant event occurs before the vegetation is established, replanting may be necessary. If replanting, protective measures, or irrigation are needed after construction, these actions can be undertaken to ensure that vegetation is established in sufficient abundance and distribution. After establishment of vegetation, project operation requires that it be maintained in a specified abundance and location to achieve project objectives, but not become excessive enough to interfere with water, sediment, or wildlife movement. Maintenance requirements range from mowing of terraces to clearing of excess woody debris, depending on the vegetative component. The

Table 16–6 Maintenance actions for channel and flood plain projects

Project location	Maintenance actions
Channel	Structures—repair of: Grade control—rock, concrete, Weirs Rock vanes Island and bar preservation, development Bank toe stabilization—rock, vegetation Rock barbs Removal of: Nuisance aquatic vegetation Woody debris accumulation
Flood plain	Repair or reformation of bank grading Actions to address encroachments Maintaining planned boundaries and conditions for rights of way Replanting or adding new vegetation due to poor establishment or lack of survival
Buffer strips, setbacks, easements	Establishment of boundaries after encroachments by adjacent land uses
Meander bends	Stabilization of eroding or unstable banks Seeding of newly formed areas

Table 16–7 Maintenance actions for different protection/enhancement features

Protection/enhancement features	Maintenance actions
Streambank stability	Repair bank armoring structures (stone filled revetments, soil-covered riprap, cellular blocks, geogrid, gabions, geotextile fabrics, soil cement, bulkheads) Terrace zone—seeding, vegetation establishment, mulching
Stream/habitat features	Repair, replacement, expansion of fish cover structures Repair, replacement of pool/riffle rocks and structures
Vegetation	Removal of excess woody vegetation Repair, maintain irrigation, water availability Replanting, replacement of trampled, dead, or impaired vegetation Maintain, repair, and replace fencing, signage, and barriers for vegetation protection Repair or replacement of brush mattress, matting, or other soil bioengineering materials Seeding or reseeding Mulching for plant and soil stability
Access and human use structures	Clearing of access pathways for humans and livestock Cleaning and repair of recreation structures—picnic tables, boat ramps, parking areas Cleaning and repair of restroom facilities

vegetation section of table 16–6 identifies potential actions to consider in vegetation management.

Access and human-use features

Many projects incorporate access points for human uses such as fishing, wildlife access, and agriculture (cattle). Recreation boat ramps, picnic areas, and restroom facilities can be incorporated into projects, increasing public use and the value of the project. These human-use features require a higher level of maintenance to meet public expectations. Exceeding the carrying capacity of the resource by too many visitors or livestock can lead to degradation and erosion of streamside lands and excessive inputs of nutrients and pollutants to the channel. Table 16–6 identifies maintenance activities for the access and human-use features.

(b) Maintenance considerations

Project-specific factors should be considered in planning for maintenance. The necessary maintenance activities for project design features are modified in light of risk, project goals, and level of effort.

Risk

In considering project monitoring and maintenance, risk pertains to the probability of project failure if maintenance is not performed. Numerous circumstances, from budgetary to natural events such as flooding, can prevent maintenance from occurring. Project planners must evaluate how susceptible a project design is to risk of failure if maintenance does not occur, is reduced in scope, or delayed. Projects that rely on structural features may be at less risk than projects dependent on natural or biological components (vegetation maintenance).

Project goals

Project goals and objectives require that maintenance activities be performed to achieve the levels of hydrologic and environmental outputs. Success or performance criteria may be developed for the objectives, specifying the quantities and levels required for project functioning. These criteria help in identifying the maintenance intensity and evaluation techniques required.

Level of effort

The level of effort or available resources (funding, equipment, labor) for maintenance should be considered in design and planning for maintenance. Maintenance plans should reflect the available personnel and other resources.

654.1604 Monitoring and maintenance plan documentation

Preparation of a plan for monitoring is similar to a plan for maintenance. In fact, these two activities are often considered together as part of the plan documentation. Plans for maintenance and monitoring are developed from goals and objectives (NEH654.02). The steps for plan preparation presented here are adapted from Components of a Monitoring Plan, Part 6B of the FISRWG (1998). The guidelines set out three steps for preparing a plan:

- project planning
- implementing and managing the project
- responding to monitoring results

(a) Planning

There are seven steps for planning a monitoring plan.

Step 1 Define the stream restoration project goals and objectives.

Restate the goals and objectives identified as part of project planning (NEH654.03).

Step 2 Develop a conceptual model of the stream, flood plain, and watershed.

A conceptual model serves to communicate relationships of water, geomorphic conditions, and biota (Henderson and O'Neil 2005). The model can be used to identify changes and impacts in the system.

Step 3 Choose performance criteria.

Performance criteria are standards to evaluate to what extent the project is achieving desired or designed outcomes. The performance criteria identify in quantitative terms (defined metrics) or qualitative terms (absence/presence) the results or outcomes of project operation. The Federal Guidelines (FISRWG 1998) provide three components for choosing performance criteria.

Link performance to goals—Goals and objectives for the project should articulate the specific outcomes and results that are expected and intended from the project. The hydrologic, geotechnical, and ecological needs and opportunities identified in planning should have resulted in clear statements for project performance. Performance criteria are meant to assess progress toward the goals. If the goals and objectives are not clear enough for identifying performance criteria, then clarification, interpretation, or explanation of the goals and objectives must be done. The effort to understand or clarify goals will allow establishment of performance criteria that are closely aligned with stated goals.

Develop the criteria—The primary reason for a maintenance and monitoring plan is to assess progress and to indicate the steps required to fix a system or component of the system that is not successful (FISRWG 1998). To that end, the performance criteria and monitoring parameters should be developed as indicators of success. Performance criteria are usually developed through an iterative process that involves listing measures of performance relative to goals and then refining them to develop the most efficient and relevant set of criteria (FISRWG 1998). Criteria are usually specified as levels of outputs (hydraulic capacities, ranges, minimums, maximums, or threshold measurements).

Maintenance performance criteria—Structural, vegetative, and management measures (such as grazing controls) are incorporated into stream restoration project designs because they provide the desired project outputs in terms of necessary hydraulic capacities, levels of protection, and habitat benefits. The necessary maintenance actions are determined by the requirements of the measures. Information from the design phase can be used for maintenance performance of structural components (design sizes, capacities). Maintenance of natural resource and vegetative components is influenced by design requirements, such as level of protection, and by natural conditions. Maintenance of management measures requires identifying the actions, such as repair of fences, needed so that the management measure functions properly (tables 16–6 and 16–7).

Monitoring performance criteria—Performance criteria for the monitoring plan establish the acceptable or desired levels for the parameters being monitored. The performance criteria are based on comparison of the parameter's measurement to the agreed on performance criteria. The monitoring parameters identified (tables 16–3 through 16–5) are measured in the field and compared to performance criteria.

Identify reference sites—Reference sites are channel study areas that are similar to the project channel, but not in need of stabilization. These sites represent the study area if it were undisturbed or stable. Figure 16–1 shows the proximity of the Teton River reference site to the Fox Creek restoration site in Idaho. Conditions (hydrologic, geomorphic, habitat) at the reference site represent the conditions that are the goals of the project. By examining the conditions at the reference site, the study team can ascertain the level of success that is possible from the project. Pre- and postconstruction evaluations can measure the change or impact from the project, but the level of success can be judged only relative to reference systems (FISRWG 1998).

Step 4 Choose maintenance and monitoring parameters and methods.

The purpose of maintenance and monitoring is to ensure the project performs the hydrologic, geomorphic, and habitat functions that are the basis of goals and objectives and project design.

Monitoring parameters—

- Table 16–8 (FISRWG 1998) identifies general project objectives and potential evaluation tools and criteria. As pointed out, the goals and objectives lead to identification of particular parameters for monitoring. Tables 16–3 through 16–5 contain more complete lists of parameters.
- The National Research Council (1992) recommends that parameters include physical, hydrological, and ecological measures. In this way, a holistic assessment of the stream and flood plain is possible. Using reference sites, pub-

Figure 16–1 Fox Creek, ID, case study reference site

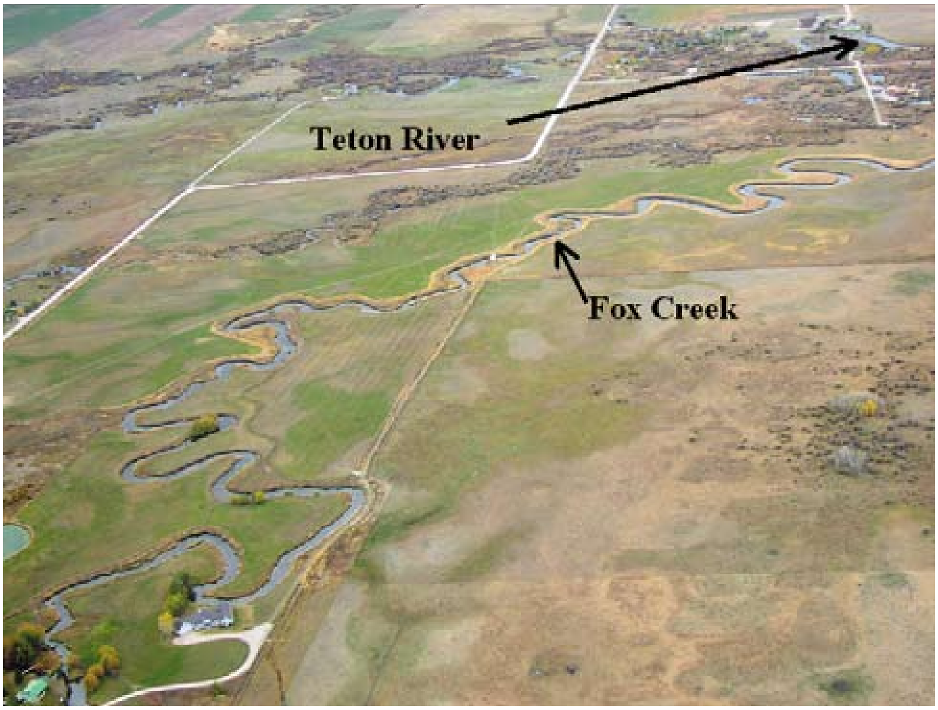


Table 16–8 General project objectives and potential evaluation tools and criteria

