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Guidance for Stream Restoration

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Cover Photos:

Top-right: Illinois River, North Park, Colorado.
Photo by Steven Yochum

Bottom-left: Whychus Creek, Oregon.
Photo by Paul Powers

ABSTRACT

Stream restoration practitioners and researchers have devoted a great deal of effort in recent decades to developing extensive guidance for stream restoration. The available resources are diverse, reflecting the wide ranging approaches used and expertise required to develop effective stream restoration projects. To help practitioners in sorting through the extensive amount of available information, this technical note has been developed to provide a guide to the available guidance. The document structure is primarily a series of short literature reviews followed by a hyperlinked reference list for readers to find more information on each topic. The primary topics incorporated into this guidance include general methods, an overview of stream processes and restoration, case studies, data compilation, preliminary assessments, and field data collection. Analysis methods and tools, and planning and design guidance for specific restoration features are also provided. This technical note is a bibliographic repository of information available to assist professionals with the process of planning, analyzing, and designing stream restoration projects. It is updated periodically.

ADVISORY NOTE

Techniques and approaches contained in this technical note are not all-inclusive, nor universally applicable. Designing stream restorations and rehabilitations 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.

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Other individuals have provided comments and clarifications to the document; all of their contributions are highly appreciated. Please email Steven Yochum with any additional comments or suggestions, for inclusion in the next update.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

Nationally, large funding amounts are annually spent on stream restoration and rehabilitation projects, with the results having variable success in satisfying project objectives. A low estimate is that more than $1 billion is spent each year on such projects (Bernhardt et al. 2005). To support this investment, over the last three decades a great deal of effort has been devoted to developing technical guidance. These resources are diverse, which reflects the wide ranging approaches used and expertise required in the practice of stream restoration. Tens of thousands of pages of relevant material are available to assist practitioners with restoration projects. The USDA Natural Resources Conservation Service's (NRCS) Stream Restoration Design manual (National Engineering Handbook, Part 654; NRCS 2007) alone consists of more than 1600 pages! With such extensive information available, it can be difficult for professionals to find the most relevant material available for specific projects.

To help practitioners sort through all this information, this technical note has been developed to provide a guide to the guidance. It is a bibliographic repository of information available to assist professionals with the process of planning, analyzing, and designing a stream restoration or rehabilitation project. The document structure is primarily a series of short literature reviews followed by a hyperlinked reference list for the reader to find more information on each topic. Due to the extensive use of hyperlinks, this document is best viewed as an on-screen pdf while connected to the web. Many potentially useful references for stream projects are cited. However, the quantity of the available literature can be intimidating, even when only summarized. Prudent use of the table of contents can help minimize the potential for being overwhelmed. Additionally, Table 1 provides a quick reference guide for common technical needs.

This document is not intended to be a philosophical framework for restoration design; that effort is left to other references. Additionally, this guidance is not limited to only what are considered restoration-focused practices; rehabilitation features are also included, to provide a more comprehensive resource. Restoration is the reestablishment of the structure and function of ecosystems to an approximation of pre-disturbance conditions while rehabilitation establishes conditions to support natural processes for making the land useful for human purposes (NRCS 2007). While both restoration and rehabilitation practices are presented in this document, for simplicity they are lumped together under the term restoration, as is common practice.

Table 1: Quick reference guide.

This document is organized in the typical sequence for assessing, analyzing, and designing stream restoration projects. Appendices provide an index for the NRCS Stream Restoration Design manual

(National Engineering Handbook, Part 654: NRCS 2007), and a glossary of fluvial geomorphology terms. Finally, the term stream restoration is used for all scales of streams, from small creeks to large rivers.

2. GOALS AND OBJECTIVES

One of the most important steps in a stream restoration project is the determination of project goals and objectives. Goals are general and are highly dependent upon context, while objectives are measurable and in support of the stated goals. Once established, goals need to be clarified through objectives that describe how the goals will be attained. Objectives need to be specific, realistic, achievable and measurable (NRCS 2007, Ch. 2). The perceived success or failure of a project is dependent upon thoughtful and consensus-based development of goals and objectives by the stakeholders and technical specialists. The social context of the restoration should be accounted for – the successful implementation of restoration is dependent upon acceptance by those who live with the stream and its floodplain (Wohl et al. 2015).

Project goals and objectives often considered in stream corridor restoration and rehabilitation projects include:

- Provide habitat enhancement for native or sport fishes, to increase abundance and age class diversity
- Prevent streambank erosion, to protect properties and infrastructure
- Restore hydrologic function, including dynamic channel processes
- Establish a multi-thread channel and companion riparian meadow, from an incised or channelized reach
- Slow the procession of headcutting in a watershed, to protect upland areas and infrastructure, and to reduce sediment delivery to downstream reaches
- Reduce rates of lateral migration of channel meandering
- Narrow an overly-wide channel, decreasing the width/depth ratio of the stream
- Improve water quality, addressing the impairments that lead to excessive temperature, nutrients, sediment, salts, and metals
- Remove non-native riparian vegetation, replacing with more desirable species
- Reestablish a sinuous channel from a channelized reach
- Establish stream reaches capable of transporting the available sediment supply
- Provide compliance with Endangered Species Act and Clean Water Act requirements

During the planning and design processes, the attributes of the project must be assessed to assure that the project objectives are being fully satisfied. Often, individual objectives are in conflict and need to be prioritized to best meet the project goals. After construction, monitoring should be performed to assess if the project is fulfilling the goals and objectives. If not, project remediation may be needed through adaptive management. In any case, documentation of project performance should be maintained, for communication with stakeholders and adding to the knowledge base of the individual professional, the project team, and the restoration community as a whole.

Additional information for establishing objectives for stream projects can be found in:

- NRCS 2007 (Ch. 2) Goals, Objectives and Risk
- Fischenich 2006 Functional Objectives for Stream Restoration

3. GENERAL METHODS

General methods are provided for stream corridor improvement projects. Topics covered include the assembly of an appropriate interdisciplinary team, the planning process, the watershed approach to restoration, an overview of riparian management, adaptive management, and the extent of design and review.

3.1 Interdisciplinary Team

Stream corridor restoration projects are inherently complicated. In most projects, no single individual has all the required skills to effectively perform a restoration; an interdisciplinary team is required. Needed expertise varies by project and may include hydrology, fluvial geomorphology, engineering, soil science, restoration ecology, botany, and aquatic biology. However, the team should be no larger than required, to reduce inefficiencies resulting from an excessive number of specialists being involved in a project.

3.2 Planning Process

Stream corridor restoration projects need a plan to develop a logical sequence of steps to satisfy the project objectives. The NRCS conservation planning process (Figure 1) is one example of a generally-accepted project-level planning process. The method consists of nine steps that focus the planning team on the overall system, to determine the cause of the problem, formulate alternatives, and evaluate the effects of each alternative on the overall stream system (NRCS 2007, Ch2). These steps are not necessarily linear; the steps may need to be cycled through iteratively to develop the best set of alternative solutions to a given problem, and ultimately select and implement a certain set of practices. The nine steps are as follows:

1. **Identify problems and opportunities:** What stream characteristics should be changed? Is the noted condition actually a problem?

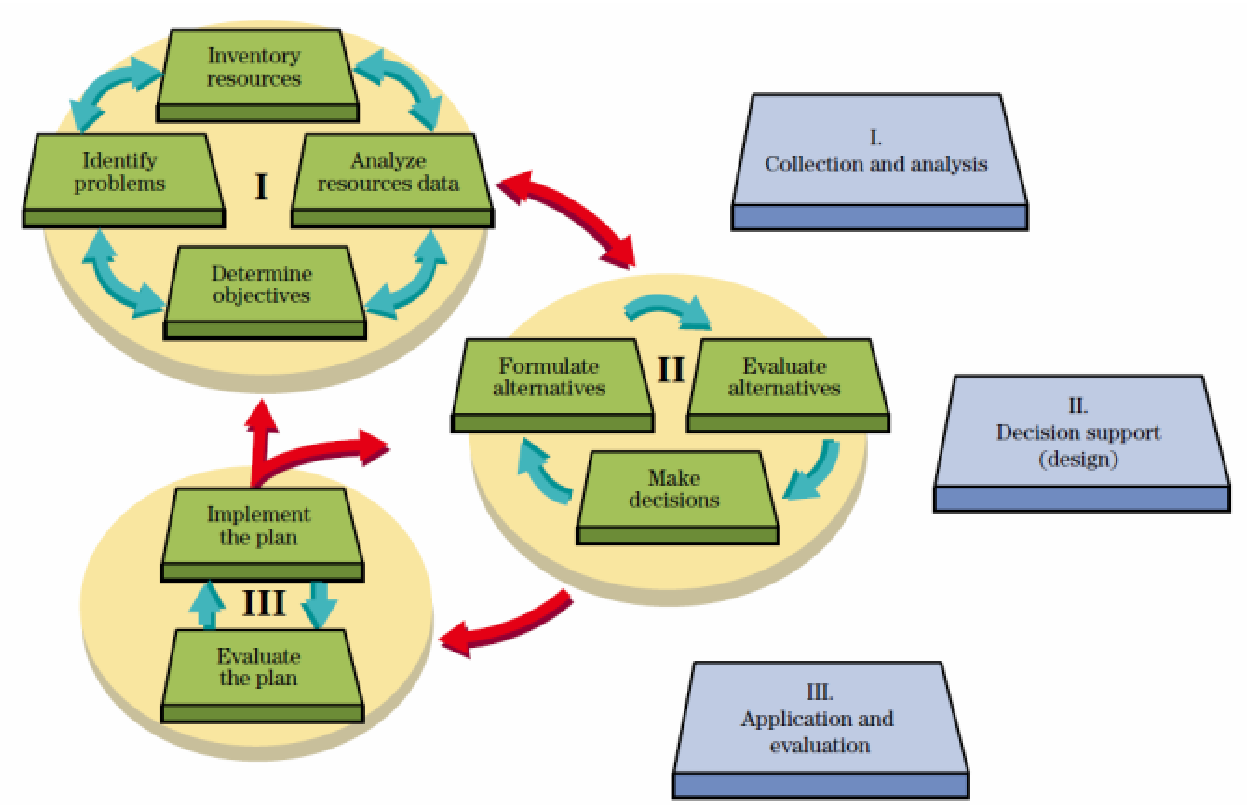


Figure 1: The NRCS planning process (NRCS 2007, Ch. 2).

2. **Determine overall goals and specific objectives:** What are the desired physical, chemical and biological changes?
3. **Inventory resources:** Study the stream to understand the dominant physical processes, water quality, and the abundance and distribution of biological populations.
4. **Analyze resource data:** Evaluate the collected information and decide what processes most influence the desired stream condition.
5. **Formulate alternatives:** Determine which processes can be changed. Include a no action option.
6. **Evaluate alternatives:** Which alternatives are sustainable, cost effective, and best meet stated goals and objectives?
7. **Make decisions:** Develop a consensus-based decision by the stakeholders and interdisciplinary team regarding which alternative to implement.
8. **Implement the plan**
9. **Evaluate the plan:** Perform post project monitoring, to assess performance with respect to goals and objectives, and revise practices if necessary.

Complimentary to this, standards for ecologically successful stream restoration projects have been developed. Palmer et al. (2005) proposed five essential criteria for measuring project success:

1. A dynamic ecological endpoint is initially identified and used to guide the restoration.
2. The ecological conditions of the stream are measurably improved.
3. Through the use of natural fluvial and ecological processes, the restored stream must be more self-sustaining and resilient to perturbations than pre-restoration conditions, so that minimal maintenance is needed.
4. The implementation of the restoration does not inflict lasting harm.
5. Pre- and post-project assessments are completed and the data are made publicly available so that the restoration community as a whole can benefit from knowledge learned.

3.3 Watershed Approach

While restoration is frequently initially considered to address local concerns, a watershed approach is often needed to address potential underlying mechanisms causing the impairments. An understanding of these mechanisms is necessary to develop an effective response. Unless the underlying causes of the degraded condition are addressed, restoration may not be ~~the~~ a wise investment.

Relevant questions to address include:

- How has land use changed throughout the watershed? What are the results of these disturbances? Impacts to consider include:
  - fires
  - invasive species
  - beetle-killed forests
  - urbanization
  - roads
  - livestock grazing
  - logging activities
  - Mining or resource extraction
- How are flow diversions or groundwater pumping impacting the aquatic habitat, and stream form and function?
- Is flow augmentation from trans-basin diversions causing channel destabilization?
- Are there substantial water storage projects in the watershed? If so, how have these projects affected the magnitude, frequency, duration, timing and rate of change of flow (Poff et al. 1997)? What are the ecologic and geomorphic impacts of the water storage projects?
- Are there a substantial number of irrigation diversion weirs or culverts in the watershed that block aquatic organism passage? If so, does this relate to the project objectives?
- Do the riparian zones of the watershed have extensive populations of invasive species? What are the hydrologic, geomorphic, and ecological ramifications?
- Are landslides or debris flows common in the watershed? Is the stream capable of transporting this material? What are the geomorphic ramifications of these disturbances?

- Is there active headcutting in the watershed? If so, does this headcutting relate to the local issues that prompted the restoration project?
- Are there historic or current mining activities in the watershed? How have these activities impacted water quality?
- Have changed watershed conditions impacted water and sediment regimes to the point where the stream is in a state of flux or out of its dynamic equilibrium?

4. RIPARIAN MANAGEMENT

Effective riparian management is fundamental for supporting proper stream corridor function, to develop a fully functioning stream system. This management includes agricultural operations, livestock grazing practices, forest harvesting practices, road building, urbanization, and the like. However, the effects of past land use can have lingering impacts that delay a beneficial response from best management practices. For example, Harding et al. (1998) found that the diversity of stream invertebrates and fish was best explained by land use in the 1950s rather than contemporary conditions ("the ghost of land use past").

Stream complexity, which can be considered a surrogate for ecological function, has been most associated with management practices. For example, in subalpine streams of the Southern Rockies the legacy effects of logging and instream wood removal has led to lower wood loads and reduced complexity (Livers and Wohl 2016), with management history having the greatest influence on functional stream channel complexity.

A summary providing a scientific assessment of the effectiveness of riparian grazing management practices was provided by George et al. (2011), as a part of a synthesis on the conservation benefits of rangeland practices (Briske 2011). This summary report provides a helpful evaluation of 20 management tools (Table 2), evaluating their value through a review of the peer-reviewed literature.

Engineered restoration is often not needed to fulfill stakeholders objectives, since livestock and wildlife management may be all that is required in some situations. In other situations, livestock and riparian management is used in combination with channel and floodplain engineering practices to satisfy project objectives in the desired timeframe. In some of the most disturbed stream systems, channelization or incision has occurred and water surface elevations and groundwater table elevations have been substantially lowered, resulting in shifts of former floodplain plant communities to upland species (Carter 2002, Reynolds & Cooper 2011, Reynolds et al. 2014). In the most altered stream systems, more intensive restoration may be needed to raise the channel back to pre-disturbance elevations and restore floodplain and wet meadow function.

In the initial stages of a project a "no action" option needs to be considered, then a management-only approach should be considered for its ability to satisfy the project objectives in the desired timeframe. If these more passive and less-costly alternatives do not satisfy the project objectives within a desired timeline, more complex, intensive (and costly) solutions should then be considered.

A list of 20 riparian conservation practices and their expected ecosystem benefits are provided (Table 2). Additionally, watershed condition can result in direct impacts to stream condition. For example, a severe fire in a watershed will lead to a large increase in sediment availability and mobilization, with various morphological and ecological consequences. Upland watershed management also needs to be considered in a restoration design.