General objectives	Potential evaluation tools and criteria
Channel capacity and stability	Channel cross sections Flood stage surveys Width-to-depth ratio Rates of bank of bed erosion Longitudinal profile Aerial photography interpretation
Improve aquatic habitat	Water depths Water velocities Percent overhang, cover, shading Pool/riffle composition Stream temperature Bed-material composition Population assessments for fish, invertebrates, macrophytes
Improve riparian habitat	Percent vegetative cover Species diversity Size distribution Age class distribution Plantings survival Reproductive vigor Wildlife use Aerial photography
Improve water quality	Temperature pH Dissolved oxygen Conductivity Nitrogen Phosphorous Herbicides/pesticides Turbidity/opacity Suspended/floating matter Trash loading Odor
Recreation and community involvement	Visual resource improvement based on landscape control point surveys Recreational use surveys Community participation in management

lished literature, and applicable standards, performance criteria are identified or developed for the physical, hydrological, and ecological monitoring parameters.

- The effects of watershed activities on the project should be considered when identifying parameters. Activities in the watershed can affect the success of the project and cause changes in monitoring parameters not related to the project. Land use changes in urban settings produce changes in water runoff and movement that should be accounted for in monitoring plans. Rural areas similarly undergo land use changes, but the changes are usually slower to take place.
- A holistic view of stream conditions should be pursued using the minimum necessary measurements. While comprehensiveness and redundancy may be desirable, this may be costly and unnecessary.

Monitoring methods—Protocols for monitoring the parameters identified as important are either identified from available sources or developed to meet the channel and regional conditions. Covering sampling and analysis methods for the range of potential monitoring parameters is beyond the scope of this chapter.

Monitoring profiles—Monitoring plans require establishing the physical location from which parameters are measured. Depending on the monitoring parameters needed to determine performance, monitoring is undertaken from a cross-sectional profile, longitudinal profile, or from bankline surveys. However, while it should be noted that other survey techniques and protocols are in use, the ones described herein are the most common.

Channel cross-sectional profile—The channel cross-sectional profile is typically used to monitor bank and channel morphology. The cross section is located across the stream perpendicular to the direction of stream flow. The cross section is used to measure bank and channel elevations, referenced to a benchmark over time. In this way, stability or changes of the bank and channel location can be determined. The channel cross section is used for projects with objectives for stabilizing meandering channels; consolidating multiple, shallow, or braided channels; establishing stable near bank habitat areas; or stabilizing channel slopes.

The cross-sectional survey involves placing endpoints and a benchmark on the stream terrace or stable flood plain, establishing sampling points, taking documentary photographs, and measuring elevations with a surveyor's level (Harrelson, Rawlins, and Potyondy 1994). At least 20 elevation measurements are usually taken at significant breaks of slope that occur across the channel. The active terrace and flood plain may be included in the cross section, dictated by the project and project objectives. Resulting information produces a channel cross section as in figure 16–2 (adapted from Harrelson, Rawlins, and Potyondy 1994). Channel slope can be determined by taking additional elevation measurements upstream and downstream from the cross sections and calculating the changes in slope. In this way, a survey plot of the stream channel and features can be developed (fig. 16–3 (adapted from Harrelson, Rawlins, and Potyondy 1994)).

As elevation measurements are taken, sampling for chemical attributes, sediment, and some biological attributes such as habitat structure (table 16–5) can be obtained at the same time. Harrelson, Rawlins, and Potyondy (1994) provide guidance on basic surveying techniques.

Longitudinal profile—The longitudinal profile establishes how the stream and flood plain change in elevation as the stream flows through the study reach. The slope is determined by successive measurements of water surface, channel bottom, bankfull stage, flood plain, and terraces. Most biological attributes (table 16–5) have distribution, size, or density dimensions requiring measurement over an area, not just a cross section. Establishing longitudinal monitoring sample locations is appropriate for projects that stabilize headcutting, restore riparian vegetation or aquatic habitat, and for some erosion protection projects.

Establishment of a permanent longitudinal profile for monitoring requires identifying a permanent location that has the project features (vegetation) that are important to monitoring. The longitudinal profile should encompass an area 300 to 500 feet along the stream (or approximately 20 times the channel width at bankfull). The survey should be wide enough to measure both banks,

Figure 16–2 Diagram of a cross-sectional survey

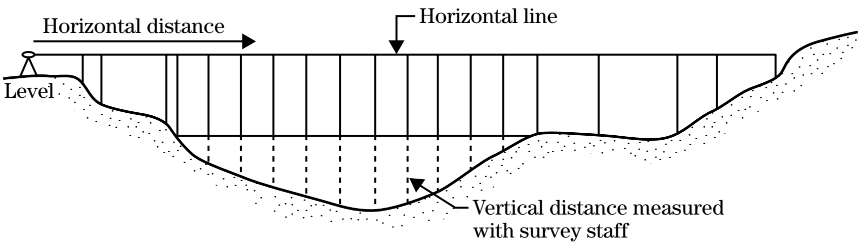
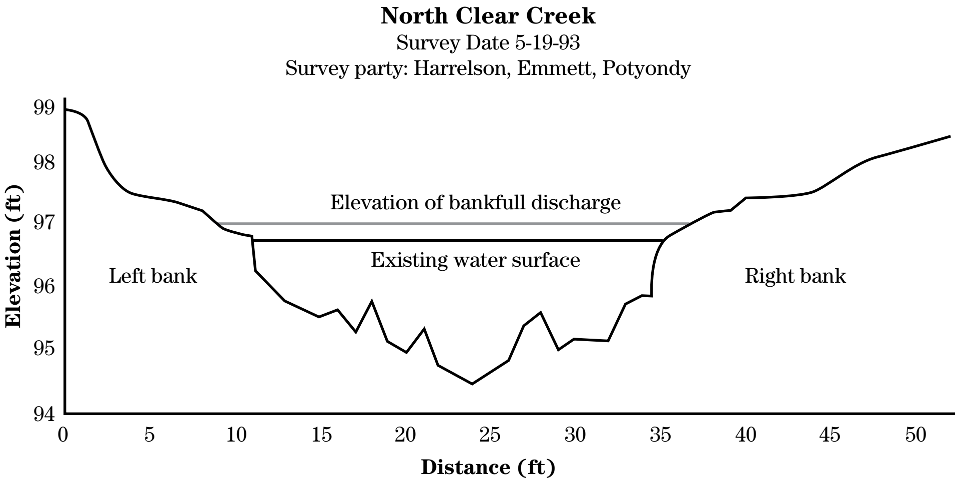


Figure 16–3 Final plot of cross section



the active flood plain, and one or more terraces. A benchmark is established and stations are located at intervals along the longitudinal profile. A surveyor's level is used to measure the elevations of the channel bottom, water surface, terrace, and flood plain. Plotting of the elevation data along the longitudinal profile results in a plot of the slopes (fig. 16–4).

Bankline surveys—The objectives of some projects are to define or stabilize the bankline, provide capacity for a certain bankfull discharge, or maintain a consistent bank width between reaches. For these projects, bankline surveys are used to monitor change in the bank position, determining if the width between the banks is consistent over time and consistent between reaches of the stream. Bankline surveys are implemented by establishing permanent points along the bankline to be measured over time. In low-gradient, meandering systems, the flood plain is well defined and bankfull stage is clearly marked. Where the flood plain is absent or poorly defined, it may be necessary to establish benchmarks or natural indicators as surrogates, such as vegetation, for the top of bank (Harrleson, Rawlins, and Potyondy 1994). The locations of the bankline reference points are documented and physically benchmarked. The bankline's lateral extent into the flood plain and bank-to-bank width are measured and documented over time.

If bank location and width between channel reaches are of concern, a series of reference bankline points are identified. Monitoring the reference points over time will identify changes in location and width of the bankline along the stream. Changes in width between reaches indicate that the cross sections are changing between sections, and the cause or source of these changes should be identified.

Step 5 Estimate costs.