5. ADAPTIVE MANAGEMENT

Due to the complexity involved in restoring degraded stream systems and the frequent lack of suitable reference sites that describe unimpaired conditions, the adaptive management process can be essential for developing the most effective projects. With adaptive management, uncertainty in the effectiveness of restoration approaches, due to limited understanding of mechanisms, is mitigated through "learning by doing and adapting based on what's learned" (William and Brown 2012).

More information on adaptive management is provided in:

- Bouwes et al. 2016 Adapting Adaptive Management for Testing the Effectiveness of Stream Restoration: An Intensely Monitored Watershed Example
- Williams and Brown 2012 Adaptive Management: The U.S. Department of the Interior Applications Guide
- Ryan and Calhoun 2010 Riparian adaptive management symposium: a conversation between scientists and management

Table 2: Riparian practices, with expected riparian ecosystem benefits (adapted from George et al. 2011).

	Ecosystem Service				
Practice name	Wildlife habitat	Water quality and quantity	Stable stream banks and soils	Carbon storage	Diverse plant and animal communities
Animal trails and walkways (feet)		X	X		
Brush management (acres)	X	X	X		X
Channel bank vegetation (acres)	X	X	X		
Conservation cover (acres)	X	X	X		
Critical area planning (acres)			X		
Fence (feet)	X	X	X		X
Filter strip (acres)		X			
Pest management (acres)	X	X			
Prescribed burning (acres)	X				X
Prescribed grazing (acres)	X	X	X		X
Range planting (acres)	X	X	X	X	X
Riparian forest buffer (acres)	X	X	X	X	X
Riparian herbaceous cover (acres)	X	X	X	X	X
Stream crossing		X	X	X	
Stream habitat improvement and management (acres)	X	X	X	X	
Stream bank and shoreline protection (feet)	X		X		
Tree/shrub establishment (acres)	X	X	X	X	X
Upland wildlife habitat management (acres)	X				
Use exclusion (acres)		X	X		X
Watering facility (no.)		X	X		

6. OVERVIEW of STREAM PROCESSES and RESTORATION

There are a wide variety of approaches implemented in stream projects, with this variety is a function of the goals and objectives, setting (urban vs. rural, private vs. public lands), the backgrounds and preferences of the restoration practitioners, and funding opportunities. Some practitioners focus on hard structures, constructed of concrete and quarried rock, while others prefer natural materials though also select practices that tend to fix the *form* of streams in place with respect to their longitudinal profile, plan pattern, and cross sectional dimension. Other practitioners, oftentimes in different settings that allow greater latitude and adjustment, take the approach of restoring natural stream *function* and allow a greater degree of dynamic channel development over time.

Reflecting this variety of approaches to stream work and restoration, there are numerous and, in some ways, conflicting references available that provide summaries and details of stream processes, threats, and restoration practices. This technical note does not provide a critique of the various techniques and schools of thought on the subject but rather provides various perspectives for the users to educate themselves for their specific projects. Examples of these references include:

- Briggs, M. 2020 Renewing Our Rivers: Stream Corridor Restoration in Dryland Regions
- Wohl et al. 2019 Managing for Large Wood and Beaver Dams in Stream Corridors
- Castro and Thorne 2019 The stream evolution triangle: Integrating geology, hydrology, and biology
- Wohl et al. 2019 The Natural Wood Regime in Rivers
- Hawley 2018 Making Stream Restoration More Sustainable: A Geomorphically, Ecologically, and Socioeconomically Principled Approach to Bridge the Practice with the Science
- Parsons and Thoms 2018 From academic to applied: Operationalising resilience in river systems
- Wohl 2018 Sustaining River Ecosystems and Water Resources
- Julien 2018 River Mechanics
- Sholtes et al. 2017 Managing Infrastructure in the Stream Environment
- Polvi and Sarneel 2017 Ecosystem Engineers in rivers: An introduction to how and where organisms create positive biogeomorphic feedbacks
- Kirkland 2017 Adaptation to Wildfire: A Fish Story (USFS Science Findings)
- EPA 2015 Connectivity of Streams & Wetlands to Downstream Waters: A Review & Synthesis of the Scientific Evidence
- Edwards 2015 A Primer on Watershed Management
- Perry et al. 2015 Incorporating climate change projections into riparian restoration planning and design
- Wohl et al. 2015 The Science and Practice of River Restoration
- Niezgoda et al. 2014 Defining a Stream Restoration Body of Knowledge as a Basis for National Certification
- Lave, R. 2012 Bridging political ecology and STS: A field analysis of the Rosgen wars
- Poff et al. 2012 Threats to Western United States Riparian Ecosystems: A Bibliography
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Weber and Fripp 2012 Understanding Fluvial Systems: Wetlands, Streams, and Flood Plains
- Simon et al. 2011 Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools
- Skidmore et al. 2011 Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals
- KIESD 2011 Stream Restoration. Sustain: A Journal of Environmental and Sustainability Issues, Kentucky Institute for the Environment and Sustainable Development
- Wohl 2011 Mountain Rivers Revisited

- Zeedyk and Clothier 2009 Let the Water do the Work – Induced Meandering, and Evolving Method for Restoring Incised Channels
- James et al. 2009 Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts
- Helfman 2007 Fish Conservation
- NRCS 2007 Stream Restoration Design
- Conyngham et al. 2006 Engineering and Ecological Aspects of Dam Removal: An Overview
- Wohl et al. 2006 River Restoration in the Context of Natural Variability (in USFS StreamNotes)
- Kershner et al. 2004 Guide to Effective Monitoring of Aquatic and Riparian Resources
- Doll et al. 2003 Stream Restoration: A Natural Channel Design Handbook
- Copeland et al. 2001 Hydraulic Design of Stream Restoration Projects
- Richardson et al. 2001 River Engineering for Highway Encroachments
- Soar and Thorne 2001 Channel Restoration Design for Meandering Rivers
- Fischenich 2001a Impacts of Stabilization Measures
- Fischenich 2001b Stability Thresholds for Stream Restoration Materials
- Fischenich & Marrow 2000 Reconnection of Floodplains with Incised Channels
- Knighton 1998 Fluvial Forms and Processes: A New Perspective
- FISRWG 1998 Stream Corridor Restoration: Principles, Processes and Practices
- Rosgen 1996 Applied River Morphology
- Leopold, L.B. 1994 A View of the River
- Maser and Sedell 1994 From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans
- Leopold et al. 1964 Fluvial Processes in Geomorphology

Additionally, the following webinars, tutorials and videos on hydrology, geomorphology, and restoration can be helpful for understanding relevant processes:

- Stage 0 Workshop: tools for reconnecting floodplains 2019
- Stream Channel Repair and Restoration Following Extreme Flooding Damage, Part 1: Background and Planning 2015 (Kip Yasumiishi, Barry Southerland, Dan Moore, Larry Johnson)
- Lessons Learned from Natural Stream Restoration/Enhancement: Insight on Natural Channel Design 2013 (Dick Everhart, Angela Greene)
- Runoff Generation in Forested Watersheds 2004 (Jeff McDonnell)
- Dividing the Waters Rethinking Management in a Water-Short World, 2004 (Sandra Postel)
- The Geomorphic Response of Rivers to Dam Removal 2004 (Gordon Grant)

7. CASE STUDIES

Case studies are valuable for understanding lessons learned from previous projects and to provide ideas for current project planning. Case studies illustrate both perceived successes and partial failures, illustrating approaches and pitfalls. References that provide case studies are provided below. Additionally, a variety of case studies are provided in NRCS (2007), with a list of topics presented in appendix A.

- Thompson et al. 2018 The multiscale effects of stream restoration on water quality
- Hunt et al. 2018 Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California
- Hausner et al. 2018 Assessing the effectiveness of riparian restoration projects using Landsat and precipitation data from the cloud-computing application ClimateEngine.org
- Meyer 2018 Deer Creek: Stage 0 Alluvial Valley Restoration in the Western Cascades of Oregon
- Prussian and Williams 2018 Partnerships are Key for a Decade of Stream Restoration on the Tongass National Forest
- Randle and Bountry 2018 Dam Removal Analysis Guidelines for Sediment (Advisory Committee for Water Information, Subcommittee on Sedimentation)
- Frainer et al. 2017 Enhanced ecosystem functioning following stream restoration: The roles of habitat heterogeneity and invertebrate species traits
- Pollock et al. 2017 The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains
- Moore and Rutherford 2017 Lack of maintenance is a major challenge for stream restoration projects
- Martínez-Fernández et al. 2017 Dismantling artificial levees and channel revetments promotes channel widening and regeneration of riparian vegetation over long river segments
- Belliti et al. 2017 Assessing Restoration effects on River Hydromorphology Using the Process-based Morphological Quality Index in Eight European River Reaches
- Glenn et al. 2017 Effectiveness of environmental flows for riparian restoration in arid regions: A tale of four rivers
- Frainer et al. 2017 Enhanced ecosystem functioning following stream restoration: The roles of habitat heterogeneity and invertebrate species traits
- Groll, M. 2017 The passive river restoration approach as an efficient tool to improve the hydromorphological diversity of rivers – Case study from two river restoration projects in the German lower mountain range
- Bair and Olegario 2017 Resurrection Creek: A Large Scale Stream Restoration on the Kenai Peninsula of Alaska
- Norman et al. 2017 Quantifying geomorphic change at ephemeral stream restoration sites using a coupled-model approach
- Mikus et al. 2016 Environment-friendly reduction of flood risk and infrastructure damage in a mountain river: Case study of the Czarny Dunajec
- Erwin et al. 2016 Post-project geomorphic assessment of a large process-based river restoration project
- Wasniewski 2016 Case Study: Jackknife Creek Watershed Restoration
- Bouwes et al. 2016 Adapting Adaptive Management for Testing the Effectiveness of Stream Restoration: An Intensely Monitored Watershed Example
- U.S. Society on Dams 2015 Guidelines for Dam Decommissioning Projects
- Schwartz et al. 2015 Restoring riffle-pool structure in an incised, straightened urban stream channel using an ecohydraulic modeling approach
- Powers 2015 Case Study: Restoration of the Camp Polk Meadow Preserve on Whychus Creek
- East et al. 2015 Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change
- RiverWiki Tool for sharing case studies and best practices for river restoration in Europe

- Buchanan et al. 2013 Long-Term Monitoring and Assessment of a Stream Restoration Project in Central New York
- Collins et al. 2013 The Effectiveness of Riparian Restoration on Water Quality – A Case Study of Lowland Streams in Canterbury, New Zealand
- Pierce et al. 2013 Response of Wild Trout to Stream Restoration over Two Decades in the Blackfoot River Basin, Montana
- Ernst et al. 2012 Natural-Channel-Design Restorations that Changed Geomorphology Have Little Effect on Macroinvertebrate Communities in Headwater Streams
- MacWilliams et al. 2010 Assessment of the Effectiveness of a Constructed Compound Channel River Restoration Project on an Incised Stream
- Major et al. 2012 Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam
- Walter et al. 2012 Assessment of Stream Restoration: Sources of Variation in Macroinvertebrate Recovery throughout an 11-Year Study of Coal Mine Drainage Treatment
- Schiff et al. 2011 Evaluating Stream Restoration: A Case Study from Two Partially Developed 4th Order Connecticut, U.S.A. Streams and Evaluation Monitoring Strategies
- Sustain 24, Spring/Summer 2011 Stream Restoration
- Chin et al. 2009 Linking Theory and Practice for Restoration of Step-pool Streams
- FEMA 2009 Engineering With Nature: Alternative Techniques to Riprap Bank Stabilization
- Levell and Chang 2008 Monitoring The Channel Process of a Stream Restoration Project in an Urbanizing Watershed – A Case Study of Kelley Creek, Oregon, USA
- Baldigo et al. 2008 Response of Fish Populations to Natural Channel Design Restoration in Streams of the Catskill Mountains, New York
- Doyle et al. 2007 Developing Monitoring Plans for Structure Placement in the Aquatic Environment: Recommended Report Format, Listing of Methods and Procedures, and Monitoring Project Case Studies
- Alexander and Allen 2007 Ecological Success in Stream Restoration: Case Studies from the Midwestern United States
- Niezgoda and Johnson 2007 Case Study in Cost-Based Risk Assessment for Selecting Stream Restoration Design Method for a Channel Relocation Project
- Medina and Long 2004 Placing Riffle Formations to Restore Stream Functions in a Wet Meadow
- Thompson 2002 Long-Term Effect of Instream Habitat-Improvement Structures on Channel Morphology Along the Blackledge and Salmon Rivers, Connecticut, USA
- Purcell et al. 2002 An Assessment of a Small Urban Stream Restoration Project in Northern California
- Piper et al. 2001 Bioengineering as a Tool for Restoring Ecological Integrity to the Carson River
- Smith et al. 2000 Breaching a Small Irrigation Dam in Oregon: A Case History

8. DATA COMPILATION

To develop sufficient understanding of the stream reach of interest, it is necessary to collect existing available data. Helpful data that can be used to assess current condition include streamflow, snowpack, water diversion, and water quality data, flow frequency estimates, biologic inventories, soils information, aerial imagery, and elevation data. A Geographic Information System (GIS) is typically the most appropriate method for viewing and analyzing spatial data.