Costs for maintenance and monitoring plans include:

- personnel and management costs to implement plan
- quality assurance
- data management
- field sampling
- data analysis and interpretation
- maintenance and monitoring report preparation
- presentation of results and recommended changes

Figure 16–4 Graphic representation of longitudinal profile

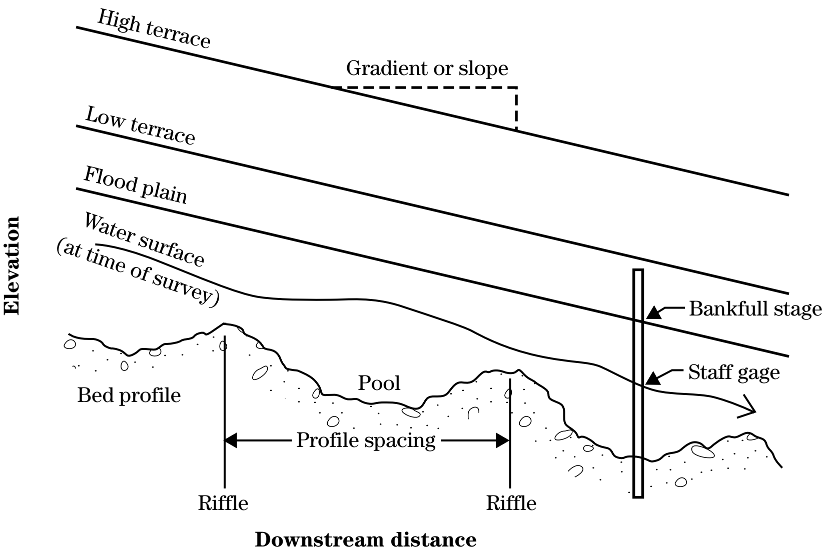


Table 16–9 categorizes the relative costs of monitoring and maintenance as high, medium, and low. Costs vary with region and the intensity and frequency of monitoring and maintenance.

Step 6 Categorize the types and emphasis for data.

The emphasis on data collection changes as the project progresses from planning to implementation to postimplementation.

Planning—

- develop baseline data at the site

Implementation of project—

- monitor construction and management activities
- collect as-built and as-constructed information

Postimplementation—

- collect performance data
- conduct other studies as needed

Step 7 Determine the level of effort and duration.

The level of effort needed for maintenance and monitoring is determined by the goals, objectives, and performance criteria identified in step 3. Maintenance for structures and vegetation is required to meet goals of the project in terms of stabilization, channel capacity, and environmental considerations (FISRWG 1998). The level of effort for monitoring is determined by the goals and objectives and by the end use of the monitoring data. Water quality monitoring to determine whether state water quality standards are met requires a higher level of effort (frequency, data gathered) than monitoring for public access.

Frequency—Frequency of maintenance actions is determined by the type of structure, vegetation, or management measure that is part of the project. Ensuring the proper functioning of the design requires development of maintenance schedules by the responsible agency personnel. For monitoring of physical, chemical, and biological parameters,

Table 16–9 Relative costs of monitoring actions

Type of monitoring and maintenance	Relative costs
Photographic monitoring	Moderate
Windshield survey monitoring	Low
Volunteer monitoring	Low
Cross-sectional profile	High
Longitudinal profile	High
Bankline survey	High
Track watershed trends	Moderate
Chemical parameter monitoring	Low
Biological monitoring	
Primary productivity	Moderate
Fish community	Moderate
Riparian vegetation	High
Habitat structure	High

a sampling plan is developed for the parameter or group of parameters (water quality parameters). Frequency of maintenance and monitoring may decrease as the project and system becomes more established and rates of change decrease. For instance, monitoring of a project may be done annual for the first 3 years, followed by monitoring at 2- to 5-year intervals for the duration of project life.

Duration—Maintenance and monitoring should extend long enough to determine either:

- reasonable assurances of sustainability of the project
- that the system has met performance criteria
- that the system will not likely meet the criteria

Timing—Timing of maintenance activities is important so that structural and vegetative components remain functional. With designs that incorporate soil bioengineering approaches and vegetation, the period after construction is critical to establishment and success of the measures, so higher levels of maintenance and monitoring are required in the immediate postconstruction period. In the winter periods, vegetation and other conditions may not be relevant to the performance criteria and project objectives. Monitoring should be carried out during the time of the year when vegetation and streamflow conditions approximate the conditions used for design.

Sensitivity—The sensitivity of the parameter to change will also determine the level of effort and duration needed to detect a change. In some cases, this may require some statistical analysis. If this is required, it may be appropriate to consult a statistician during the design of the monitoring plan.

(b) Implementing and managing monitoring

Planning for maintenance and monitoring occurs while site design and construction plans are underway and there is normally a great deal of activity. Following construction and beginning of operation of the project, it is important that the monitoring plan is implemented successfully. This takes deliberate effort by the operating agency or authority, with the emphasis then on project operation. Consult the Interagency Guidelines (FISRWG 1998) for suggestions and insights for implementing and managing the monitoring plan.

(c) Responding to monitoring results

Monitoring provides information on performance, biological resources, trends, and risks. The monitoring information serves as the basis for making modifications to the project and operations. The adaptive management section below presents a process for responding to monitoring results. If long-term water quality monitoring shows that the performance criteria are met, then water quality can be considered for deletion from future monitoring. If biological parameters show a lack of nonjuvenile fish, then a fisheries investigation may be indicated. If performance monitoring indicates that performance criteria are not being met, an investigation of the cause should be initiated. This may lead to modification of the project or to the identification of changing conditions within the watershed.

654.1605 Adaptive management

(a) Background for adaptive management

Stream restoration and/or stabilization projects are part of dynamic systems, and over time the project outcomes will likely change (increase or decline) as project life increases. Aquatic habitat, streambank and riparian communities, water flow capacity, and other project conditions may show improvements or deteriorations. Sometimes, there is uncertainty on the point of sustainability (equilibrium), relative to sedimentation, streambank location, or habitat diversity. The prevailing assumptions on which project objectives are based may prove to be erroneous. System relationships and connections may be weak or nonexistent, watershed and local conditions may change, or project design measures may be overkill, and lesser levels of structures, maintenance, or human interference may be called for. The uncertainty in project outcomes and the need for change in project design, operation, and management have given rise to adaptive management. Adaptive management is an approach to natural resource management that incorporates monitoring of project outcomes and uses the monitoring results to make revisions and refinements to ongoing management and operations actions (adapted from National Academy of Science 2002). Figure 16–5 shows the relationship of adaptive management to monitoring, construction, and planning.

(b) Maintenance program and adaptive management

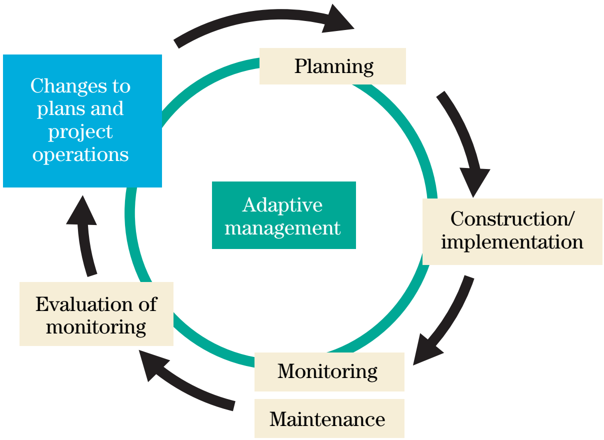
The maintenance and monitoring plans described result in information on project performance (hydrological, geomorphic) and ecological (habitat, water quality) outputs of the projects. In a sense, the system composed of the operating stream restoration project is like an experiment, and the monitoring reports are the findings for the experiment. Assumptions may be proved or disproved, and understandings of relationships may change based on monitoring information. Adaptive management, therefore, incorporates an element of research into conservation projects. Specifically, it is the integration of design, management, and monitoring to systematically test assumptions to adapt and learn (Salafsky, Margoluis, and Redford 2001).

(c) Adaptive management and NRCS projects

The increasing number of projects that incorporate experimental designs and rely on hydrologic, geomorphic, and riparian processes for success has led to application of adaptive management in large and small systems (Save Our Bosque Task Force 2004). Examples of references to adaptive management are (USDA NRCS 1996a):

- Year two process will develop this concept further at the local decisionmaking level. The findings of the interrelationship of ecosystem components will be better understood and promoted for broader planning approaches (ecosystem, whole farm, holistic).
- Steering committee/subcommittee structure with regular meetings and technical input will allow for adjustments to reflect the results of periodic reviews and new scientific information or methodologies. The plan will be revisited regularly and modified as needed.
- Data collected as part of the project monitoring process will be analyzed. Results will be shared to determine if further study is warranted.

Figure 16–5 Adaptive management



(d) Adaptive management in the maintenance and monitoring process

Adaptive management is a part of project operations, most closely related to monitoring. Separate adaptive management programs may be established for larger systems (Raynie and Visser 2002). For most stream restoration projects, reviews of monitoring and inspection information will likely initiate changes in monitoring, maintenance, and operations.

Adaptive management evaluation
Monitoring information is reviewed to answer the following questions (FISRWG 1998):

- Were the project structures, vegetation, and management measures constructed and implemented correctly?
- Did the project measures achieve the desired goals and objectives of the project?
- Are the assumptions used in the project design and cause-effect relationships correct?

Changes resulting from adaptive management evaluations
Revision of project operations, monitoring, and maintenance procedures are identified through adaptive management evaluation. These changes should be incorporated in the project maintenance and monitoring plans and in project operations documentation.

654.1606 Conclusion

Any open channel design work, whether it is a natural stream restoration or a single-purpose design, is done to achieve some specific planned goals or objectives. Maintenance and monitoring plans are often overlooked. However, these are important components of stream design and restoration projects. Monitoring plans ensure that a project is performing as designed and achieving the intended goals. All open channel projects carry some level of inherent risk to life, property and project investment, and monitoring, maintenance, and adaptive management can reduce these risks. Monitoring may also help to avoid catastrophic project failure by identifying problems or performance issues while they can be more cheaply addressed. Finally, the lessons learned from monitoring can be applied to future projects of similar type.