8.1 Data Sources

Multiple federal and state agencies collect and distribute data that are relevant for stream restoration and projects. National and regional data sources that can be helpful include the following:

8.1.1 Water Quantity

- USGS water data: real-time and historical streamgage information, from the U.S. Geological Survey
- USGS StreamStats: watershed and stream statistics, including approximate flow frequency values, mean flows and minimum flows for ungaged streams. Historic and current USGS streamgage information are also provided.
- Streamflow data sources ACWI Subcommittee on Hydrology
- Springs Online Springs inventory data, from the Springs Stewardship Institute
- National Forest streamflow contributions: On a Forest unit and stream basis, contributions of National Forests to streamflow is provided
- RWIS: Reclamation Water Information System, water data from the Bureau of Reclamation
- FEMA floodplain mapping: 100-year flood inundation boundaries, from the Federal Emergency Management Agency
- USFS national flow gage gap analysis, on and near National Forests

8.1.2 Water Quality and Sediment

- USGS water quality data: real-time field parameter data, such as temperature, conductivity, and pH, as well as historical data for many constituents
- USGS Regional Stream Quality Assessment: tool to "characterize multiple water-quality factors that are stressors to aquatic life – contaminants, nutrients, sediment, and streamflow alteration – and to develop a better understanding of the relation of these stressors to ecological conditions in streams throughout the region"
- NorWeST Stream Temp: stream temperature data and geospatial map outputs from a regional temperature model for the Western United States
- Water-Quality Changes in the Nation's Streams and Rivers: Trends in water chemistry (nutrients, pesticides, sediment, carbon, and salinity) and aquatic ecology (fish, invertebrates, and algae) for four time periods: 1972-2012, 1982-2012, 1992-2012, and 2002-2012
- USGS Regional SPARROW Model Assessments of Streams and Rivers: water-quality results from SPAtially-Referenced Regression on Watershed attributes modeling
- EPA STORET: repository for water quality, biological, and physical data. Hosted by the Environmental Protection Agency
- USDA STEWARDS: Water-quality data from the Agricultural Research Service
- NAL WAIC: National Agricultural Library Water and Agriculture Information Center, for agricultural-related water information

8.1.3 GIS Data and Mapping

- Data.gov: U.S. Government Open Data
- Forest Service GeoData Clearinghouse: Spatial data collected and managed by Forest Service programs
- Watershed Index Online: A National Watershed Data Library and Tool
- NRCS Geospatial Data Gateway: GIS data, such as ortho imagery, topographic images and hydrologic unit boundaries

- USFS Geospatial Technology and Applications Center: provides the Forest Service with a range of geographic information products and related technical and training services
- ArcGIS online imagery: High-resolution aerial imagery (oftentimes 30 cm) to use as GIS basemap. Enter "imagery" in search field for ArcGIS online and select "World Imagery"
- National Map: Visualize, inspect and download topographic base data, elevation data, orthoimagery, landcover, hydrography, and other GIS products (USGS)
- EarthExplorer: USGS historic aerial photography archive
- FSA Aerial Photography Field Office: historic aerial imagery from the USDA Farm Service Agency
- USFS Watershed Condition: watershed condition class and prioritization information for National Forests
- National Hydrography Dataset: Digital vectorized dataset of such features as such as lakes, ponds, streams, rivers, canals, dams and streamgages
- EPA ECHO: Enforcement and Compliance History, from the Environmental Protection Agency
- NRCS Web Soil Survey: soil data and information
- SoilWeb: Smart phone app. providing GPS-based access to NRCS soil data
- National Wetland Inventory: Wetlands and deepwater habitats, from the U.S. Fish and Wildlife Service

8.1.4 Climate Data

- National Centers for Environmental Information: climate and weather data, from the National Oceanic and Atmospheric Administration (NOAA)
- NOAA HDSC Precipitation Frequency: precipitation-frequency data, from the National Oceanic and Atmospheric Administration, National Hydrometeorological Design Studies Center
- PRISM climate mapping system: Parameter-elevation Regressions on Independent Slopes Model. Precipitation product available from NRCS Geospatial Data Gateway
- SNOTEL: NRCS SNOwpack TELemetry
- CoCoRaHS: Community Collaborative Rain, Hail and Snow Network, high-resolution volunteer-collected precipitation data

8.1.5 Vegetative Information

- USNVC U.S. National Vegetation Classification: A central organizing framework for documentation, inventory, monitoring, and study of vegetation on scales ranging from forests to plant communities.
- GAP Land Cover Data Portal: national land cover data, from the National Gap Analysis Program (USGS)
- PLANTS Database: standardized information about vascular plants, mosses, liverworts, hornworts, and lichens of the U.S. and its territories (NRCS)
- Ecological Site Information System: Repository for ecological site descriptions and information associated with the collection of forestland and rangeland plot data (NRCS)
- Plant Materials Program: application-oriented plant material technology (NRCS)
- RiversEdge West: education and technical assistance for the restoration of riparian lands

8.1.6 Literature

- Websites for discovering published texts and journal articles relevant for a restoration project:
  - Google Scholar
  - Google
  - National Forest Service Library (internal USFS only)
  - USFS Treesearch
  - Water Resources Abstracts
  - USGS Publications Warehouse
  - Science.gov
  - Web of Knowledge

- DigiTop: USDA access to journal articles from principle publishers

8.2 Geographic Information System

A Geographic Information System (GIS) is the most effective method for organizing spatial data, with the overlying layers facilitating the use of a watershed approach to planning and design. Viewing data spatially helps understand context for particular stream reaches. Hence, GIS provides a powerful tool for analyzing stream systems and developing stream restoration designs. Fundamental data that are useful for all projects include orthographic aerial imagery, topographic imagery (USGS topographic maps), watershed boundaries, diversion location data, and gridded elevation data. Inspection of multiple years of aerial imagery, including historical imagery, can provide a great deal of assistance in understanding dominant mechanisms causing the deficiency in question. However, the temptation to use only spatially-referenced data should be resisted, since information that could otherwise be valuable for understanding a system may be discarded.

8.3 Historical Information

Historical information (historic analogs) can be an important tool for understanding the anthropogenic impacts and the historical range of variability of streams (Wohl 2011), to provide guidance for the potential condition. Such information can be invaluable for identifying reasonable goals and objectives for a restoration. Key questions that should be asked regarding a plan or design, with respect to historical information, are:

- Does the plan allow or promote the historic condition?
- Have the elements that led to degradation been alleviated?

Methods for the use of historic information in design is provided in NRCS (2007), TS2. Potentially-useful historic information includes:

- Contemporary descriptions
- Climatic records
- Land use records and historic maps
- Land surveys
- Historic aerial photography (see GIS Data and Mapping section)
- Ecological site descriptions
- Ground-based oblique photography

Where channels have been substantially modified, field evidence can be evident of the prior condition, including abandoned channels, relic terraces, soil and vegetative patterns, old infrastructure, etc.…

However, since historical information often do not provide information on trends, but merely a snapshot in time, such information should be used with caution. This is analogous to the care needed when using reference reaches (spatial analogs), since such information alone does not show disturbance history.

9. PRELIMINARY FIELD ASSESSMENT

The preliminary field assessment is a highly-valuable step in diagnosing stream impairments and their root causes. When combined with the compilation of existing data and other information, the preliminary field assessment allows qualified practitioners to assess condition and develop hypotheses regarding the causes of impairments. Potential mitigation measures to address the impairments can then be thoughtfully elucidated prior to a potentially intensive and expensive field data collection effort. This stage serves as a decision point for the technical specialists and stakeholders on if it is desired to proceed with the project and what general approach may be best for the situation.

Considering that particular indicators or measurements of stream channel condition mean different things for different context and histories, a *diagnostic approach* to stream assessment and monitoring (Figure 2; Table 3), similar to what is used in medical practice, was suggested by Montgomery and MacDonald (2002) as an advisable approach to stream assessment and restoration monitoring design. The preliminary field assessment is an essential part of such a diagnostic approach.

Such a diagnostic approach requires practitioners with both appropriate training and experience, a team sufficiently diverse in expertise to understand the system, and professionals with the ability to analyze the system independent of bias. Additionally, the overall riparian condition typically needs to be assessed for a restoration project, rather than just the channel.

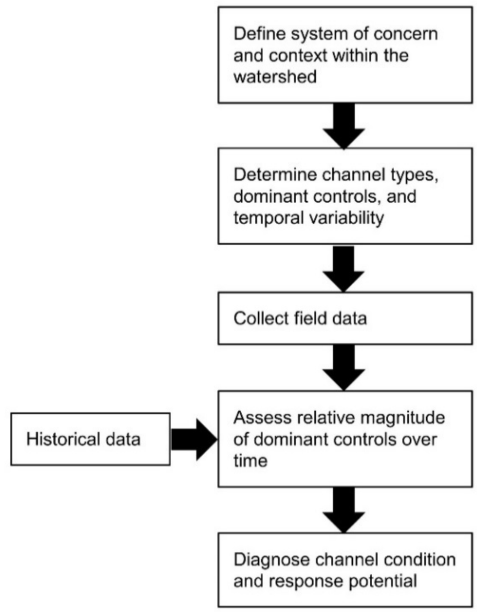


Figure 2: Channel diagnostic procedure (adapted from Montgomery and MacDonald 2002).

Table 3: Role of primary field indicators for diagnosing channel condition (adapted from Montgomery and MacDonald 2002).

Field Indicator	Role
	Valley Bottom Characteristics
Slope	Primary control on channel type and energy dissipation mechanisms
Confinement	Primary control on channel type and energy dissipation mechanisms, and an indicator of anthropogenic disturbances
Entrenchment	Indicates longer-term balance (or lack of) between runoff and sediment loads, likely range of responses to high flows, and anthropogenic disturbances
Riparian Vegetation	Primary control on channel characteristics and ecological condition
Overbank Deposits	Indicates type and magnitude of recent flood deposits
	Active Channel Characteristics
Channel Pattern	Braided channels imply high sediment loads, non-cohesive banks, or steep slopes. Well vegetated multithread channels can indicate a high ecologically-functioning stream valley, and are often associated with large wood.
Bank Condition	Location and extent of eroding banks relative to stream type can indicate recent disturbance
Gravel Bars	Number, location, extent, and condition related to sediment supply
Pool Characteristics	Distribution and amount of fine sediment deposition can indicate role of flow obstructions and whether sediment loads are high for a given channel type
Bed Material	Size and distribution of surface and subsurface bed material can indicate relative balance between recent discharge and sediment supply

Potential impairments to consider when initially evaluating an impaired stream are wide ranging, including: excessive bank erosion; channel straightening and incision; channel modification from multi-thread to single-thread form; discharge modification by reservoir regulation, streamflow diversions, and urbanization; water quality impairments, from historic or current mining, agricultural operations, industry, septic systems (etc.); lack of geomorphic complexity, such as deep pools, width and bank variations, multi-thread channels, and large instream wood; insufficient riparian vegetation, for bank stabilization, cover, shading, and energy input to streams; and excessive fine sediment.

Certain issues can lead to fundamental alteration and destabilization of stream systems, with resulting negative consequences to infrastructure and riparian ecosystems. Specifically, *channel straightening* often results in incision, bank instability, lowering of groundwater tables, and shifts in valley-bottom plant communities; *discharge modification* can lead to aggradation, incision, bank instability, and aquatic life impairments through shifts in the flow regime; and *insufficient bank vegetation and large wood* can result in bank destabilization, channel widening, increased water temperatures (impairing cold-water fish species), reduced longitudinal profile variability (including frequency and depth of pools), reduced flow resistance, and channel incision. These situations need to be noted in the preliminary field assessment of riparian corridors.

Field indicators can be evaluated for evidence of channel degradation, aggradation, or stability (Table 4), as a part of a stability assessment for a stream reach (Figure 3). Importantly, stability may not be the goal; instead, effective stream function for maximizing ecological conditions may be the goal. The setting and context of the proposed project is key.

The initial field assessment should hypothesize about a few key points, specifically:

- What are the dominant fluvial processes in the stream system?
- Is there a problem? If so, is it anthropogenic? Is the issue within the historical range of variability of the stream system?

Table 4: Possible field indicators of stream adjustment or stability (adapted from NRCS 2007, Ch3). Note that stability may not be the goal of a restoration project.

evidence of degradation
perched tributaries
headcuts and nickpoints
terraces
exposed pipe crossings
perched culvert outfalls
undercut bridge piers
exposed tree roots
early-seral vegetation colonization
hydrophytic vegetation high on bank
narrow and deep channel
diversion points have been moved
failed revetments due to undercutting
evidence of aggradation
buried culverts and outfalls
reduced bridge clearance
uniform sediment deposition across
tributary outlets buried in sediment
buried vegetation
channel bed above the floodplain elevation
significant tributary backwater effects
hydrophobic vegetation low on bank or dead in floodplain
evidence of stability
vegetated bars and banks
limited bank erosion
older bridges and culverts with at-grade bottom elevations
mouth of tributaries at or near mainstem stream grade
no exposed pipline crossings or bridge footings

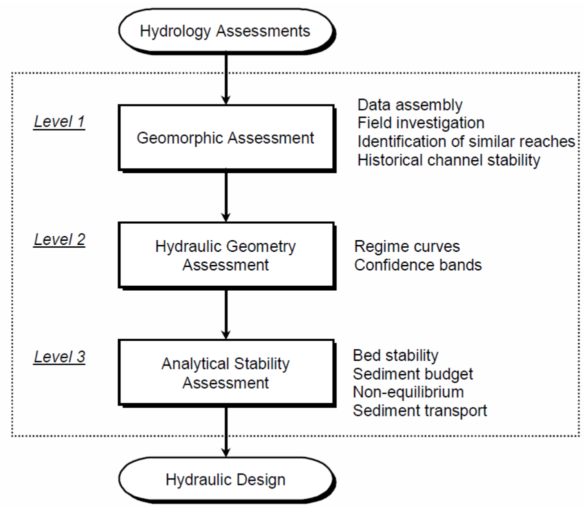


Figure 3: Levels of stability assessments (Copeland et al. 2001).

- What are the factors contributing to the problem? What are potential mitigation strategies?
- What stream channel state best meets the needs of the reach and watershed, from both ecological and human needs perspectives?

General tools and guidance helpful for informing preliminary stream assessments include:

- Bledsoe et al. 2017 Design Hydrology for Stream Restoration and Channel Stability
- NRCS 2007, TS3A Stream Corridor Inventory and Assessment Techniques.
- Montgomery and MacDonald 2002 Diagnostic Approach to Stream Channel Assessment and Monitoring
- Boulton 1999 An overview of river health assessment: philosophies, practice, problems and prognosis
- Stream Functions Pyramid Framework: A guide for assessing and restoring stream functions
    - Overview
    - Function-based rapid stream assessment methodology (Starr et al. 2015)

9.1 Fundamental Principles

From a streamflow hydraulics perspective, there are several fundamental principles that are valuable for assessing mechanisms underlying impairments to stream and riparian function. Utilizing these principles while performing a preliminary field assessment can help practitioners develop understanding of the processes behind impairments, allowing more thoughtful formulation of restoration strategies that address the underlying mechanisms.

9.1.1 Total and Unit Stream Power

With an assumption that there is an insignificant amount of flow acceleration, all the lost potential energy of streamflow must be used by friction against the bed and banks or work (erosion/geomorphic adjustment) on the bed and banks. Stream power (Ω; watt/m or lb/s) is the rate of energy expenditure against the channel bed and banks per unit downstream length. Unit stream power (ω; watts/m^2 or lb/ft-s) is the total stream power per unit channel width.

Total and unit stream power are computed as:

$$\Omega = \gamma Q S_f$$

$$\omega = \frac{\Omega}{w} = \frac{\gamma Q S_f}{w}$$

where γ is the specific weight of water (9810 N/m^3 or 62.4 lb/ft^3), Q is the discharge (m^3/s or cfs), S_f is the friction slope (m/m, often assumed to be the average water surface or bed slope), and w is the flow width (m or ft).

From an applied perspective, unit stream power can be especially valuable when performing preliminary field assessments. For example, if a stream reach has incised or has been channelized and has little to no floodplain to expel energy across during a flood, the width is minimized and unit stream power will be elevated and can force erosion of the bed (further incision) or margins (accelerated streambank or terrace erosion). At higher discharges, unit stream power will also be elevated, with this increase counteracted by erosion or increased friction. Also, total and unit stream power are directly proportional to the sediment transport conveyance capacity; when performing hydraulic modeling of a stream system, changes in total and unit stream power can feed insight into erosional or depositional tendencies of specific stream reaches. Furthermore, unit stream power can be valuable for estimating the erosion risk of channel margins within fluvial erosion hazard zones (Yochum et al. 2017), which can be a primary risk to stream corridor infrastructure during floods.

9.1.2 Shear Stress

Shear stress in stream channels (τ; N/m^2 or lb/ft^2) represents the force per unit area of the flowing water on the streambed. It is computed as:

$$\tau = \gamma h S_f$$

where h is the average depth of water (m or ft).

As with total and unit stream power, shear stress is directly proportional to sediment transport conveyance capacity. For instance, if depth increases given the same discharge, shear stress will increase, leading to increased sediment transport potential as well as, possibly, increased incision.

9.1.3 Momentum

The momentum of moving water transfers the force of streamflow onto obstacles, such as bridge piers, large wood, or a wading stream scientist. Momentum is computed as:

$$F = \rho Q \Delta V$$

where F is the force acting upon an object (N or lb), ρ is the density of water (1000 kg/m^3 or 1.9 slugs/ft^3), and ΔV is the change in velocity from a linear direction (m/s or ft/s).

From an application perspective, momentum transfer is valuable for understanding the forces on flow obstacles and may have value for understanding erosion on channel bends.

9.1.4 Roughness and Flow Resistance

Roughness in channels and floodplains is a fundamental characteristic of stream corridors. Roughness induces the flow resistance needed to dissipate energy, as quantified by stream power. Flow resistance in stream channels is generally due to (1) viscous and pressure drag on grains of the bed surface (grain roughness); (2) pressure drag on bed and bank undulations (form roughness), and (3) pressure and viscous drag on sediment in transport above the bed surface (Griffiths 1987). Additionally, spill resistance associated with hydraulic jumps and wave drag on elements protruding above the water surface can be the dominant flow resistance mechanism in high-gradient channels (Curran and Wohl 2003, Comiti et al. 2009, David et al. 2011). Hence, resistance is due to roughness induced by bed and bank grain material, bedforms (such as dunes and step pools), planform, vegetation, large instream wood, and other obstructions.

In the SI unit system, flow resistance is quantified using the Manning and Darcy-Weisbach methods:

$$V = \frac{R^{2/3} S_f^{1/2}}{n} = \sqrt{\frac{8gRS_f}{f}}$$

where V is the average velocity (m/s), n is the Manning's coefficient, f is the Darcy-Weisbach friction factor, g is acceleration due to gravity (m/s^2), and R is the hydraulic radius (m). In the English unit system, the Manning's equation is:

$$V = \frac{1.49 R^{2/3} S_f^{1/2}}{n}$$

where V is in ft/s and R is in ft. Manning's n is typically preferred by practitioners while f is often preferred by researchers. Either can be used for estimating mean channel velocity or flow resistance (friction slope).

A lack of flow resistance is often a primary cause of impairments in stream corridors. Roughness elements (such as vegetation, instream wood, bank irregularities) add heterogeneity and can be highly valuable for ecological function. Higher streamflow velocities due to insufficient roughness and flow resistance (lower n) can lead to larger momentum transfer forces on flow obstacles and channel banks.

Flow resistance coefficient estimation is approximate, requiring redundancy for confidence in the implemented values. For information on roughness and flow resistance quantification estimates, refer to the Flow Resistance Estimation section of this publication.

9.1.5 Lane's Balance

For understanding how basic variables of stream channel form and discharge relate to each other, Lane's balance (Figure 4) can be helpful. It illustrates how sediment discharge (Q_s) and median size (D_{50}) relate to flow discharge (Q_w *or* Q) and the channel slope (S). Channel aggradation and degradation respond to shifts in the four variables, with increased discharge and slope, the product of which is representative of stream power, typically results in channel degradation until increases in sediment conveyance and sediment size balance the increased stream power. With decreased discharge and slope (decreased stream power), aggradation occurs, with decreased sediment transport and material size. Variation in Lane's balance and stream power correspond with variation between erosional-, transport- and depositional-dominated stream reaches.

Goals for stream restoration frequently target either balance (in a transport reach) or aggradation (in a depositional reach). Depositional reaches are often the focus of restorations that strive to maximize ecological conditions, using such process-based methods as Stage 0 restoration.

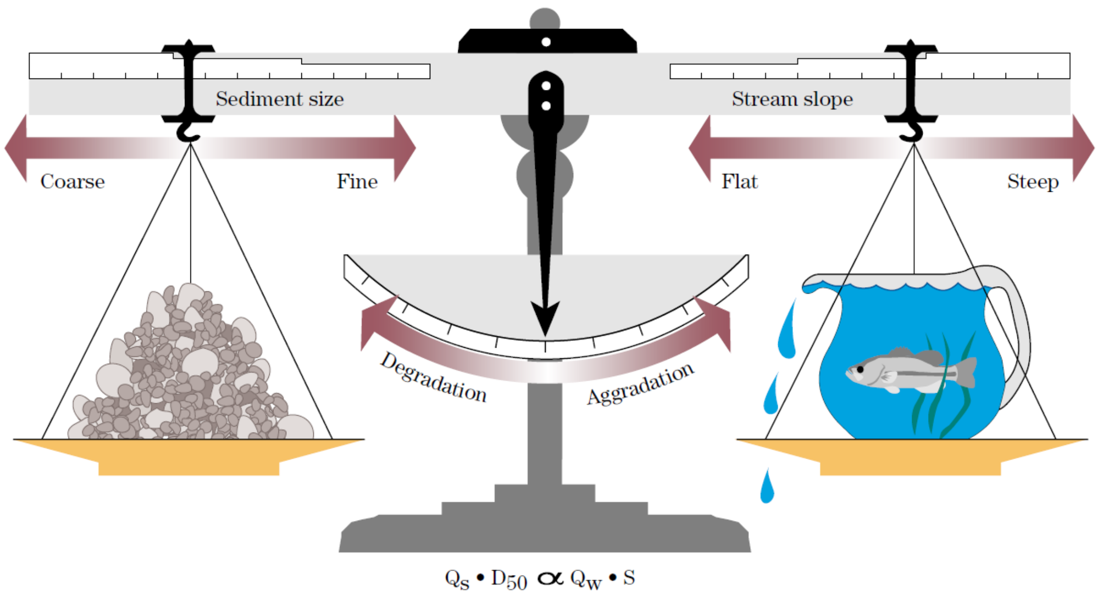


Figure 4: Lane's Balance (NRCS 2007, TS3C).

9.2 Stream Channel States and Evolution Models

Stream channel states are different forms that generally occur in response to variations in flow, sediment, and vegetation. These variations are in response to perturbations, such as large floods, wildfires, excessive livestock grazing, loss of large in-channel wood, stream channelization, etc. An early example of the application of channel states in fluvial geomorphology is the channel evolution model.

The *channel evolution model* (Schumm et al. 1984), is a powerful tool for understanding the dynamics of stream disturbance and recovery processes. The method describes the movement of a channel disturbance, such as a headcut, through a channel reach and the consequential evolution of the channel over time and space (Figure 5), providing an evaluation of longitudinal response and restoration potential. At a specific location the channel evolves from an initial stable state (stage 1) through incision (stage 2), widening (stage 3), deposition and stabilization (stage 4), and once again stable (stage 5). Stages 2 and 3 are the most challenging stages of the evolution model for managers; this is the stage where instability and sediment supply is highest and restoration options are limited. Over time, the incision moves upstream, forcing evolution of the valley bottom on successive upstream reaches. Using the channel evolution model, past channel states can be understood and future states predicted with a *space* *for time* substitution – this conceptual model has great value for on-the-ground application during stream restoration planning. Additional information regarding this model is provided in NRCS (2007, Ch3) and SVAP2 (NRCS 2009), as well as the original and other references.

The Natural Channel Design methodology (NRCS 2007, Ch11) draws on lessons learned from the channel evolution model, through its use of successional stages of channel evolution (Figure 6). Understanding the present and potential future successional stages (or states) and stream classifications of a stream can be very helpful for understanding channel stability and trends, and identifying realistic project goals.

Since its introduction, the channel evolution model has been modified by a number of scientists. Simon and Hupp (1987) and Simon (1989) modified the model to include an additional stage for an anthropogenic-induced, un-incised channelized streams while Watson et al. (2002) extended the method by providing a quantitative method for developing channel-restoration strategies. Cannatelli and Curran (2012) modified the channel evolution model for dam removals, incorporating local hydrological conditions and vegetative growth in the evolution process.

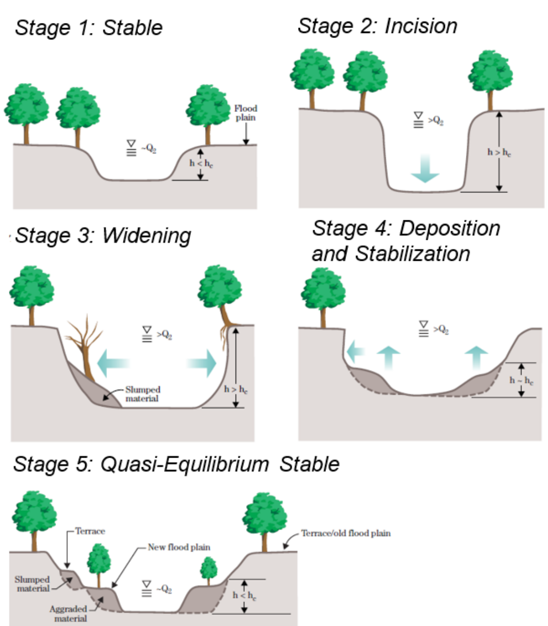


Figure 5: Channel evolution model, with channel cross sections illustrating the 5 channel stages (modified from NRCS 2007, Ch3).

Recognizing the ecological value of vegetated multi-thread channels as well as the evolution of stream states as sometimes cyclical, rather than linear, Cluer and Thorne (2013) adapted the channel evolution model into the *stream evolution model* (Figure 7; Table 5). Compared to the channel evolution model, this model adds precursor and late stages for a multi-thread channel pattern as well as a cyclical pattern where stream state alternately advances through the standard stages, skips stages, recovers to a previous stage, or repeats stage cycles. Anastomosing wet complexes are typically biologically rich, they were common before floodplain settlement in North America during the 19th and 20th centuries, and, hence, can be a preferred alternative to other restoration strategies in some situations.

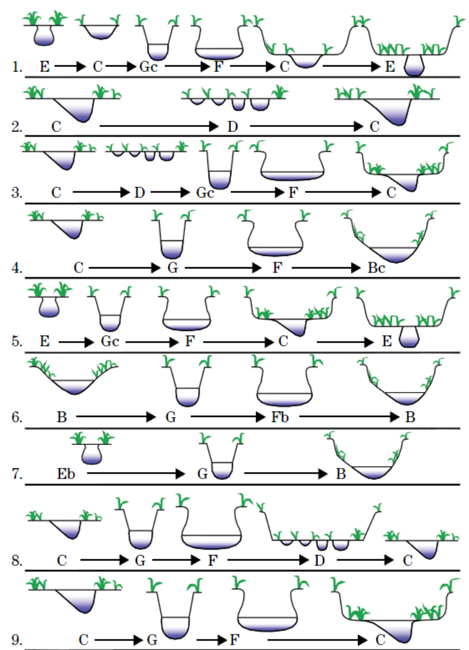


Figure 6: Various stream succession stages (NRCS 2007, Ch11).

Drawing from rangeland ecology, it has been proposed that *state and transition models* can be valuable for understanding channel evolution (Phillips 2011; Phillips 2014; Van Dyke 2016). These models provide structure for identifying modes of changes in ecosystems and landscapes, and tools for interpreting past adjustments and predicting future changes. Traditional succession models implemented in ecology are a special case of state-and-transition models, with a linear sequence (Phillips 2011; Figure 8). The channel evolution model, stream evolution model, and the succession stages identified by Rosgen (Figure 6) can be considered state-and-transition models (Phillips 2014), generally of a linear succession form but also including cyclical and radiation properties in the case of the stream evolution model.

In a variation of evolution models, river evolution diagrams (Brierley and Friers 2015) assess and illustrate system responses to changing conditions, as well as plot evolution trajectories. This tool can be valuable with adaptive management, framing decision making in the context of possible future stream states.

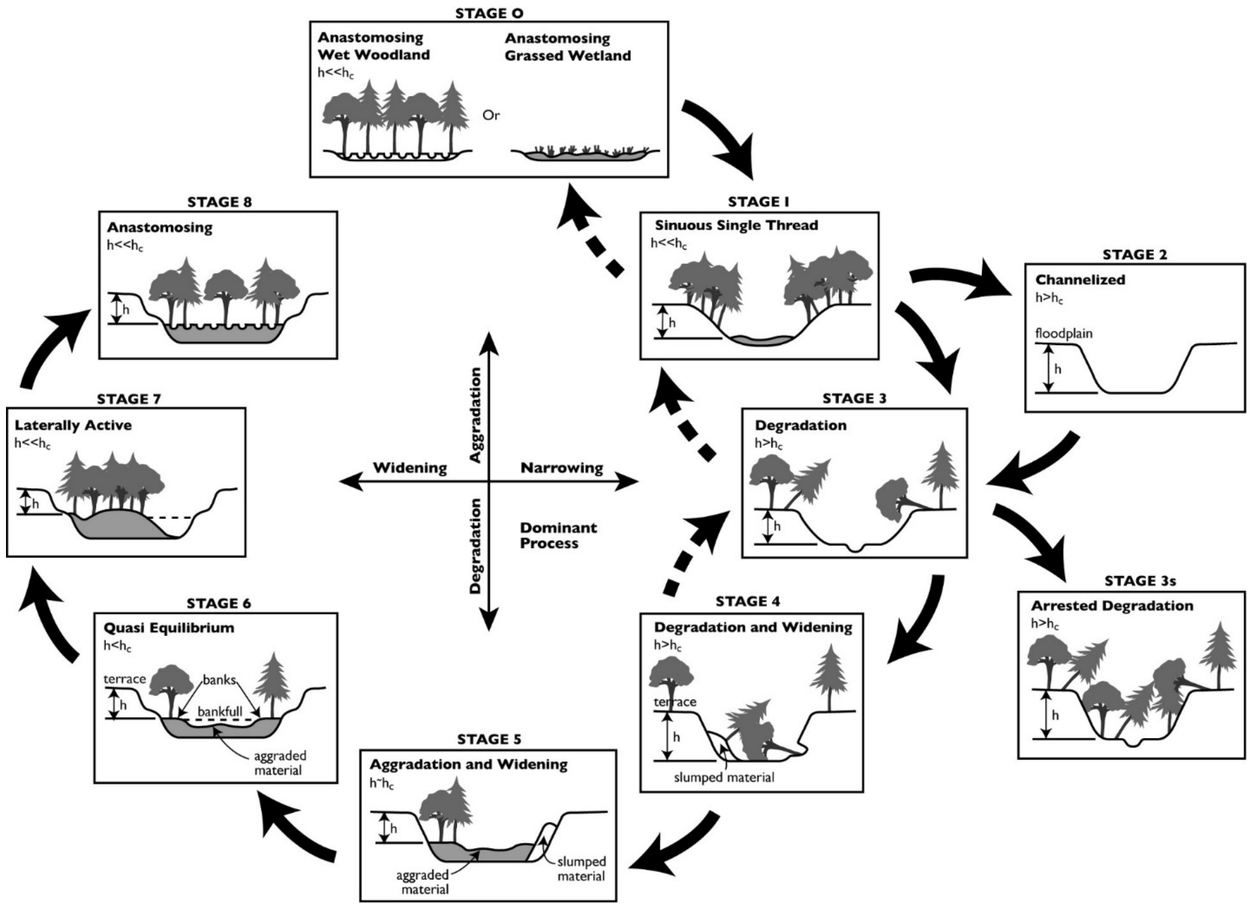


Figure 7: Stream evolution model (Cluer and Thorne 2013). Stage descriptions are provided in Table 5. Dashed arrows indicate “short circuits” in the normal progression.

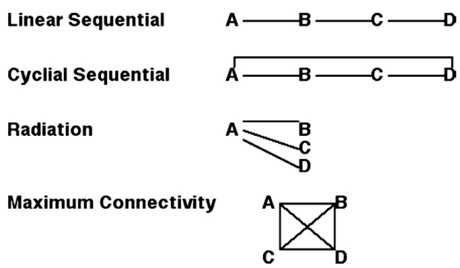


Figure 8: Archetypal state-and-transition model network structures (Phillips 2011).