Maintenance is the set of actions taken to ensure that a project's goals or objectives continue to be met. Maintenance may involve the repair of specific project features in response to some damage or the periodic and/or scheduled actions. While projects should be designed to minimize maintenance requirements, the designer should consider what may be required and how it can be linked to the monitoring plan. An ideal maintenance and monitoring plan should provide specific parameters to be assessed to ensure that the project is performing as intended, as well as what maintenance actions should be undertaken.

Adaptive management is an approach to natural resource management that incorporates monitoring of project outcomes and uses the monitoring results to make revisions and refinements to ongoing management and operations actions.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 17 Permitting Overview

Issued August 2007

Cover photo: Federal, state, local, and tribal laws, ordinances, and permitting requirements must be thoroughly recognized and understood during the restoration planning process.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 17 Permitting Overview

Contents

Tables

Figures

Chapter 17 Permitting Overview

654.1700 Purpose

Stream restoration and design activities are subject to various Federal, state, and local regulatory programs. Most of these regulations are aimed at protecting natural resources and the integrity of the Nation's water resources. This chapter provides a brief overview of the regulatory authorities and programs that may be applicable to stream design work. The focus of this chapter is to provide an awareness-level understanding of this important issue and to list sources where current information can be obtained. The reader should not interpret the information herein as the only source of regulatory requirements. Federal, state, and local regulatory authorities should always be researched and consulted as part of the initial planning and design efforts.

654.1701 Introduction

Every stream design or restoration effort is subject to regulatory requirements. Designers should be aware of project permitting requirements and develop a project plan and budget identifying resources and project approaches that meet permit conditions. Depending on the type of project and its location, these can range from minimal to a full set of required Federal, state, and local permits. The applicable programs and permits can include:

- National Environmental Policy Act
- Endangered Species Act
- National Historic Preservation Act
- Wild and Scenic Rivers Act
- Fish and Wildlife Coordination Act
- Clean Water Act
- Rivers and Harbors Act of 1899
- Magnuson-Stevens Fishery Conservation and Management Act
- Local and state water quality permits
- Water rights
- National Flood Insurance Program
- Local and state flood permits
- Local zoning permits

655.1702 Initiating a permitting process

Permitting agencies should be approached as soon as conceptual plans are developed. In regulatory-intensive areas, as well as in areas of high environmental risk, it may be advisable to consult with them in the early planning stages. In general, designers and planners should provide at least the following to the permitting agency:

- site map
- description of existing environmental conditions (written and maps, photos, drawings)
- description of the proposed work (written and drawings)
- property ownership
- access and staging information
- preferred times of implementation

Refer to permitting agency guidance (usually available online), or contact an agency representative for additional information on what to provide. Local planning agencies often are able to steer designers towards the applicable Federal and state agencies and requirements. Table 17–1 provides some examples (Federal Interagency Stream Restoration Working Group (FISRWG) 1998).

654.1703 U.S. Army Corps of Engineers Regulatory Program

One of the most prominent national permitting requirements is the regulatory program administered by the U.S. Army Corps of Engineers (USACE). The mission of the USACE Regulatory Program is to protect the Nation's aquatic resources, while allowing reasonable development through fair, flexible, and balanced permit decisions. Streams, wetlands, and other water features are important in protecting overall water quality, fish and wildlife habitat, flood storage, natural products, recreation, aesthetics, and navigation.

The USACE evaluates permit applications for most construction activities that occur in the Nation's waters, including wetlands. USACE permits are also necessary for any work in, or affecting the Nation's navigable waters, including construction and dredging. The USACE balances the reasonably foreseeable benefits and detriments of proposed projects and makes permit decisions that recognize the essential values of the Nation's aquatic ecosystems to the general public, as well as the property rights of private citizens who want to use their land. During the permit process, the USACE considers the views of other Federal, state, and local agencies; interest groups; and the general public. The intended result of this public interest review is fair and equitable decisions that allow reasonable use of private property, infrastructure development, and growth of the economy, while offsetting the authorized impacts to the waters of the United States. The adverse impacts to the aquatic environment are offset by mitigation requirements, which may include avoiding and minimizing impacts to, as well as restoring, enhancing, creating, and preserving, aquatic functions and values. The USACE strives to make its permit decisions in a timely manner that minimizes impacts to the regulated public.

The USACE administers and enforces the regulatory program over waters of the United States, including wetlands and navigable waters, through its Regulatory Program. The day-to-day administration of the Regulatory Program is accomplished through the USACE district offices. USACE offices for each zip code and points of contact within the USACE Regulatory Program are listed on the USACE Web site at:

http://www.usace.army.mil/inet/functions/cw/cecwo/reg/

Table 17–1 Examples of permit requirements for restoration activities

Local/state

Permits required	Activities covered	Administered by:
Varies—thresholds and definitions vary by state	Clearing/grading, sensitive/critical areas, water quality, aquatic access	Local grading, planning, or building departments; various state departments

Federal

<table>
<tr><th colspan="3">Permits required</th><th>Activities covered</th><th>Administered by:</th></tr>
<tr><td colspan="3">Section 10, Rivers and Harbors Act of 1849</td><td>Building of any structure in the channel or along the banks of “navigable waters” of the United States that changes the course, condition, location, or capacity</td><td>USACE</td></tr>
<tr><td rowspan="7">Section 404, Federal Clean Water Act</td><td colspan="2">Letters of permission</td><td>Minor or routine work with minimum impacts</td><td rowspan="7">USACE</td></tr>
<tr><td rowspan="4">Nationwide permits</td><td>3</td><td>Repair, rehabilitation or replacement of structures destroyed by storms, fire, or floods in past 2 years</td></tr>
<tr><td>13</td><td>Bank stabilization less than 500 feet in length solely for erosion protection</td></tr>
<tr><td>26</td><td>Filling of up to 1 acre of a nontidal wetland or less than 500 linear feet of nontidal stream that is either isolated from other surface waters or upstream of the point in a drainage network where the average annual flow is less than 5 ft^3/s</td></tr>
<tr><td>27</td><td>Restoration of natural wetland hydrology, vegetation, and function to altered degraded nontidal wetlands, and restoration of natural functions of riparian areas on private lands provided a wetland restoration or creation agreement has been developed</td></tr>
<tr><td colspan="2">Regional permits</td><td>Small projects with insignificant environmental impacts</td></tr>
<tr><td colspan="2">Individual permits</td><td>Proposed filling or excavation that causes severe impacts, but for which no practical alternative exists; may require an environmental assessment</td></tr>
<tr><td colspan="3">Section 401, Federal Clean Water Act</td><td>Water quality certification</td><td>State agencies</td></tr>
<tr><td colspan="3">Section 402, Federal Clean Water Act National Pollutant Discharge Elimination System (NPDES)</td><td>Point source discharges, as well as nonpoint pollution discharges</td><td>State agencies</td></tr>
<tr><td colspan="3">Endangered Species Act Incidental Take Permit</td><td>Otherwise lawful activities that may take listed species</td><td>USFWS</td></tr>
</table>

(a) Legislative history

The legislative origins of the USACE regulatory program are the Rivers and Harbors Acts of 1890 (superseded) and 1899 (33 U.S.C. 401, et seq.). The authority is granted to the Secretary of the Army. Various sections establish permit requirements to prevent unauthorized obstruction or alteration of any navigable water of the United States. The most frequently exercised authority is contained in Section 10 (33 U.S.C. 403). The references mentioned are available on the USACE Web site at:

> *http://www.usace.army.mil/inet/functions/cw/cecwo/reg/*

Section 10 addresses construction, excavation, or deposition of materials in, over, or under such waters or any work that would affect the course, location, condition, or capacity of those waters. Section 9 addresses dams and dikes, Section 13 addresses refuse disposal, and Section 14 addresses temporary occupation of work built by the United States. Various pieces of legislation have modified these authorities, but not removed them.

In 1972, amendments to the Federal Water Pollution Control Act added what is commonly called Section 404 authority (33 U.S.C. 1344) to the USACE regulatory program. In it, the Secretary of the Army, acting through the Chief of Engineers, is authorized to issue permits, after notice and opportunity for public hearing, for the discharge of dredged or fill material into waters of the United States at specified disposal sites. Selection of such sites must be in accordance with guidelines developed by the U.S. Environmental Protection Agency (EPA) in conjunction with the Secretary of the Army. These guidelines are regulatory and are known as the 404(b)(1) Guidelines.

The discharge of all other pollutants into waters of the United States is regulated under Section 402 of the act, which supersedes the Section 13 permitting authority mentioned above. The Federal Water Pollution Control Act was amended in 1977 and given the common name of Clean Water Act and again amended in 1987 to modify criminal and civil penalty provisions and to add an administrative penalty provision.

Also in 1972, with enactment of the Marine Protection, Research, and Sanctuaries Act, the Secretary of the Army, acting through the Chief of Engineers, was authorized to issue permits under Section 103 for the transportation of dredged material for ocean disposal. This authority also carries with it the requirement of notice and opportunity for public hearing. Disposal sites for such discharges are selected in accordance with criteria developed by EPA in consultation with the Secretary of the Army.