Additionally, the flow-channel fitness model (Phillips 2013) was developed to predict the qualitative response of alluvial channels to modified flow regimes, with fitness referring to the "fit" between a given discharge and channel capacity. Changes in discharge, slope, shear stress, and sediment supply are utilized to predict the change in channel state.

Table 5: Descriptions of stream evolution model (SEM) stages, with comparison to the channel evolution model (CEM) stages presented in Schumm et al. (1984) (adapted from Cluer and Thorne 2013).

	SEM Stage	CEM Stage	Description
	0: Anastomosing		Pre-disturbance, dynamically meta-stable netw ork of unabranching channels and floodplain w ith vegetated islands supporting w et w oodland or grassland.
Single-Thread Channels	1: Sinuous	1: Pre-modified	Dynamically stable and laterally active channel w ithin a floodplain complex. Flood return period 1-5 year range.
Single-Thread Channels	2: Channelized		Re-sectioned land drainage, flood control, or navigation channels.
Single-Thread Channels	3: Degrading	2: Degradation	Incising and abandoning its floodplain. Feturing headcuts, knick points or knick zones that incise into the bed, scours aw ay bars and riffles, and removes sediment stored at bank toes. Banks stable geotechnically.
Single-Thread Channels	3s: Arrested degradation		Stabilized, confined, canyon-type channels. Incised channel in w hich bed low ering and channel evolution have been halted becouse of non-erodible materials (bedrock, tight clays) have been encountered.
Single-Thread Channels	4: Degradation and w idening	3: Rapid w idening	Incising w ith unstable, retreating banks that collapse by slumping and/or rotational slips. Failed material is scoured aw ay and the enlarged channel becomes disconnected from its former floodplain, w hich becomes a terrace.
Single-Thread Channels	4-3: Renew ed incision		Further headcuting w ithin Stage 4 channel.
Single-Thread Channels	5: Aggrading and w idening	4: Aggradation	Bed rising, aggrading, w idening channel w ith unstable banks in w hich excess load from upstream together w ith slunped bank material build and silt beds. Banks stabilizing and berming.
Single-Thread Channels	6: Quasi-equilibrium	5: Stabilization	Inset floodplain reestablished, quasi-equilibrium channel w ith tw o-stage cross section featuring regime channel inset w ithin larger, degraded channel. Berms stabilize as pioneer vegetation traps fine sediment, seeds, and plant propagules.
Single-Thread Channels	7: Laterally active		Channel w ith frequent floodplain connection developes sinuous course, is laterally active, and has asymmetrical coss section promoting bar accretion at inner margins and toe scour and renew ed bank retreat along outer margins of expanding/migrating bends.
	8. Anastamosing		Meta-stable channel netw ork. Post-disturbance channel featuring anastomosed planform cvonnected to frequently-inundated floodplain that supports w et w oodland or grassland that is bound by set-back terraces on one or both margins.

9.3 Stream Classification

Stream classification systems are important tools for communication between practitioners through use of a common vocabulary that is based upon the geomorphic condition. Two of the most common approaches for lower-order streams are the Montgomery and Buffington (1997) and Rosgen (1994, 1996) systems. The River Styles Framework (Fryirs and Brierley 2013) provides another classification method. There has been debate and criticism about some classification systems being based on an assessment of form, rather than a quantification of processes. A comparitive assessment performed in the Middle Fork John Day River watershed, in the Columbia River basin, indicates that such criticism may be overstated (Kasprak et al. 2016).

The Montgomery and Buffington system (Figure 9) was developed for mountainous drainage basins, with eight reach-level channel types that directly relate to dominant geomorphic processes and sediment transport regime. The Rosgen stream classification system (Figure 10) is based upon the geomorphic characteristics of entrenchment, width/depth ratio, sinuosity, bed material, and channel slope. For a more in depth description of the Rosgen classification system, including a summary of the associated geomorphic valley types, see [NRCS (2007), TS3E](#).

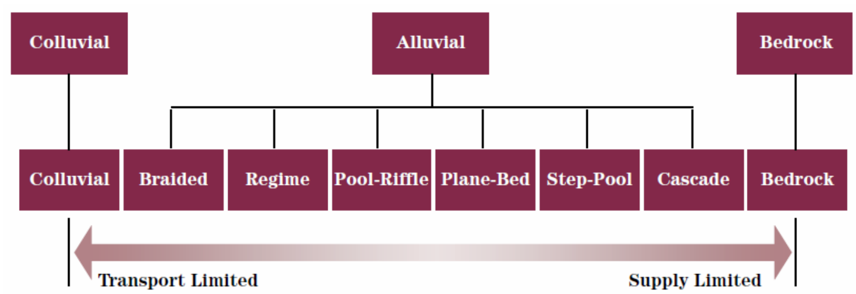


Figure 9: Montgomery and Buffington classification system (NRCS 2007, Ch3).

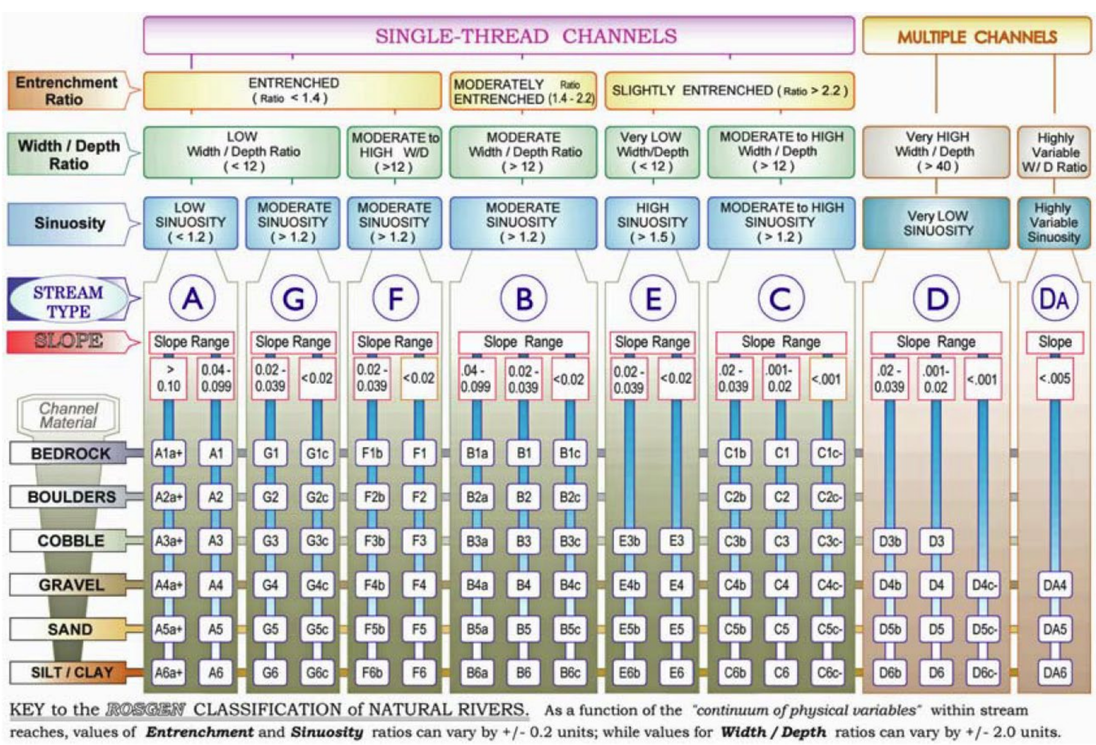


Figure 10: Rosgen classification system (NRCS 2007, Ch3).

9.4 Stream Evolution Triangle

The Stream Evolution Triangle is a conceptual tool that recognizes the equal value of biology with hydrology and geology, as a mechanisms that drives stream condition (Castro and Thorne 2019; Figure 11). Biological outcomes, such as enhanced salmonid habitat, are frequently the most common goals to warrant the investment in stream restoration, though biology has commonly taken a lesser role in design than physics-based processes. Using the Stream Evolution Triangle, these three fundamental processes are co-equal drivers, providing a design framework that can best provide desired biological outcomes.

Typically, hydrology and geology concepts and processes (such as Lane's balance) drive stream restoration design practices. The dominance of engineering and physics-based approaches to restoration can result in less desirable outcomes in some situations. For example, using an engineering approach of maintaining sediment conveyance through a restoration reach, which may be appropriate where restoration has the goal of streambank stability for infrastructure protection, can be inappropriate in a wide depositional valley where enhanced aquatic habitat for fish spawning and rearing is the goal. The Stream Evolution Triangle, with its equivalency of biology with hydrology and geology, can alter design approaches for better satisfying biologically-focused goals in restoration.

Information regarding this concept can be obtained from:

- Castro and Thorne 2020 The Stream Evolution Triangle (StreamNotes)
- Castro and Thorne 2019 The stream evolution triangle: Integrating geology, hydrology, and biology
- Castro and Thorne 2019 The stream evolution triangle: Integrating geology, hydrology, and biology (SEDHYD-2019)

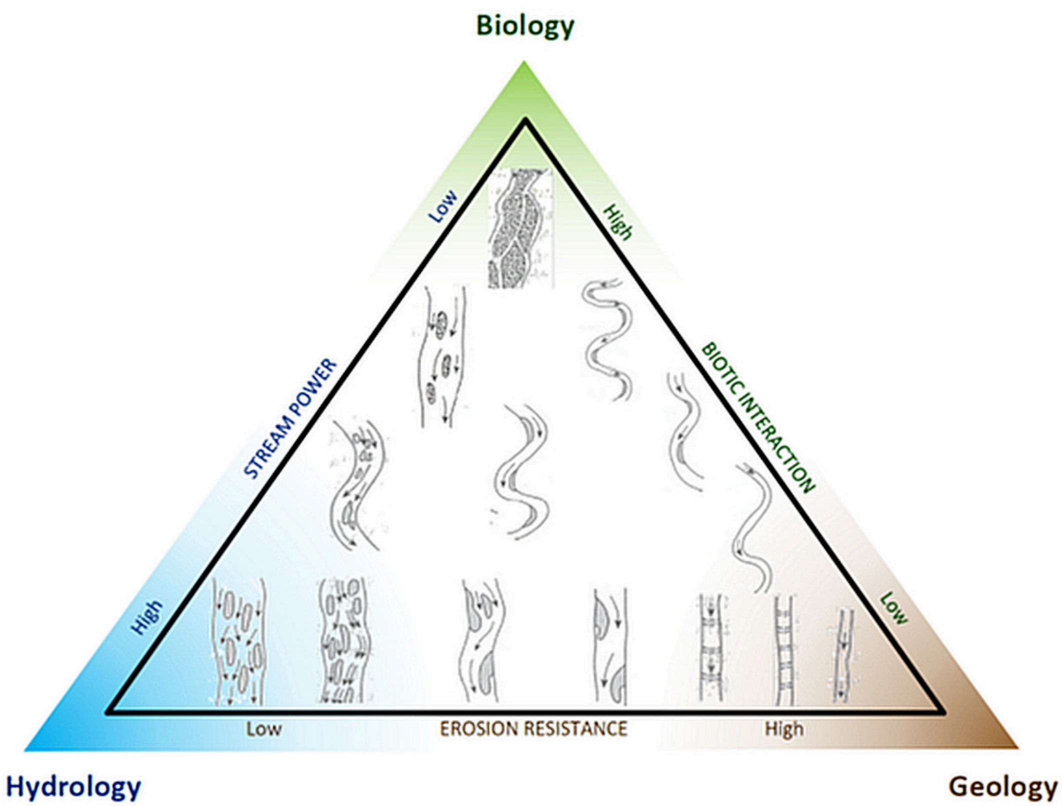


Figure 11: The Stream Evolution Triangle (SET) with planform patterns defined by Schumm (1985) illustrating typical planforms expected to occur in different process-domains. The SET represents the relative influences of geology (erosion resistance), hydrology (stream power), and biology (biotic interaction). From Castro and Thorne (2019).

9.5 Stream Ecological Valuation (SEV)

The Stream Ecological Valuation (SEV) tool was originally developed from a series of workshops in Auckland, New Zealand, and later modified by a technical panel. This assessment method is based on 14 stream functions, specifically:

- hydraulic functions (natural flow regime, floodplain effectiveness, longitudinal connectivity, groundwater connectivity);
- biogeochemical functions (water temperature, dissolved oxygen, organic matter input, instream organic particle retention, pollutant decontamination);
- habitat functions (fish spawning, aquatic fauna); and
- biodiversity functions (intact fish, invertebrate, riparian vegetation populations).

This method covers a wide range in stream functions that are relevant for assessing proper stream function, consequently providing a method that has potential for application for wider geographic areas.

Information regarding this method can be obtained from:

- Neale et al. (2011) Stream Ecological Valuation (SEV): A User's Guide

9.6 Basic Assessment Tools

Basic qualitative assessments can be useful tools for providing a structured evaluation of a riparian corridor. These methods evaluate important components of stream condition such as channel and floodplain form, hydrologic alteration, canopy cover, riparian plant communities, in-stream habitat, and nutrient enrichment (NRCS 2009).

These qualitative assessments are often one of the first steps performed to provide a general approximation of stream condition and develop a basic understanding of the impairments impacting a stream reach of interest. However, it needs to be understood that these tools are only qualitative measures; substantially different results can be obtained by different observers. Additionally, dependence upon such tools is not a substitute for experienced practitioners in stream restoration to thoughtfully assess available information and field conditions to diagnose the condition and hypothesize on impairments and potential restoration strategies.

Available qualitative tools include:

- SVAP 2: Version 2 of the NRCS Stream Visual Assessment Protocol. Provides an initial evaluation of the overall condition of wadeable streams, riparian zones and instream habitat. Assigns a score of 1 through 10 for 16 elements, with 10 representing the highest-quality conditions. Average scores greater than 7 represent good overall stream condition. (NRCS 2009)
- Proper Functioning Condition (PFC): Provides a consistent methodology for considering hydrology, vegetation, and soils/sediment characteristics in describing the condition of streams, riparian, and wetland areas. Condition is described as either proper functioning, functional – at risk, nonfunctional, or unknown in either lotic or lentic systems (Dickard et al. 2015, Gonzalez and Smith 2020).
- Morphological Quality Index (MQI): A relatively simple, process-based method for evaluating the hydromorphological condition of stream reaches over time (Rinaldi et al. 2015).
- Pfankuch Method: Stream Reach Inventory and Channel Stability Evaluation. This is a procedure to systemize measurements and evaluations of the resistive capacity of mountain stream channels, evaluate the detachment of bed and bank materials, and to provide information about the capacity of streams to adjust and recover from potential changes in flow and sediment production (Pfankuch 1975).

10. MONITORING AND DATA COLLECTION FOR RESTORATION

Monitoring and field data collection to support restoration projects can consist of many different activities. The specific data needing to be collected varies by the stream reach of concern, the specific project objectives, and should be collected both before and after restoration is completed. Data should be collected prior to restoration to understand dominant mechanisms and impairments in the stream reach, and to provide a comparison for conditions following restoration. It is also critical to collect monitoring data post-restoration to assess the success of the restoration project.

Nationally, more than $1 billion is spent each year on stream restoration projects though only 10% of projects report collecting monitoring and assessment data (Bernhardt et al. 2005). Consequently, relatively little information has been gathered on the effectiveness of restoration practices. To help develop a greater understanding of the effectiveness of tax dollars spent, the collection, analysis, and reporting of pre- and post-project monitoring data should be a priority. The results should be documented at a minimum in project reports, and for more interesting projects and to reach wider audiences, in conference proceedings and journal articles.