(b) Geographic jurisdiction

The USACE, acting under Section 404 of the Clean Water Act and Section 10 of the River and Harbors Act of 1899, regulates certain activities occurring in waters of the United States and navigable waters of the United States. The term Waters of the United States is defined in 33 CFR 328.3, as:

> *(a) The term "Waters of the United States" means*
>
> *(1) All waters which are currently used, or were used in the past, or may be susceptible to use in interstate or foreign commerce, including all waters which are subject to the ebb and flow of the tide;*
>
> *(2) All interstate waters including interstate wetlands;*
>
> *(3) All other waters such as intrastate lakes, rivers, streams (including intermittent streams), mudflats, sandflats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds, the use, degradation or destruction of which could affect interstate or foreign commerce including any such waters:*
>
> *(i) Which are or could not be used by interstate or foreign travelers for recreation or other purposes; or*
>
> *(ii) From which fish or shellfish are or could be taken and sold in interstate or foreign commerce; or*
>
> *(iii) Which are used or could be used for industrial purpose by industries in interstate commerce;*
>
> *(4) All impoundments of waters otherwise defined as waters of the United States*
>
> *(5) Tributaries of waters identified in Paragraphs (a) (1–4) of this section;*
>
> *(6) The territorial seas;*

> *(7) Wetlands adjacent to waters (other than waters that are themselves wetlands) identified in Paragraphs (a) (1)–(6) of this section.*

Waste treatment systems, including treatment ponds or lagoons designed to meet the requirements of CWA (other than cooling ponds as defined in 40 CFR 123.11(m), which also meet the criteria of this definition), are not waters of the United States.

The limit of USACE jurisdiction under Section 404 in the territorial seas is 3 nautical miles seaward from the baseline along the shore. The limit in tidal waters of the United States extends to the high tide line in the absence of adjacent wetlands and extends to the limit of the wetlands when adjacent wetlands are present.

Ordinary high water

The limit of USACE jurisdiction in nontidal waters of the United States, in the absence of adjacent wetlands, is the ordinary high water mark. The ordinary high water mark is the limit of USACE jurisdiction for such water features as streams, reservoirs, lakes, and ponds. Ordinary high water mark is defined as that line on the shore established by the fluctuations of water and indicated by physical characteristics such as clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas. Even very small ephemeral streams may have an ordinary high water mark and be waters of the United States.

Wetlands

When adjacent wetlands are present, USACE jurisdiction under Section 404 extends beyond the ordinary high water mark to the limit of the adjacent wetlands. Wetlands are defined as those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. Delineations of wetlands must be conducted using the USACE of Engineers Wetland Delineation Manual, USACE Waterways Experiment Station Wetlands Research Program Technical Report Y–87–1, dated January 1987. (Online edition including all supplemental guidance is available on the USACE Web site at:

> *http://www.usace.army.mil/inet/functions/cw/cecwo/reg/wlman87.pdf*

Adjacent is defined as bordering, contiguous, or neighboring. Wetlands separated from other waters of the United States by manmade dikes or barriers, natural river berms, beach dunes and the like are adjacent wetlands. When the water of the United States consists only of wetlands, USACE jurisdiction extends to the limit of the wetland.

Wetlands are areas that are covered by water or have waterlogged soils for long periods during the growing season. Plants growing in wetlands are capable of living in saturated soil conditions for at least part of the growing season. Wetlands such as swamps and marshes are often obvious, but other wetland types are not easily recognized, often because they are dry during part of the year or do not look very wet from the roadside. Some of these wetland types include, but are not limited to:

- bottomland forests
- pocosins
- pine savannahs
- bogs
- wet meadows
- potholes
- wet tundra

The USACE uses the following three characteristics when making wetland delineations:

- vegetation
- soil
- hydrology

Unless an area has been altered or is a rare natural situation, wetland indicators of all three characteristics must be present for an area to be a wetland.

There are some general situations in which an area has a strong probability of being classified as a wetland. These conditions include:

- The area occurs in a flood plain or otherwise has low spots in which water stands at or above the soil surface during the growing season. **Caution: Most wetlands lack both standing water and waterlogged soils during at least part of the growing season.**
- The area has plant communities that commonly occur in areas having ponded or saturated soil conditions for part of the growing season (cypress-gum swamps, bottomland hardwood forests, cordgrass marshes, cattail marshes, bulrush and tule marshes, and sphagnum bogs).
- The area has hydric soils such as peats and mucks. While most soils map show areas of hydric soils that could be wetlands, it is important to note that there are soils, in addition to peat or mucks, that qualify as wetland soils.
- The area is periodically flooded by tides, even if only by strong, wind-driven, or spring tides.
- U.S. Geological Survey (USGS) topographic maps, National Wetland Inventory maps, U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) soil surveys, local NRCS office aerial photos that show wetland areas, and other Federal, state, and local maps and photos that provide wetland information.

If any of the above situations occur or if other conditions exist that indicate that a wetland or other water of the United States may be present, the designer should ask the local USACE office for assistance in making a determination. Procedures for determining the hydrology of wetlands and can provide guidance in determining the minimal effect provisions of wetland determination are provided in NEH630.19.

Navigable waters

Under Section 10 of the River and Harbors Act of 1899, the USACE regulates navigable waters of the United States, a subset of waters of the United States. Navigable waters of the United States are defined at 33 CFR 329 as those waters that are subject to the ebb and flow of the tide and/or are presently used, or have been used in the past, or may be susceptible for use to transport interstate or foreign commerce. A determination of navigability, once made, applies laterally over the entire surface of the water body, and is not extinguished by later actions or events which impede or destroy navigable capacity. The several factors which must be examined when making a determination whether a water body is a navigable water of the United States are listed. Generally, the following conditions must be satisfied:

- past, present, or potential presence of interstate or foreign commerce
- physical capabilities for use by commerce as in paragraph (a) of this section
- defined geographic limits of the water body

The limit of USACE jurisdiction for navigable waters of the United States for oceanic and tidal waters is the mean high tide line shoreward and 3 nautical miles seaward from the point where the shore directly contacts the open sea. The limit for rivers and lakes is the ordinary high water mark and jurisdiction extends to the entire water surface and bed of the water body.

Navigable waters of the United States include many coastal waters including bays and portions of major rivers. You may obtain information about navigable waters located within each USACE district by contacting that district.

Regulated activities

A permit is required from the USACE for discharges of dredged or fill material into waters of the United States (33 CFR Part 323). Dredged material is material that is excavated or dredged from waters of the United States (33 CFR 323.2(c)). The discharge of dredged material is material excavated or dredged from waters of the United States and redeposited into waters of the United States, runoff or overflow from a contained land or water disposal area, or the redeposit of dredged material other than incidental fallback (33 CFR 323.2(d)). Discharge of dredged material does not include discharges associated with onshore processing of dredged material extracted for commercial use, activities involving only cutting or removing vegetation so that root systems are not disturbed, or incidental fallback of dredged material.

Fill material is material that is placed into waters of the United States where the material has the effect of replacing a water with dry land or changing the bottom elevation of any portion of a water of the United States (33 CFR 323.2(e)). However, fill material does not include trash or garbage. The discharge of fill material is the addition of fill material into waters of the United States. The definition identifies activities that may be associated with the placement of fill including any structure or infrastructure; impoundments; recreational, industrial, commercial, residential, or other uses; causeways or roads; dams or dikes; artificial islands; property protection or reclamation devices; beach nourishment; levees; sewage treatment facilities; intake and outfall pipes; subaqueous utility lines; construction or maintenance of any liner, berm, or other infrastructure of solid waste landfill; placement of overburden, slurry or tailings or similar mining-related materials; and artificial reefs. Plowing, cultivating, seeding, and harvesting for the production of food, fiber, and forest products are excluded.

All discharges of dredged or fill material into waters of the United States require a permit, unless they are exempted or excepted in regulations. Section 404(f) exemptions (33 CFR 323.4) include normal farming, forestry, and ranching activities; maintenance of recently damaged structures; construction/maintenance of farm ponds and irrigation ditches; construction of temporary sedimentation basins; Section (208)(b)(4) approved state program activities; and construction/maintenance of farm, forest, and mining roads using approved best management practices. However, discharges that are a part of an activity whose purpose is to convert an area of waters of the United States to a use to which it was not previously subject, and the flow or circulation of waters of the United States would be impaired or the reach of such waters reduced, must have a permit.

For additional information about regulated activities and exemptions, the designer should contact the local USACE district office.

(c) Permitting

Activities requiring a permit from the USACE under Section 404 of the Clean Water Act or Section 10 of the Rivers and Harbors Act of 1899 may be permitted by General Permit or Individual Permit. There are three types of general permits: Nationwide General Permit, Regional General Permit, and Programmatic General Permit. There are two types of individual permits: letter of permission and standard individual permit. Standard individual permits require a public notice. Under Section 401 of the Clean Water Act, certification of compliance with state water quality standards by the state Water Quality Agency is required for any discharge of pollutants into waters of the United States. All Section 404 permits, individual or general, require Section 401 water quality certification. Conditions may be associated with state water quality certification and may apply to both individual and general permits.

General permits

A general permit is issued nationwide or regionally for a category or categories of activities that are either similar in nature and cause only minimal individual and cumulative adverse impacts (nationwide and regional general permits) or would result in avoiding unnecessary regulatory control exercised by another Federal, state, or local agency, and the environmental consequences of the activity would be individually and cumulatively minimal (Programmatic General Permit). General permits always include terms and conditions for compliance, may require preconstruction notification of the USACE, and may be issued for a period not to exceed 5 years (See 33 CFR 320.1 (c), 322.2 (f), 323.2 (h), 325.2 (e)(2), and 330).

Nationwide General Permit—A Nationwide General Permit (NWP) is a type of general permit issued nationally. The regulations that govern NWPs are found at 33 CFR 330. NWPs are valid for 5 years from the date of issuance. NWP regional conditions for may be adopted by each USACE district for a particular state.

Preconstruction notification (PCN) to the USACE is required in many cases, and resource agency coordination with the EPA, U.S. Fish and Wildlife Service (USFWS), and state water quality, fish and wildlife, and cultural resource agencies is required in some cases. A PCN to the USACE is required (even if a PCN is not otherwise required) if threatened or endangered species or its critical habitat may be affected by or is in the vicinity of the proposed activity, or if historic properties listed or eligible for listing in the National Register of Historic Places may be affected by the proposed project. No activity may be authorized if the continued existence of a federally listed threatened, endangered, or proposed threatened or endangered species is jeopardized or critical habitat is destroyed or adversely modified.

No activity which may affect historic properties listed or eligible for listing in the National Register of Historic Places is authorized until the district engineer has complied with the provisions of 33 CFR part 325, appendix C. The prospective permittee must notify the USACE if the authorized activity may affect any historic properties listed, determined to be eligible, or which the prospective permittee has reason to believe may be eligible for listing on the National Register of Historic Places and may not begin the activity until notified by the USACE that the requirements of the National Historic Preservation Act have been satisfied and that the activity is authorized. For activities that may affect historic properties listed or eligible for listing, in the National Register of Historic Places, the preconstruction notification must state which historic property may be affected by the proposed work and include a vicinity map indicating the location of the historic property.

The USACE has 30 days to review a PCN to determine if it is complete. PCNs must include:

- name, address, telephone number
- location of the proposed project
- brief description of the proposed project
- the project's purpose
- direct and indirect adverse environmental effects
- other nationwide permits or individual permits to be used
- other permit specific items for NWPs 7, 12, 14, 18, 21, 29, 33, 34, 38, 39, 40, 41, 42, 43, 44

If the PCN is not complete, the USACE can request the required information only once. Within 45 days of receipt of a complete PCN, the USACE must advise the prospective permitee of its determination whether the proposed activity meets the terms and conditions of the NWP, or exercise discretionary authority.

Resource agency coordination is required only for NWP activities that require a preconstruction notification to the USACE and result in the loss of greater than a acre of waters of the United States. If resource agency coordination is required, the agencies have 10 calendar days to notify the USACE that they intend to provide comments. If an agency so notifies the USACE, the USACE must wait an additional 15 calendar days for the comments. A signed compliance certification must be submitted by every permittee who has received NWP verification from the USACE. Postconstruction reports are required for nonreporting NWP 39 (residential, commercial, and institutional developments).

A permittee may use more than one NWP to authorize a single and complete project, provided the acreage loss of waters of the United States does not exceed the highest specified acreage limit of the NWPs used to authorize that single and complete project. Projects must be designed and constructed to avoid and minimize adverse effects to waters of the United States to the maximum extent practicable at the project site. Mitigation in all forms (avoidance, minimization, and compensation) may be required to the extent necessary to ensure minimal adverse impacts on the aquatic environment.

NWP 27 authorizes certain activities in waters of the United States associated with the restoration of former waters, the enhancement of degraded tidal and nontidal wetlands and riparian areas, and the restoration and enhancement of nontidal streams and nontidal open water areas. This NWP may be particularly appropriate for Section 404 authorization of many stream restoration projects.

Regional General Permit—A Regional General Permit (RGP) is a type of general permit that is issued regionally. Regulations addressing RGPs are found at 33 CFR 322.2(f), 323.2(h), and 325.2(e)(2). RGPs are similar to NWPs and contain terms and conditions intended to protect the environment including natural and cultural resources. Work that would not comply with those provisions may require authorization by individual permit. However, compliance with the conditions contained in this RGP does not guarantee authorization of the work by RGP. Work or structures that would have unacceptable impacts on the public interest are not authorized. Activities requiring Department of the Army authorization that are not specifically authorized by an RGP are prohibited unless they are authorized by another general permit or an individual permit.

Programmatic General Permit—A Programmatic General Permit (PGP) is a type of general permit that is issued to avoid unnecessary duplication of regulatory control exercised by another Federal, state, or local agency. With a PGP, a permit applicant generally must only apply to one agency, rather than applying to both agencies for permits for the same work. PGPs have characteristics similar to NWPs and RGPs.

Individual permit

The basic form of authorization is the individual permit. Processing such permits involves evaluation of individual, project-specific applications in what can be considered three steps: preapplication coordination (for larger projects), formal permit application review, and decisionmaking. Preapplication is helpful for more complex cases and is addressed later in this chapter. Once a complete application is received, the formal review process begins. The project manager prepares a public notice (if required), evaluates the impacts of the project and considers all comments received, addresses potential modifications to the project if appropriate, and drafts or oversees drafting of appropriate documentation to support a recommended permit decision. The permit decision document includes the environmental impacts of the project, findings of the public interest review process, and any special evaluation required by the type of activity such as determinations of compliance with the Section 404(b)(1) Guidelines. As noted above, water quality certification from the state water quality agency must be obtained before a Section 404 permit may be issued.

Letter of permission—A letter of permission (LOP) is a type of permit issued through an abbreviated processing procedure that includes coordination with Federal and state fish and wildlife agencies, as required by the Fish and Wildlife Coordination Act, and a public interest evaluation, but without the publishing of an individual public notice (see 33 CFR 325.2(e)(1)). An LOP procedure is an alternative procedure for evaluating individual permit applications for activities in waters of the United States authorized by the USACE. The LOP procedure serves to reduce the administrative procedures and to expedite permit decisions for cases that include only minor work in waters of the United States that do not have significant individual or cumulative environmental impacts and should encounter no appreciable opposition. The LOP may not be used to authorize the transportation of dredged material for the purpose of dumping it in ocean waters. LOPs may be used in those cases subject to Section 10 of the Rivers and Harbors Act of 1899 when, the proposed work would be minor, would not have significant individual or cumulative impacts on environmental values, and should encounter no appreciable opposition.

To use LOPs in cases subject to Section 404 of the Clean Water Act, the USACE must first consult with Federal and state fish and wildlife agencies, the EPA, the state water quality certifying agency, and, if appropriate, the state Coastal Zone Management Agency, on appropriate categories of activities for authorization under LOP procedures. The USACE must also issue a public notice advertising the proposed list and the LOP procedures, request comments, and offer an opportunity for public hearing. Finally, 401 certification must be issued or waived and, if appropriate, CZM consistency concurrence obtained or presumed either on a generic or individual basis.

An LOP may include general conditions and appropriate case-specific provisions necessary to protect the environment including natural and cultural resources. LOP procedures may not have an expiration date, but LOPs issued under the procedure always will have an expiration date. The USACE must conduct a public interest evaluation, but there is no requirement for a public notice. The permittee is responsible for obtaining any additional Federal, state, or local permits that may be required. Refer to the applicable LOP procedure for the application procedures and other requirements in each case.

Work that does not comply with the provisions of LOP procedure may require authorization by standard individual permit. Compliance with the LOP procedure, including the general conditions, does not guarantee authorization of the work by an LOP.

Standard individual permit—Activities that do not qualify for authorization under a general permit or an LOP procedure may qualify for authorization by standard individual permit (SP). Authorization under SP may be obtained only through application with the USACE. These permits are issued for activities that have more than minimal adverse impacts to waters of the United States, and evaluation of each permit application involves more thorough review of the potential environmental and socioeconomic effects of the proposed activity. The applicant must submit required information (33 CFR 325.1(d)) on an Individual Permit Application Form (Form 4345) or an approved alternative form. An alternative analysis and a mitigation plan are not required for a complete application to prepare a public notice, but are very helpful. The SP evaluation process may be summarized as follows:

- preapplication coordination
- Individual Permit Application Form submitted
- after receipt of a complete application, the USACE issues joint public notice for Section 404 and Section 401 water quality certification
- 15- to 30-day Public Notice comment period
- opportunity for public hearing
- USACE reviews comments, evaluates the permit application based on regulations, and completes required documentation
- USACE makes a decision: issue, issue with conditions, or deny

Permit decisions are based on probable impacts associated with the proposed project, including cumulative impacts, on the public interest (33 CFR 320.4). Public review interest factors include:

- conservation
- economics
- aesthetics
- general environment
- wetlands
- cultural values
- fish and wildlife values
- land use
- flood hazards
- property ownership
- flood plain values
- navigation
- recreation
- shore erosion and accretion
- water supply/water quality
- energy needs
- safety
- mineral needs
- food and fiber production
- needs and welfare of people

A permit will be granted if the proposed project is not contrary to the public interest and meets other legal requirements, such as the Section 404(b)(1) Guidelines and state water quality certification.

The Section 404(b)(1) Guidelines are the substantive criteria developed by the EPA and used by the USACE to evaluate proposed discharges into waters of the United States. The USACE may not issue a permit under Section 404 if the proposal does not meet the 404(b)(1) guidelines. The USACE may only issue a permit for the least environmentally damaging practicable alternative. Practicability includes consideration for cost, existing technology, and logistics.