In this section, several types of monitoring data are briefly discussed including aquatic organisms, riparian vegetation, topographic surveying, bankfull stage identification, discharge and water quality measurements, bed material composition and transport, and groundwater. While such data collection and analysis can be essential, monitoring can take a substantial investment of time and money – only monitoring data needed to satisfy the project objectives and minimize failure risk should be collected.

Numerous monitoring protocols have been developed for evaluating the status and trends in stream condition. References for monitoring protocols and other information relevant to pre- and post-project data collection are provided at:

- Weber et al. 2020. Low Tech Process Based Restoration Project Implementation and Monitoring Protocol
- BLM 2020 AIM National Aquatic Monitoring Framework: Field Protocol for Wadeable Lotic Systems.
- US EPA National Rivers and Streams Assessment 2018-2019 Field Operations manual for wadeable and non-wadeable systems
- Heredia et al. 2016 Technical Guide for Field Practitioners: Understanding and Monitoring Aquatic Organism Passage at Road-Stream Crossings
- BLM 2015 AIM National Aquatic Monitoring Framework: Introducing the Framework and Indicators for Lotic Systems
- Archer et al. 2016a Effectiveness monitoring for streams and riparian areas: Sampling protocol for stream channel attributes (PIBO)
- Archer et al. 2016b Effectiveness Monitoring Program for Streams and Riparian Areas: 2014 Sampling Protocol for Vegetation Parameters (PIBO)
- Stream Functions Pyramid: A tool for assessing success of stream restoration projects
- Burton et al. 2011 Multiple Indicator Monitoring of Stream Channels and Streamside Vegetation
- Bonfantine et al. 2011 Guidelines and Protocols for Monitoring Riparian Forest Restoration Projects.
- Rosgen et al. 2008 River Stability Field Guide
- Doyle et al. 2007 Developing Monitoring Plans for Structure Placement in the Aquatic Environment (USFS)
- NRCS 2007, Ch11 Rosgen Geomorphic Channel Design
- NRCS 2007, Ch16 Maintenance and Monitoring
- Guilfoyle and Fischer 2006 Guidelines for Establishing Monitoring Programs to Assess the Success of Riparian Restoration Efforts in Arid and Semi-Arid Landscapes

- Kershner et al. 2004 Guide to Effective Monitoring of Aquatic and Riparian Resources (PIBO)
- Rosgen 1996 Applied River Morphology
- Thom and Wellman 1996 Planning Aquatic Ecosystem Restoration Monitoring Programs
- Harrelson et al. 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique

Additionally, field data collection through mobile device applications has become popular by some workers. Camp and Wheaton (2014) provide an overview of tools developed at Utah State University.

10.1 Aquatic Organisms

Habitat improvement for aquatic organisms is a common objective for stream restoration projects. To have measurable objectives in such projects, quantifying aquatic organism populations (Figure 12, Figure 13) is necessary both in the planning phase as well as after construction. Both fish sampling and macroinvertebrate sampling are valuable tools for assessing status. Environmental DNA (eDNA) is also being used for monitoring the presence or absence of aquatic species.

Figure 12: Fish sampling (NRCS 2007).

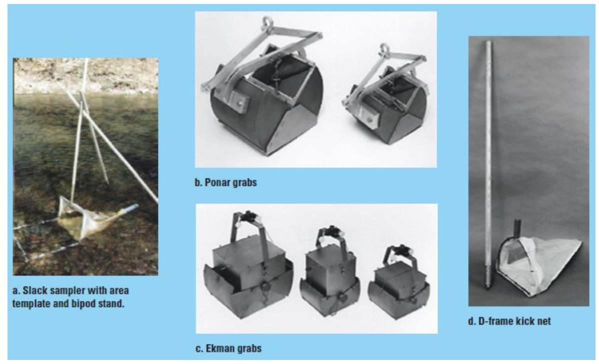


Figure 13: Macroinvertebrate sampling equipment (Moulton et al. 2002).

References and websites for assessing aquatic organism populations include:

- eDNA Sampling for aquatic organism detection. Forest Service National Genomics Center for Wildlife and Fish Conservation
- Penaluna et al. 2018 Aquatic Biodiversity from a Bottle of Water: Using eDNA to Understand Species Richness (StreamNotes)
- Heredia et al. 2016 Technical Guide for Field Practitioners: Understanding and Monitoring Aquatic Organism Passage at Road-Stream Crossings
- Young et al. 2016 Environmental DNA (eDNA) Sampling: Revolutionizing the Assessment and Monitoring of Aquatic Species (StreamNotes)
- Carin et al. 2015 Protocol for Collecting eDNA Samples from Streams. USDA Forest Service, Rocky Mountain Reseach Station.
- Becker and Russell 2014 (internal Forest Service only) Fish Detection and Counting Device: Automated Capacitive Sensing of Aquatic Life in Remote Streams and Rivers
- Aquatic Insect Encyclopedia: Aquatic insects of trout streams
- NRCS 2007, Ch3 Site Assessment and Investigation
- Moulton et al. 2002 Revised Protocols for Sampling Algal, Invertebrates, and Fish Communities as Part of the National Water-Quality Assessment Program (USGS)
- Davis et al. 2001 Monitoring Wilderness Stream Ecosystems

- Barbour 1999 Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish

10.2 Riparian Vegetation

Riparian vegetation (Figure 14) offers many benefits to streams, including reduced erosion rates and sediment input to streams, ~~and~~ increased bank stability, increased flow resistance and reduced velocities, increased water quality, increased vadose zone recharge, the provision of cover for temperature regulation, vertical structure for riparian wildlife habitat, and energy input to streams. Riparian vegetation is essential for healthy benthic macroinvertebrate populations, which in turn provides a critical food resource for fish. Hence, understanding the status and potential of riparian plant communities is an essential component of stream restoration planning and design.

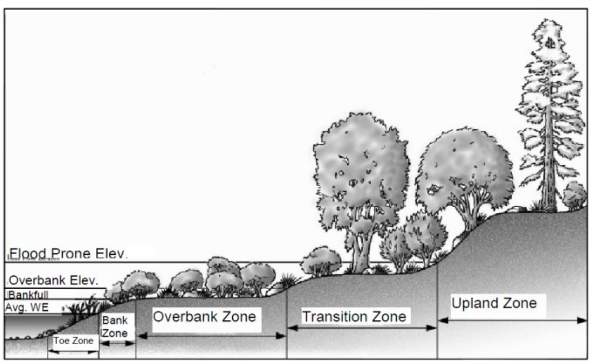


Figure 14: Vegetation zones within a riparian cross section (Hoag et al. 2008).

References available for quantifying riparian vegetation include:

- Merritt et al. 2017 The National Riparian Core Protocol: A Riparian Vegetation Monitoring Protocol for Wadeable Streams of the Conterminous United States
- Reynolds and Merritt 2017 Tools for Understanding Riparian Vegetation Distribution using a Plant Guilds Approach (StreamNotes)
- Stromberg and Merritt 2015 Riparian Plant Guilds of Ephemeral, Intermittent, and Perennial Rivers
- Archer et al. 2016b Effectiveness Monitoring Program for Streams and Riparian Areas: 2014 Sampling Protocol for Vegetation Parameters (PIBO)
- Burton et al. 2018 Multiple Indicator Monitoring of Stream Channels and Streamside Vegetation
- Hoag et al. 2008 Field guide for Identification and Use of Common Riparian Woody Plants of the Intermountain West and Pacific Northwest Regions.
- Scott and Reynolds 2007 Field-based evaluation of sampling techniques to support long-term monitoring of riparian ecosystems along wadeable streams on the Colorado Plateau.
- Kershner et al. 2004 Guide to Effective Monitoring of Aquatic and Riparian Resources
- Winward 2000 Monitoring the Vegetation Resources in Riparian Areas

10.3 Topographic Survey Data

For stream projects, topographic survey methods typically fall into two categories: differential leveling and land surveying. Differential leveling uses a tripod-mounted level (traditional or laser) and measuring tape (Figure 15; Harrelson et al. 1994). This is an older technique for stream projects. Land surveying includes methods such as total station and survey-grade GPS (RTK systems; Figure 16). RTK in particular allows single individuals to collect much more frequent and accurate data points (allowing for a general land survey). Additionally, total stations are essential for data collection in some areas with dense vegetative cover where RTK do not perform well; they are frequently used in combination with RTK systems. Airborne-collected Light Detection and Ranging (LiDAR) data are increasingly available at many locations, and can be more economical to contract for than ground-based surveys over larger areas. They allow for an excellent description of landforms, but these datasets are typically only relevant for measurements above the water surface at the time of data collection. When combined with ground-based data collection for below-water features, validation is needed to assure that the datasets are compatible. Additionally, green LiDAR technology allows for bathymetry measurement in some settings.

Key advantages of survey-grade GPS is the enhanced capability of georeferencing the survey so that the data points can be easily overlayed with other data layers in GIS or Computer Aided Drafting and Design (CADD). More accurate construction layout can also be performed. A disadvantage of survey-grade GPS is its limited capabilities in areas with vegetative canopy, though this can be mitigated by surveying during leaf-off periods, using an antenna designed to be more effective under canopy, or using a total station for filling in data gaps in areas of dense canopies. To properly georeference the data, an Online Positioning User Service (OPUS) solution can be obtained for the base station location, with this setup location and coordinates consistently used for all project surveying. For a description of the difference between ellipsoid and geoid vertical datum, see this NGA website.

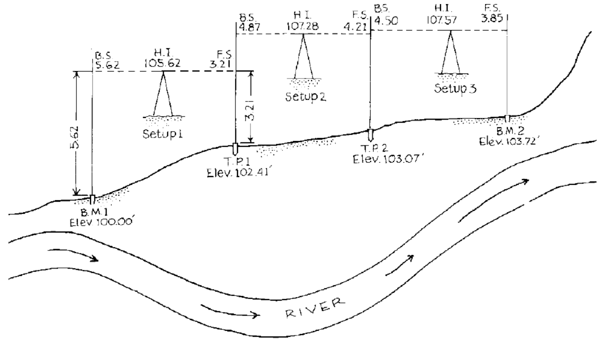


Figure 15: Differential surveying (Harrelson et al. 1994).

Figure 16: Survey-grade GPS.

The extent of topographic survey data required to perform the needed analyses depends upon the project objectives and extent. For example, if a project is limited to bank stabilization along a single bank over a short reach, the only survey data that may be needed could be a thalweg and bankfull longitudinal profiles and a few cross sections. Alternatively, if the project is more extensive, for example the construction of a new channel (or channels) to address previous stream channelization activities, more survey data will be needed to analyze and design the project.

A project with a high level of complexity may require a general land survey of the riparian zone, up to the 100-year flood or expected flood potential level (Yochum et al. 2019), so that a hydraulic model with a detailed sequence of cross sections can be developed, as well as development of more complex hydraulic models (2-D, 3-D) if they are deemed necessary. This type of survey should not be simply a series of cross sections but rather a feature survey to measure the entire channel and floodplain form. Using one approach, features are surveyed to measure the location of relevant landforms and grid data are collected to define the shape and gradient between the features. This grid density varies with the amount of variability of the land surface between the features. Typical features surveyed include a longitudinal profile of the channel thalweg, bottom and top of channel banks, and the bottom and top of terrace slopes.

For both simpler and more complex projects, geometric data should be collected both upstream and downstream of the reach of interest, to assist with the design of project transitions and to help understand potential interactions with neighboring untreated sections. For example, a downstream headcut that shows signs of migration would indicate a strong potential for incision within a restoration reach; a survey should include such features. Additionally, these upstream and downstream areas may be valuable for collecting data on reference conditions.

Tools and guidance helpful for collecting, processing, and transforming survey data for stream work include:

- CHaMP Transformation Tool: An ArcGIS add in for transforming survey data into real-world coordinates
- CHaMP Topo Processing Tools: topographic survey processing add in for ArcGIS, from the Columbia Habitat Monitoring Program
- OPUS: Online Positioning User Service to locate benchmarks using RTK survey-grade GPS, from NOAA
- Geomorphic Change Detection (GCD): software to determine differences in digital elevation models (DEM differencing), for such applications as computing volumetric changes in sediment storage

10.4 Bankfull Stage Identification

The bankfull channel represents the result of the channel-forming discharge being, on average, the most effective discharge for producing and maintaining the channel's geomorphic condition (i.e., width, depth, slope). Not all stream channels display this feature, but perennial alluvial streams typically do for at least portions of their length. There are confounding (and sometimes controversial) issues tied to effective discharge and bankfull width, stage and discharge. Discussions on this are left primarily to the supporting documents, such as the references provided in the Overview of Stream Processes and Restoration section.

Due to the fundamental nature of bankfull discharge, accurate identification of bankfull elevation is often necessary. This elevation is used for the definition and communication of channel shape, as well as physical and biologic processes. Common physical indicators for bankfull elevation are:

- Level of incipient flooding onto an active floodplain
  - Lowest flat floodplain surface, not a higher abandoned surface (terrace) that the stream has incised below
- Elevation of the top of the highest depositional surface of an active bar, such as a point bar
- Break in slope of the bank
- Change in particle size, with finer material deposited on the floodplain
- Change in vegetation, with perennials slightly below, at or above the bankfull level

To properly identify bankfull in the field, it is important to identify bankfull features not just at a point but instead as a continuous feature along a portion of the reach, to reduce the potential for misidentification. A good practice is to mark the continuous surface with pin flags then stand on the far bank and observe the markers for accuracy and consistency.

References for identifying bankfull include:

- NRCS 2007, Ch5 Stream Hydrology
- Copeland et al. 2001 Hydraulic Design of Stream Restoration Projects
- Rosgen 1996 Applied River Morphology
- Harrelson et al. 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique.
- Leopold, L.B. 1994 A View of the River

Additionally, the following videos illustrate some of the best approaches for identifying bankfull elevation:

- In-Depth Critical Concepts: Bankfull, Bench, and Scour line, 2020, BLM Lotic AIM program
- Identifying Bankfull Stage in Forested Streams in the Eastern United States 2003 (M. Gordon Wolman, William Emmett, Elon Verry, Daniel Marion, Lloyd Swift, Gary Kappesser)
- A Guide for Field Identification of Bankfull Stage in the Western United States 1995 (Luna Leopold, William Emmett, H. Lee Silvey, David Rosgen)

DVD's containing uncompressed versions of these videos are available from the Forest Service National Stream and Aquatic Ecology Center.

10.5 Discharge Measurements

Discharge measurements are often collected to inform stream restoration work. These data are collected to measure such things as bankfull and low flow discharge, to calibrate hydraulic models, for geomorphic design, and for habitat assessments. Discharge measurements provide information regarding channel roughness, including how this roughness varies by stage and location.

Discharge can be measured using the traditional velocity-area method as well as with more advanced tools, such as an acoustic doppler current profiler. The velocity-area method divides the stream channel into numerous vertical subsections where depth and average velocity is measured, with the overall discharge computed by summing the incremental subsection values. Details for discharge measurements techniques can be found in:

- WMO 2010 Manual on Stream Gauging
- Turnipseed and Sauer 2010. Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods.
- Paradiso 2000 A Bank-Operated Traveling-Block Cableway for Stream Discharge and Sediment Measurements
- Harrelson et al. 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique
- Buchanan and Somers 1969 Discharge Measurements at Gaging Stations

10.6 Water Quality

Inadequate water quality is an impairment that can prevent the achievement of some restoration objectives, such as the establishment or protection of a fishery in a project reach. For example, lack of shading in or upstream of a restoration reach can lead to excessive peak summertime temperatures for cold water fishes, metal loading from historic mining activities within the watershed can create toxic conditions for aquatic life, and excessive nutrients from riparian livestock grazing and septic systems can cause algae blooms that can depress dissolved oxygen levels.