The level of review of a proposed project is commensurate to the level of impact to waters of the United States. The USACE may not issue a permit if the proposed project is not in compliance with other laws (such as Section 401 of the Clean Water Act; National Environmental Policy Act; Fish and Wildlife Coordination Act; Endangered Species Act (threatened or endangered species information); Coastal Zone Management Act; National Historic Preservation Act; Magnuson-Stevens Fishery Conservation and Management Act; Essential Fish Habitat); if the activity would result in significant degradation of aquatic environment (net after mitigation); or if there is not appropriate and practicable mitigation. Public interest reviews, Section 404(b)(1) analyses and National Environmental Policy Act analyses require a resource impact assessment, which may include Hydrogeomorphic Approach (HGM), Wetland Evaluation Technique (WET), Habitat Evaluation Procedures (HEP) or another technique for wetlands, or the EPA's rapid bioassessment method or another technique for streams.

Preapplication coordination

Processing permit applications and requests for verification of general permit authorization may involve preapplication coordination. Preapplication coordination usually involves one or several telephone conversations or meetings between an applicant and USACE district staff and may include interested resource agencies (Federal, state, or local), and sometimes, the interested public. The basic purpose of such conversations or meetings is to provide for informal discussions about the pros and cons of a proposal and potential alternatives before an applicant makes irreversible commitments of resources (funds, detailed designs). The process is designed to provide the applicant with an assessment of the viability of some of the more obvious alternatives available to accomplish the project purpose, discuss measures for reducing the impacts of the project, and inform the applicant of the factors the USACE must consider in its decisionmaking process. In many cases, preapplication coordination with the USACE has produced project changes that resulted in streamlined regulatory requirements; for example, a general permit was sufficient for the revised project where a standard individual permit would have been required for the original proposal.

Mitigation

A fundamental precept of the Regulatory Program is the Department of the Army's mitigation policy (33 CFR Part 320.4 (r)), which applies to all Regulatory Program authorizations including general permits. When the USACE reviews a project that would require Department of the Army authorization, its evaluation typically includes a determination of whether the applicant has taken sufficient measures to mitigate the project's likely adverse impact on the aquatic ecosystem.

In a Memorandum of Agreement (MOA) signed February 6, 1990, between the USACE and the EPA, mitigation was defined as a sequential process of avoiding, minimizing, and compensating for adverse impacts to the aquatic ecosystem.

- Avoid: Take all appropriate and practicable measures to avoid those adverse impacts to the aquatic ecosystem that are not necessary.
- Minimize: Take all appropriate and practicable measures to minimize those adverse impacts to the aquatic ecosystem that cannot reasonably be avoided.
- Compensate: Implement appropriate and practicable measures to compensate for adverse project impacts to the aquatic ecosystem that cannot reasonably be avoided or further minimized. This step is also referred to as compensatory mitigation. The purpose of compensatory mitigation is to replace those aquatic ecosystem functions that would be lost or impaired as a result of a USACE-authorized activity.

The district engineer will normally require the implementation of all appropriate and practicable compensation as a condition of the Department of the Army authorization. Compensatory mitigation is required at minimum 1:1 ratio (acres mitigated to acres impacted) for all wetland impacts requiring a preconstruction notification for a nationwide permit unless it has been waived (determined on a case-by-case basis).

Regulatory Guidance Letter 02–2 applies to all compensatory mitigation proposals associated with permit applications submitted for approval after December 24, 2002. USACE districts will use watershed and ecosystem approaches when determining compensatory mitigation requirements, consider the resource needs of the watersheds where the impacts will occur, and also consider the resource needs of neighboring watersheds. USACE districts may have districtwide or statewide mitigation guidelines, as well.

Mitigation banking is the restoration, enhancement, creation, and, in exceptional circumstances, preservation undertaken to compensate in advance for adverse impacts to the aquatic ecosystem. Mitigation banking may be appropriate when compensatory mitigation cannot be practicably achieved or would not be as environmentally beneficial at the impact site or a nearby site. The USACE, EPA, RCS, USFWS, and National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA Fisheries Service) Federal Mitigation Banking Final Policy (Federal Register: November 28, 1995 (Volume 60, Number 228)) guidance regarding the establishment, use, and operation of mitigation banks for the purpose of providing compensation for adverse impacts to wetlands and other aquatic resources is provided to clarify the manner in which mitigation banks may be used to satisfy mitigation requirements of the CWA Section 404 permit program and the wetland conservation provisions of the Food Security Act (FSA) (Swampbuster provisions). Recognizing the potential benefits mitigation banking offers for streamlining the permit evaluation process and providing more effective mitigation for authorized impacts to wetlands, the agencies encourage the establishment and appropriate use of mitigation banks in the Section 404 and Swampbuster programs.

An in-lieu-fee program allows a permittee to pay a fee to an established trust fund in lieu of implementing specific onsite or offsite compensatory mitigation. The amount of the in-lieu-fee paid will normally represent the fair market cost of replacing those aquatic ecosystem resources that would be lost or impaired as a result of the authorized activity. The trust fund, in turn, finances mitigation projects that are designed to restore, enhance, create, or preserve aquatic ecosystem functions. The Federal Guidance on the Use of In-lieu-fee Arrangements for Compensatory Mitigation, under Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act, elaborates on in-lieu-fee mitigation arrangements in the Banking Guidance by outlining the circumstances where in-lieu-fee mitigation may be used, consistent with existing regulations and policy.

The USACE supports a strong partnership with states in regulating activities under Section 404 of the Clean Water Act. This is achieved with joint permit processing procedures (joint public notices, meetings, and hearings), programmatic general permits founded on effective state programs, joint EISs, special area management planning, and regional conditioning of nationwide permits, where appropriate.

(d) Clean Water Act, National Pollutant Discharge Elimination System

The EPA administers the Clean Water Act (CWA) program. The primary objective of the CWA is to restore and maintain the Nation's waters. This program covers point discharge permits for construction stormwater runoff, erosion control permit, or ongoing discharges of pollutants. The CWA's primary control program is the National Pollutant Discharge Elimination System (NPDES). The CWA prohibits the discharge of pollutants from point sources (any single identifiable source of pollution, a pipe, ditch, and ship) to waters of the United States without a NPDES permit. The EPA or the approved state environmental control agency has responsibility for administering NPDES permits. More information is available on the following Web site:

http://cfpub.epa.gov/npdes/

As of 1992, any earth disturbance greater than 5 acres was required to have a stormwater permit, and as of March 2003, a permit must be obtained for any earth disturbance greater than 1 acre. This includes sites that are less than 1 acre if they are "…part of a larger common plan of development or sale or within 500 feet of a lake or stream."

States can impose more stringent pollution limits than the Federal rules require. States can also require more frequent monitoring and reporting and the use of numerous best management practices to control the pollution and the regulation of small sites. Although there are some differences between states, all construction stormwater permits will be general permits. While there are exceptions, most of what is required is a Stormwater Management Plan.

654.1704 National Flood Insurance Program

In 1968, Congress created the National Flood Insurance Program (NFIP) to reduce damages and loss of life caused by floods. The Mitigation Division of the Federal Emergency Management Agency (FEMA) manages the NFIP. Nearly 20,000 communities across the United States voluntarily participate in the NFIP via the adoption and enforcement of flood plain management ordinances. In exchange, the NFIP makes federally backed flood insurance available to these communities. However, in general, it is local governments that typically regulate development and other activities in the flood plain, not FEMA.

(a) Flood plain maps

This program is administered with the aid of Flood Hazard Boundary maps, Flood Insurance Rate maps, and Flood Boundary and Floodway maps. Flood plain maps provide the basis for flood management, regulation, and insurance requirements by identifying areas subject to flooding that threaten life safety and damage to property.

These maps identify several areas of flood hazards such as Special Flood Hazard Area (SFHA) floodways and floodway fringes. The SFHA is defined as an area of land that would be inundated by a base flood (typically the 1% chance event). New construction within the SFHA must comply with FEMA requirements. Evaluations to determine these areas follow the procedures in the Flood Insurance Study Guidance and Specifications for Study Contractors, FEMA 37 (FEMA, 11085). FEMA 37 defines a floodway:

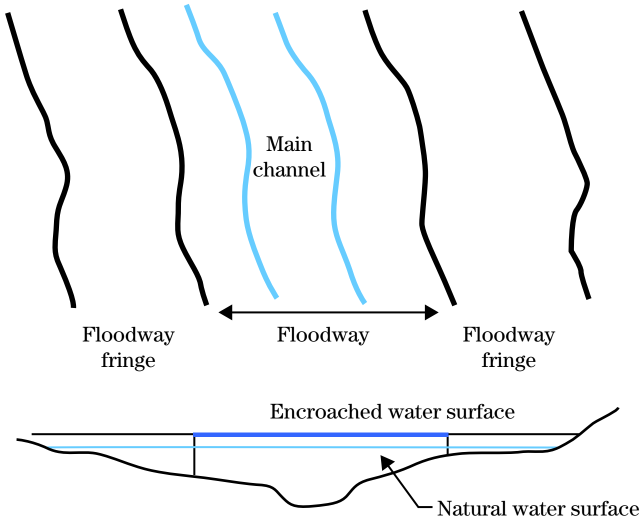
> *…as the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water-surface elevation by more than designated height.*

While there are exceptions, the base flood is typically the 1-percent chance event, and the designated height is 1 foot. The floodway is where the water is typically the deepest and fastest. It is the area of the waterway that should be kept free of obstructions to allow floodwaters to move downstream. Since most stream and channel work occurs within this area, a detailed analysis is typically required. The floodway fringe is the area that can be blocked by an encroachment without raising the base flood by more than the designated height. To define a flood map, calculations are made (often using HEC–RAS computer software) to determine how much of the fringe can be completely blocked. Figure 17–1 illustrates this determination.