For cold water fishes, excessive peak summertime temperatures are often the primary impairment. Nationally, increasing trends in stream temperatures have been observed, while decreasing trends are much less common (Kaushal et al. 2010). Stream temperatures typically have a daily (diurnal) cycle (Figure 17). Excessive peak temperatures can have sub-lethal effects (e.g., reductions in long-term growth and survival) and, if high enough, are deadly. If the project objectives are to increase habitat for trout, excessive temperatures would need to be mitigated. With stream temperatures a function of upstream cover and solar radiation input to the stream, upstream riparian condition can be fundamental for controlling temperature in a reach of interest.

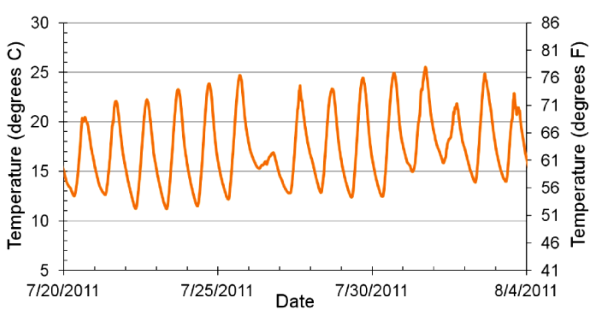


Figure 17: Diurnal temperature fluctuations.

Hach kits, for instantaneous measurements of dissolved oxygen, nitrogen and phosphorus, can provide data at a low cost, and are simple to use. pH paper and a thermometer can also be effective for measuring basic field parameters. Logging multi-parameter probes can be of great value for assessing the basic water quality of the site. The most common sensors measure temperature, pH, dissolved oxygen, conductivity, and depth. However, this equipment is expensive. Simple and cost effective temperature monitoring systems are available, such as the Hobo U22; equipment are available to collect the data needed to assess limiting conditions for cold water fish species.

If existing data are not available for the stream of interest, it may be necessary to collect water quality samples and have laboratory analyses performed. The U.S. Geological Survey (USGS variously dated) provides extensive documentation on procedures for the collection of water quality samples. Water quality analyses can be performed at various commercial labs, the EPA, as well as the USGS National Water Quality Laboratory, at the Denver Federal Center.

General references for assessing water quality in streams include:

- EPA Standards for Water Body Health Water Quality Criteria for Aquatic Life and Human Health
- Drever 1997 The Geochemistry of Natural Waters
- Stumm and Morgan 1996 Aquatic Chemistry – Chemical Equilibria and Rates in Natural Waters

Specific references helpful to practitioners for monitoring water quality include:

- Steel and Fullerton 2017 Thermal Networks – Do You Really Mean It? (StreamNotes)
- USFS 2012 (internal USFS only) Monitoring Water Quality: Collecting Stream Samples
- USFS 2008 (internal USFS only) Collecting Water Samples for Chemical Analysis: Streams
- Isaac 2011 Stream Temperature Monitoring and Modeling: Recent Advances and New Tools for Managers
- Dunham et al. 2005 Measuring Stream Temperature with Digital Data Loggers – A User's Guide
- Davis et al. 2001 Monitoring Wilderness Stream Ecosystems

10.7 Bed Material Sampling

Knowledge of bed material size distributions is necessary for describing channel type, and quantifying incipient motion, sediment transport capacity, and flow resistance. Bed material size can also indicate the quality of biologic habitats, such as fish spawning opportunities.

Methods vary by material size (i.e. sand versus cobble and gravel), with Bunte and Abt 2001 providing an overall reference for sampling bed material in gravel and cobble-bed channels. Bed material can be characterized using such methods as grid sampling, where particles are measured under a preselected number of grid points (i.e. pebble count, photographic grid count), and aerial sampling, where all particles exposed on the surface of a predefined area are measured (i.e. adhesive sampling, photographic aerial sampling). Additionally, volumetric sampling, where a predefined volume or mass of sediment is collected from the bed and measured using field or laboratory sieving, is a common measurement approach for most bed material sizes.

Simple methods such as pebble counts can be spatially integrated (reach average) or spatially segregated (sampling each geomorphic unit individually). Both surface (armor layer) and subsurface material can be sampled, depending upon the purpose. When salmonid habitat enhancement is a primary objective, sediment sampling to determine the degree of fine sediment intrusion into gravel beds can provide key information on spawning habitat. From the collected data, a particle size distribution is computed (Figure 18) and such bed material characteristics as D_{84} (particle size at which 84 percent of the material is finer) and D_{50} (median particle size) are extracted. Practitioners should pay attention to the location of fine sediments. Sorted sediments are important to the ecology of stream systems. Fines deposited in the margins and slow water areas allow for nutrient retention and development of a diverse macroinvertebrate population. Lumping a total particle count in a cross section might lead to a mischaracterization of a cross section and imply embeddedness of the substrate where this is not actually the case.

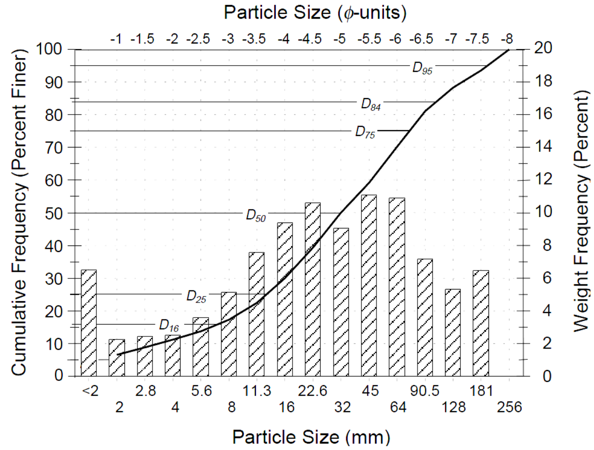


Figure 18: Example bed material particle size distribution (Bunte and Abt 2001).

References helpful for quantifying bed material size distributions include:

- NRCS 2007, TS13A Guidelines for Sampling Bed Material
- Bunte and Abt 2001 Sampling Surface and Subsurface Particle Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring
- Copeland et al. 2001 (Appendix D) Hydraulic Design of Stream Restoration Projects
- Harrelson et al. 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique

Available tools for analyzing bed-material size distributions include:

- Spreadsheet Tools for River Evaluation, Assessment, and Monitoring Ohio Department of Natural Resources and Ohio State (Dan Mecklenburg and others)
- Size-Class Pebble Count Analyzer Spreadsheet USFS National Stream and Aquatic Ecology Center
- Rivermorph: Stream restoration software developed for application of the Rosgen geomorphic channel design method.

10.8 Sediment Transport Measurements

To understand sediment transport processes within a specific restoration reach, it may be necessary to measure sediment transport rates. In general, sediment transport in a stream consists of suspended load and bedload, where suspended load consists of the finer particles that are held in suspension within the water column by turbulent currents and bedload consists of coarser particles that roll, slide or bounce along the streambed. Typically, bedload makes up a larger proportion of total load as drainage area decreases and channel slopes increase (Gray et al. 2010).

Bedload and suspended sediment sampling provide valuable data for developing and calibrating sediment rating curves. Suspended sediment is measured using such devices as a DH-81 handheld depth-integrated sampler. Bedload is measured using such equipment as the Helley-Smith sampler or bedload traps (Figure 19). In gravel-bed streams it has been found that, in comparison to bedload traps, that the Helley-Smith sampler can substantially overestimate bedload transport for less than bankfull flow (Bunte et al. 2004). Technology is also being developed to measure bedload transport continuously, using impact plates (Hilldale et al. 2015).

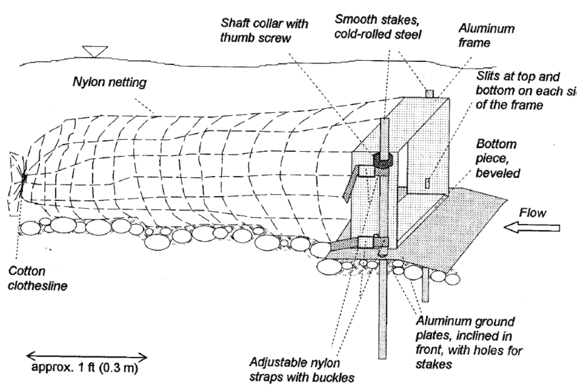


Figure 19: Bedload trap (Bunte et al. 2007).

References to assist with sediment transport data collection include:

- Hilldale et al. 2015 Installation of Impact Plates to Continuously Measure Bed Load: Elwha River, Washington, USA
- Gray et al. 2010 Bedload-Surrogate Monitoring Technologies
- Bunte et al. 2007 Guidelines for Using Bedload Traps in Coarse-Bedded Mountain Streams – Construction, Installation, Operation, and Sample Processing
- Edwards and Gysson 1999 Field Methods for Measurement of Fluvial Sediment

10.9 Groundwater Monitoring

The interactions between streams and underlying groundwater are complex and difficult to observe and measure (Partington et al. 2017). Adequately measuring and understanding groundwater requires, at a minimum, placing groundwater wells or piezometers and staff gages at strategic locations along the reach of interest (Cooper and Merritt 2012). Arrays can be designed longitudinally along the stream and laterally across the adjacent riparian area, or installed in a more random pattern if a water table contour map is desired. Staff gages that measure the stream water surface are required if mapping of gaining and losing reaches is important. Data collected from such an array of wells and staff gages (water levels, water chemistry, and tracers) will indicate how the surface water and groundwater interact. In the future, remote sensing for obtaining groundwater data, such as UAS technology, will also be available (Harvey et al. 2019).

Publications for the assessment and monitoring of riparian groundwater and groundwater-dependent ecosystems, with a focus on National Forests and adjacent lands, include:

- Groundwater Monitoring Wells in Wetlands and Shallow Water Tables: Part 1 – Installation (USFS Baseflows Newsletter, Spring 2017)
- Groundwater Monitoring Wells in Wetlands and Shallow Water Tables: Part 2 - Monitoring (USFS Baseflows Newsletter, Fall 2017)
- Groundwater Monitoring Wells in Wetlands and Shallow Water Tables: Part 3 – Data Analysis (USFS Baseflows Newsletter, Spring 2018)
- Technical Guide to Managing Ground Water Resources (USDA Forest Service, 2007)
- Groundwater-Dependent Ecosystems: Level I Inventory Field Guide (USDA Forest Service General Technical Report WO-86a, 2012)
- Groundwater-Dependent Ecosystems: Level II Inventory Field Guide (USDA Forest Service General Technical Report WO-86b, 2012)
- Groundwater Resource Hub, GDE Rooting Depths Database, The Nature Conservancy

General Forest Service resources for groundwater are available at:

- Groundwater Program publications

11. DESIGN APPROACHES and ANALYSES for STREAM RESTORATION

As presented at the beginning of this document, restoration is the reestablishment of the structure and function of ecosystems to an approximation of pre-disturbance conditions while rehabilitation establishes conditions to support natural processes for making the land useful for human purposes (NRCS 2007). For simplicity these approaches are lumped together under the term restoration, as is common practice.

The design approach and focus of analyses is typically determined by the project setting and extent, goals and objectives, and the experiences and preferences of the restoration team. Stream restoration approaches are often taken to provide a channel (or channels) that will be in a physical form that is in dynamic equilibrium with its water and sediment load. Alternatively, design approaches (and supporting analyses) are taken to provide the conditions for varying flow dynamics driving erosional, transport, and depositional reaches, with the assumption that such variability leads to heterogeneity that can be most valuable for ecological function.

Stream connectivity, both laterally and longitudinally, is desirable for streams to function most effectively. Connectivity can refer to ecologically-related fluxes, such the lateral and longitudinal movement of flow, sediment, nutrients, large wood and other organic matter, heat, and biota (Leibowitz et al. 2018; Boulton et al. 2017; Stanley et al. 1997), as well as such lateral-connectivity effects as flood flow conveyance and attenuation, as well as unit stream power reduction and enhanced geomorphic stability (Yochum et al. 2017). Consequently, connectivity can be a primary goal in restoration projects.

The most appropriate analyses for stream restoration projects are a function of the general design approach judged to be most appropriate for the setting, goals, and objectives. A *process-based approach* develops the baseline conditions that will allow the stream channel(s) and floodplains to evolve through fluvial processes and riparian succession towards more complex and dynamic habitats. In contrast, a *form-based approach* defines channel pattern, profile, and dimension and uses structural features (such as rock vanes, toe wood, and rip rap) to minimize channel adjustment. Classifying restoration approaches in this manner is detailed in Wohl et al. (2015). However, over reliance on these terms can be problematic since form implies process, with current form being the result of past processes. Additionally, rather than being bipolar, form and process-based approaches to restoration can be considered a spectrum (Figure 20). In addition to process or form approaches to restoration, the *ecological restoration* approach has been defined as methods that recover self-sustaining ecological systems, including the organisms, and ecosystem and dynamic processes that support them (Palmer and Ruhl 2015).

The use of approaches that are more process-based have the advantage of allowing the stream and valley to adjust to potential disturbances, such as changes in land use changes, fires, and climate change. Stream restoration often takes the approach of providing single thread streams in restored reaches. However, considering that multithread streams were likely common prior to anthropogenic manipulation (Cluer and Thorne 2013), the development of a multithread channel form in restoration may be best for satisfying ecologically-focused goals and objectives, and process-based design approaches. A more process-based approach can often be used on public lands, where adjustments can be adapted to in deference for satisfying ecologically-based management priorities. However this approach is often not appropriate due to societal constraints – if infrastructure, residences, or highly productive agricultural land are threatened by channel and floodplain adjustments, an approach that is more form-based may be most appropriate.