(b) Types of studies

Several types of analyses may be required as part of a stream project. The most common type of study for simple projects is the so called no rise or no impact analysis. This must show that the proposed work will not impact the preproject base flood elevation. This can be a simple estimate of conveyance before and after the proposed project. In areas of higher risk or for projects involving more significant changes to the channel, a more complicated computer analysis may be required. Certification of this must be obtained before construction. The engineering or no rise analysis must be supported by technical data that is typically based upon the same engineering methodology used

Figure 17–1 Example calculation of a blocked floodway fringe



to develop the original mapped floodway. While local governments may review and approve the no rise submittal, they may request technical assistance from the FEMA regional office.

In some circumstances, it is not possible to demonstrate that a proposed project will not cause a rise in water surface during the base flood. In this situation, it can sometimes be argued that the potential increase in the base flood would not cause damage to habitable structures. For example, the area of possible impact may only be cropland. This type of study is the no damage analysis.

If a project results in significant changes in the flood plain, it may be necessary to revise the flood plain map. These involve the use of Letters of Map Revision (LOMR). The modeling and administrative work to obtain these can be significant.

(c) Flood plain map changes

Flood plain maps are periodically updated and revised to reflect changing conditions, such as new topography, land development, as well as updated mapping studies. They may also be updated to reflect stream and river projects. These flood plain map changes take one of the following forms:

- Publication of a new Flood Insurance Rate Map (FIRM)—the official map of a community on which FEMA has delineated both the special hazard areas and the risk premium zones applicable to the community.
- Letters of Map Change (LOMC)
  - Conditional Letter of Map Amendment (CLOMA)—provides FEMA's comment on whether a proposed project would be excluded from the Special Flood Hazard Area (SFHA) as shown on the NFIP map. This letter does not revise an effective map, but it does indicate whether the project would or would not be removed from the SFHA.
  - Conditional Letter of Map Revision (CLOMR)—provides for a review of whether a proposed project within the SFHA meets the minimum flood plain management criteria of the NFIP. If it does, it may provide what revisions will be made to the community's NFIP map of the project. A CLOMR may be required before a project can be built.
  - Conditional Letter of Map Revision based on Fill (CLOMRF)—similar to above, but is for project impacts based on fill that would exclude an area from the SFHA shown on the NFIP map.
  - Letter of Map Amendment (LOMA)—an amendment to the currently effective FEMA map that establishes that a property is not located in a SFHA. A LOMA is issued only by FEMA.
  - Letter of Map Revision (LOMR)—an official amendment to the currently effective FEMA map and reflects changes in flood zones, delineations, and elevations. A LOMR is issued only by FEMA.
  - Letter of Map Revision based on Fill (LOMRF)—similar to the LOMR, but based on fill.
- Local map changes

More information on this program is provided at the following Web site:

http://www.fema.gov/fhm/

654.1705 Endangered Species Act, as amended 1973

The Endangered Species Act (ESA) is a Federal statute that was designed to protect threatened and endangered species from extinction, excluding all recognized insect pests from this distinction. It is designed to ensure that Federal agencies will not take actions that might jeopardize listed, threatened, or endangered species. Specifically, it states:

> *The purposes of this Act are to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved, to provide a program for the conservation of such endangered species and threatened species, and to take such steps as may be appropriate to achieve the purposes of the treaties and conventions set forth…*

The USFWS (Department of the Interior) and NOAA Fisheries Service (Department of Commerce) are responsible for promulgating the provisions of the ESA. The USFWS's primary responsibilities include designating species as threatened or endangered, establishing recovery plans, designating critical habitat, and assisting the states and other Federal agencies with conservation and implementation of the ESA. Generally, NOAA Fisheries Service is responsible for protecting anadromous salmonids and marine mammals, while the USFWS's scope of authority covers a wider range of terrestrial and freshwater species (birds, butterflies, plants, snails, large mammals, and fish). The agencies maintain a list of endangered and threatened species. Any species that have been removed from endangered status are said to have been delisted.

The ESA mandates cooperation between Federal, state, and foreign governments in the conservation of listed species. The Secretaries of the Interior and Commerce must cooperate with the states to acquire and manage land for conservation purposes and have the authority to enter into cooperative agreements to provide assistance to states that establish programs for the conservation of listed species. For example, Section 6 of the ESA provides Federal financial assistance and incentives to states that develop and maintain conservation programs for resident listed resources.

Under the ESA, *all* Federal agencies must participate in the conservation and protection of threatened and endangered species. Specifically, Section 7 of the ESA charges Federal agencies to aid in the conservation of listed species (Section 7 (a)(1)) and requires Federal agencies to ensure that their activities will not jeopardize the continued existence of listed species or adversely modify designated critical habitats (Section 7 (a)(2)). Under the provisions of Section 7(a)(2), a Federal agency that permits, licenses, funds, or otherwise authorizes activities must consult with the Services to ensure that its actions will not jeopardize the continued existence of any listed species. Consequently, stream restoration projects funded, designed, or authorized by the NRCS are subject to Section 7 consultation, even if the effects or outcome of the project are completely beneficial to listed resources. The following Web sites provide additional information on listed species and the ESA:

http://www.fws.gov/endangered/

http://www.nmfs.noaa.gov/pr/species/esa_species.htm

654.1706 Fish and Wildlife Coordination Act, as amended 1965

The Fish and Wildlife Coordination Act (FWCA), as amended, proposes to assure that fish and wildlife resources receive equal consideration with other values during the planning of federally funded water resources development projects. The act was passed because the goals of water-related projects (flood control, irrigation, navigation, hydroelectric power) may conflict with the goal of conserving fish and wildlife resources. Conversely, project developers can design water development projects to enhance the quality and enjoyment of fish and wildlife resources if such goals are incorporated into project plans. The USFWS, NOAA Fisheries Service, and the state fish and wildlife agencies comment on USACE Individual Permit applications under this authority during the 30-day public comment period.

The Act authorizes the Secretary of the Interior to provide assistance to and cooperate with Federal, state, and public or private agencies and organizations in the development and protection of fish and wildlife resources and habitat, make surveys and investigations of the fish and wildlife in the public domain, and accept donations of land and funds that will further the purposes of the Act. The following Web site provides information on requirements for Federal agencies to manage fish and wildlife species under the FWCA:

http://laws.fws.gov/lawsdigest/fwcoord.html

654.1707 National Environmental Policy Act, as amended 1982

The purposes of the National Environmental Policy Act (NEPA) are to:

- declare a national policy which will encourage productive and enjoyable harmony between people and their environment
- promote efforts that will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of society
- enrich the understanding of the ecological systems and natural resources important to the Nation
- establish a Council on Environmental Quality

The NEPA requires that Federal agencies use a systematic, interdisciplinary approach in planning and decisionmaking that may impact the human environment. The Act calls for Federal decisionmakers to consider the environmental impacts of their actions before implementing them. The following Web site provides information on requirements as they relate to NEPA:

http://ceq.eh.doe.gov/nepa/regs/nepa/nepaeqia.htm

654.1708 Magnuson-Stevens Fishery Conservation and Management Act, as amended 1996

The purposes of the Magnuson-Stevens Fishery Conservation and Management Act are to take immediate action to:

- conserve and manage the fishery resources found off the coasts of the United States and the anadromous species and Continental Shelf fishery resources of the United States
- adapt exclusive fishery management authority beyond the exclusive economic zone over such anadromous species and Continental Shelf fishery resources and fishery resources in the special areas

The act supports and encourages the implementation and enforcement of international fishery agreements for the conservation and management of highly migratory species and encourages the negotiation and implementation of additional such agreements as necessary. The following Web site provides information on the requirements:

http://www.nmfs.noaa.gov/sfa/magact/

654.1709 State regulations and permitting—general

Each state has individual statutes and codes that provide the legal framework for developing and managing water resource-related projects. A variety of permits are required to work within rivers, streams, and/or wetlands. State fish and wildlife agencies and land management agencies are the typical implementing agency. Local permit requirements should be fully identified when developing project plans, designs, and construction specifications. The following list has links to examples for state and local permit requirements. Typically, the state environmental protection, environmental quality, ecology, or natural resources is responsible for administrating permits.

California:

http://www.swrcb.ca.gov/quality.html

Maine:

http://www.maine.gov/dep/permits.htm

Oregon:

http://licenseinfo.oregon.gov/

Washington:

http://www.ecy.wa.gov/programs/sea/pac/jarpa.html

Some state wetland regulatory programs also exist as noted at the following Web site:

http://www.aswm.org/swp/states.htm

654.1710 State regulations and permitting—fish passage

Many states have specific language regarding fish passage and fish screen requirements, whereas others are more general in scope. Design engineers and biologists should be aware of all state regulations pertaining to fish passage and screen requirements. A few examples of state codes and regulations that require fish passage or fish screening are listed below. However, some states do not have specific codes requiring fish passage or screens. Contact the local fish and wildlife agency for more information.

California:

http://www.dfg.ca.gov/1600/1600code.html

Maine:

http://www.maine.gov/mdot/environmental-office-homepage/documents/finalfishpassage2003.pdf

Oregon:

http://www.dfw.state.or.us/ODFWhtml/InfoCntrFish/InfoCntrFish.html

Washington:

http://www.wdfw.wa.gov/hab/engineer/habeng.htm

654.1711 Conclusion

Any stream project must meet or exceed all Federal, state, and local regulatory requirements. Regulatory issues can cover a wide range of areas. To ensure full compliance, it is recommended that early contact and frequent consultation be made with all the appropriate agencies.