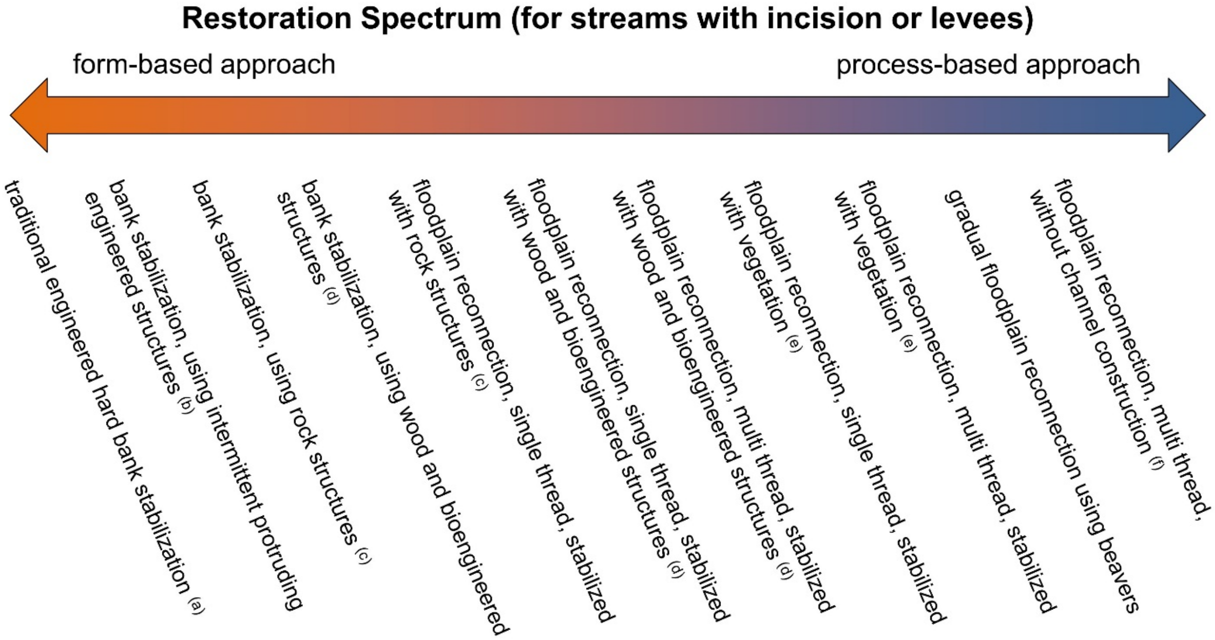


Figure 20: Form- to processed-based restoration approach spectrum for incised or artificially-confined streams. Notes: (a) hard bank stabilization includes concrete revetments, grouted rip rap, and rip rap; (b) intermittent protruding structures includes bendway weirs, spur dikes, and some other bank vanes; (c) rock structures include cross vanes, j-hooks, toe rock, and intermittent rip rap; (d) wood and bioengineered structures includes log vanes, toe wood, root wad revetments, and other bioengineering features; (e) vegetation stabilization refers to the implementation of strong revegetation and management plans that provide for natural bank stabilization; (f) "Stage 0" restoration, analogous to large flood disturbances.

Analysis and design approaches that are generally utilized for restoration projects are: the analogy method, which bases channel dimensions on a reference reach; the hydraulic geometry method, which relies upon hydraulic geometry relationships to select a dependent design variable (such as channel width and depth); and the analytical method, which uses computational modeling (NRCS 2007, Ch7). Designs are often best developed using a combination of approaches, with the redundancy in proportion to stream variability, and the need to work around limitations in data availability, understanding of physical processes, and computational power.

Details of the analysis approach needed for projects can be unclear. For example, if a reference reach approach is used, how is the most appropriate reference reach selected? Are the available reference reaches a good analogy for the actual stream potential? Is a combination of multiple disturbed reference reaches that are showing signs of recovery the best available analogs to utilize for the design? When is a sediment transport analysis needed? At what flows should sediment transport be computed, at bankfull flow or for a range in discharges? When is sediment load low enough so that threshold analysis is adequate? The thoughtful consideration of these and other issues is needed.

Finally, incorporating resilience into stream management and restoration can be fundamental for creating long-term conditions that best support both societal use and ecosystems. Resiliency-based management policy fosters the ability of societies to develop and sustain themselves in dynamic stream systems (Parsons and Thoms 2018).

11.1 Extent of Analysis, Design, and Review

To help assess the appropriate level of design and review for a specific project, Skidmore et al. (2011) developed a project screening matrix (Figure 21) based on the underlying principle of doing no lasting harm to aquatic habitat. Factors addressed in this matrix include project scale, physical attributes of the restoration, planned monitoring, bed and bank composition, bed scour risk, and the dominant hydrologic regime. The appropriate level of assessment is needed to balance project risk with design and review expenses. To assist with project review, River RAT was developed by the NOAA National Marine Fisheries Service to walk reviewers through a series of 16 key questions that help assess if fundamental considerations have been addressed in a project. This tool is available at:

- River RAT (River Restoration Analysis Tool)

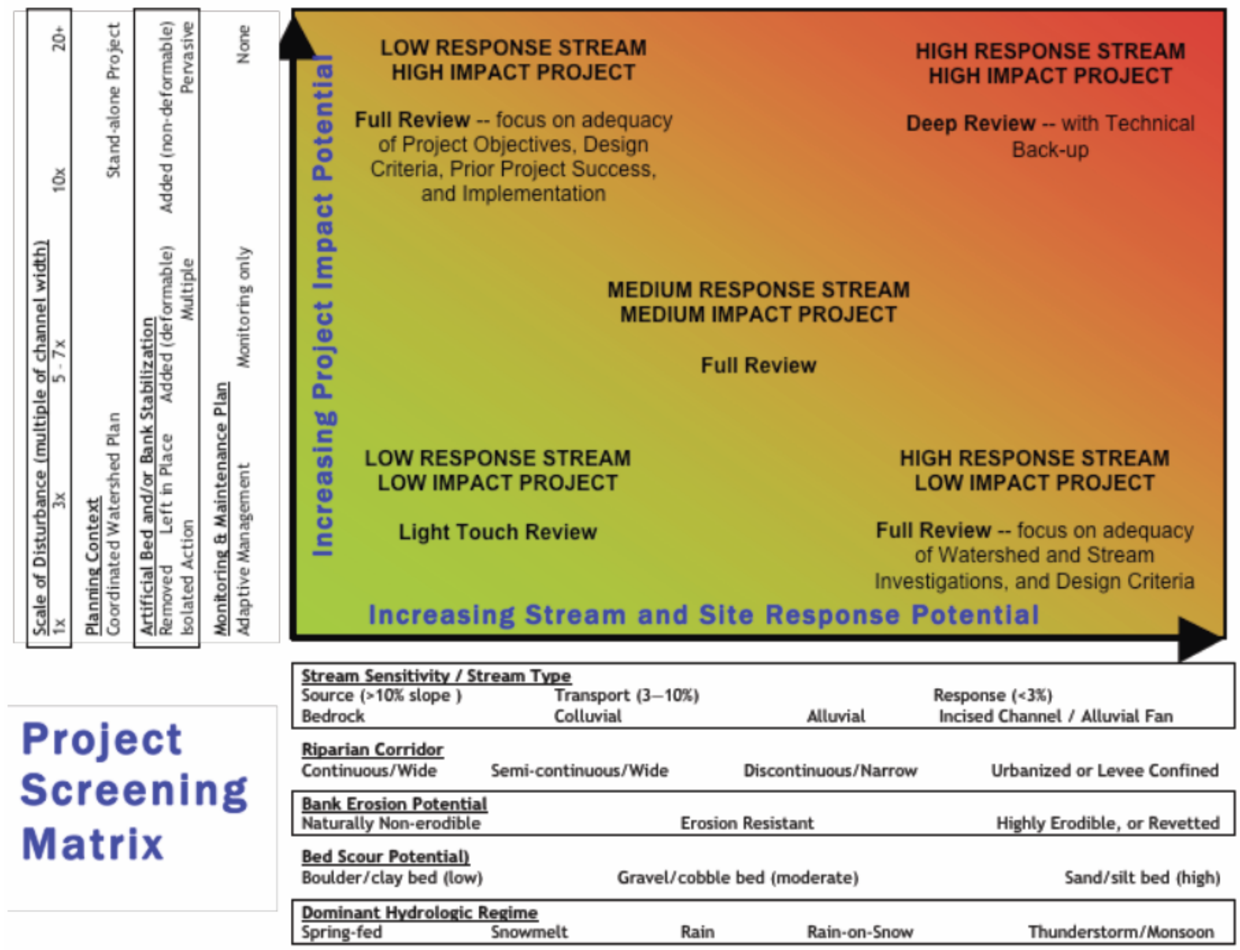


Figure 21: Project screening matrix (Skidmore et al. 2011).

11.2 Hydrology for Stream Restoration and Stability at Stream Crossings

Bledsoe et al. (2017) developed *Design Hydrology for Stream Restoration and Channel Stability*, which provides recommendations for design hydrology analyses at stream crossings, primarily for support of stream restoration associated with roadway and railroad crossing infrastructure. This document has the intent of supporting what is considered by these authors to be a more robust method for hydrologic analysis in support of stream restoration activities, specifically a sediment continuity or sediment impact analysis, along with guidance where such a level of analysis is needed. The publication is available at:

- Bledsoe et al. 2017 Design Hydrology for Stream Restoration and Channel Stability

The approach consists of two general phases to be implemented after goals and objectives are defined: phase 1, assess the current conditions adjacent to the stream crossing and in the watershed to determine the design method; and phase 2, design the stream channel through the stream crossing.

Relevant online tools (within the eRAMS platform) for this approach include:

- SWAT-DEG (Soil and Water Assessment Tool)
- Flow Analysis Model, for analyzing streamgage characteristics
- Sediment Capacity-Supply Ratio tool

11.2.1 Phase 1

Phase 1 consists of a procedure for relating stream response potential and the availability of a suitable reference reach to determine an appropriate level of design analysis. Specifically, this phase incorporates that following questions to guide decision making:

1. How does the availability of an analog reach change the level of design guidance?
2. What level of hydrologic analysis should be undertaken?
3. Is it appropriate to perform sediment transport analysis, and, if so, what type of analysis is needed?
4. What spatial domain (i.e., how far upstream and/or downstream from the project location) is recommended for conducting the analysis?

Greater amounts of stream response potential relate directly to the needed design effort. This potential, as defined in Bledsoe et al. (2017), is based upon channel bed material size and the flow regime flashiness, a simple rapid geomorphic assessment (Figure 22), and reference reach guidance.

Bed Material = Medium to Coarse Gravel

Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ coarse cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	High	High	Very High
Intermediate	Med	High	High
Frequent	Low	Med	High

Bed Material = Small Cobbles/Very Coarse Gravel

Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ large cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	Med	Med	High
Intermediate	Low	Med	Med
Frequent	Low	Low	Med

Bed Material = Large Cobbles

Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ large cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	Low	Med	Med
Intermediate	Low	Low	Med
Frequent	Low	Low	Low

Figure 22**:** Rapid geomorphic assessment risk categories (low, medium, high), by bed material size, grade control frequency, and bank stability.

11.2.2 Phase 2

The phase 2 design analysis consists of the following steps:

1. Establish a sediment supply reach using flow duration curve, half load discharge, and/or sediment capacity-supply ratio
2. Evaluate need to for additional field reconnaissance
3. Perform channel design using a set of recommended methods
4. Compare channel design to reference reaches (if available)
5. Select a robust design, using the weight of the evidence

11.3 Flow Estimates

Stream restorations frequently use bankfull discharge as a primary design discharge, in addition to low flow values for aquatic life. However, larger floods are also relevant for designs since larger floods contribute the largest individual pulses of sediment loads to the channel as well as provide the high stresses and geomorphic adjustment potential that instream structures are designed to resist.

11.3.1 Flood Frequency

If the project is adjacent to a streamgage that has a sufficient record length, flow frequency estimates (Figure 23) can be obtained from the USGS or computed using the methods presented in Bulletin 17C (England et al. 2018). Importantly, instantaneous peak flow data need to be used in the flow-frequency analysis; the use of average daily flow values can substantially underpredict flow frequency relationships.

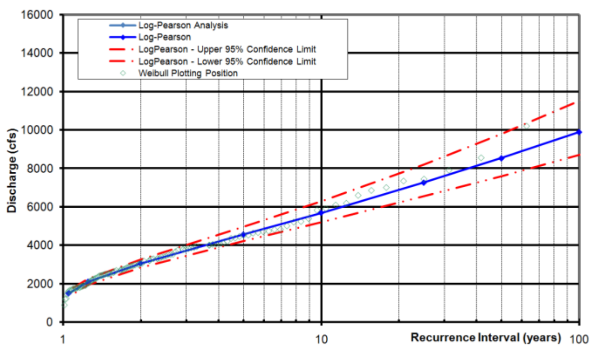


Figure 23: Flow frequency estimates for the Cache la Poudre River, CO (USGS 06752000).

However, most projects occur on streams that have never been gaged or are distant from the nearest streamgage, with substantially different watershed areas. In these situations it is necessary to use methods developed for ungaged locations. Regional flow frequency estimation techniques, using multivariate regression approaches from streamgaged locations, can be helpful in these circumstances. Based on such regional analyses, approximate flow frequency estimates can be easily obtained from USGS Streamstats, though these values can be substantially over or underestimated; particular attention needs to be paid to the prediction errors when using this tool. Comparison of regional regression equation results with the results of the Flood Potential method (discussed below) as well as flow frequency computed at local streamgages can be an important step to understand bias at the ungaged site of interest.

Alternatively, results developed using a custom regional regression approach may be preferred. This methodology is discussed in NRCS (2007), Ch5. Also, in rainfall dominated watersheds rainfall-runoff models can be developed for estimating flow-frequency relationships. Such methods should typically not be attempted in watersheds where snowmelt events typically produce the annual peak flows at the frequency of interest.

Inherent in flow frequency analysis is an assumption of stationarity, specifically that the annual peak flows have a constant mean and variance throughout the record. Violation of this assumption due to changes in land use, such as urbanization, wildfires, and conservation practices, as well as climate change and reservoir construction, has repercussions on the use of flow frequency relationships for stream restoration design. For example, Haucke and Clancy (2011) found that conservation practices can decrease frequent annual flood events, despite corresponding increases in precipitation. Estimations of flood frequencies adjusted for climate change projections are available.

References and tools available for flow-frequency prediction, as well as general references for explaining flow-frequency relationships, include:

- Western Flow Metrics: Climate change discharge projections, from the U.S. Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate
- England et al. 2018 Guidelines for determining flood flow frequency—Bulletin 17C
- IACWD 1982 Guidelines for Determining Flood Flow Frequency (Bulletin 17B)
- Streamflow data sources ACWI Subcommittee on Hydrology
- Regional skew and flood frequency reports ACWI Subcommittee on Hydrology

- PKFQWin USGS Flood Frequency Analysis Software, based on methods provided in Bulletins 17B and 17C.
- HEC-SSP U.S. Army Corps of Engineers Hydrologic Engineering Center – Statistical Software Package (17B and 17C methods)
- log-Pearson Frequency Analysis Spreadsheet USFS National Stream and Aquatic Ecology Center (17B methods)
- USGS Streamstats watershed and stream statistics, including approximate flow frequency values, mean flows and minimum flows for ungaged streams.
- USGS Questions and answers about floods
- NRCS 2007, Ch5 Stream Hydrology

11.3.2 Flood Potential

An alternative to flood-frequency analysis has been developed for understanding flood hazards: the Flood Potential method. This approach assists with predicting, comparing, and communicating about large floods. Where available, it is recommended that both flood frequency and flood potential methods be utilized when assessing a site's flood hazard.

This method uses a space-for-time substitution to predict expected flood magnitudes given the streamgage record in similarly-responding nearby watersheds. Regressions of maximum peak discharges using drainage area and additional watershed characteristics were fit across areas with similar flood records (zones). Each of these regressions define the expected flood potential (expected flood magnitudes) for each zone. The 90% prediction limit defines the maximum likely flood potential, with discharges above this level being extreme.

Indices were developed to compare flood hazards as they vary across regions and continents. Of most relevance to stream restoration is the flood potential index (Figure 24), with larger values indicating larger flood magnitudes and higher expected stream power and the potential for geomorphic adjustment when a large floods occurs. The flood variability index is also relevant – this index quantifies zonal flood variability in space and time.

More information on the Flood Potential method is available at:

- Flood Potential: U.S. Forest Service, National Stream and Aquatic Ecology Center
- Yochum et al. 2019 Methods for Assessing Expected Flood Potential and Variability: Southern Rocky Mountains Region
- Yochum 2019 Flood Potential: A New Method for Quantifying and Communicating the Magnitude and Spatial Variability of Floods (StreamNotes, October 2019)

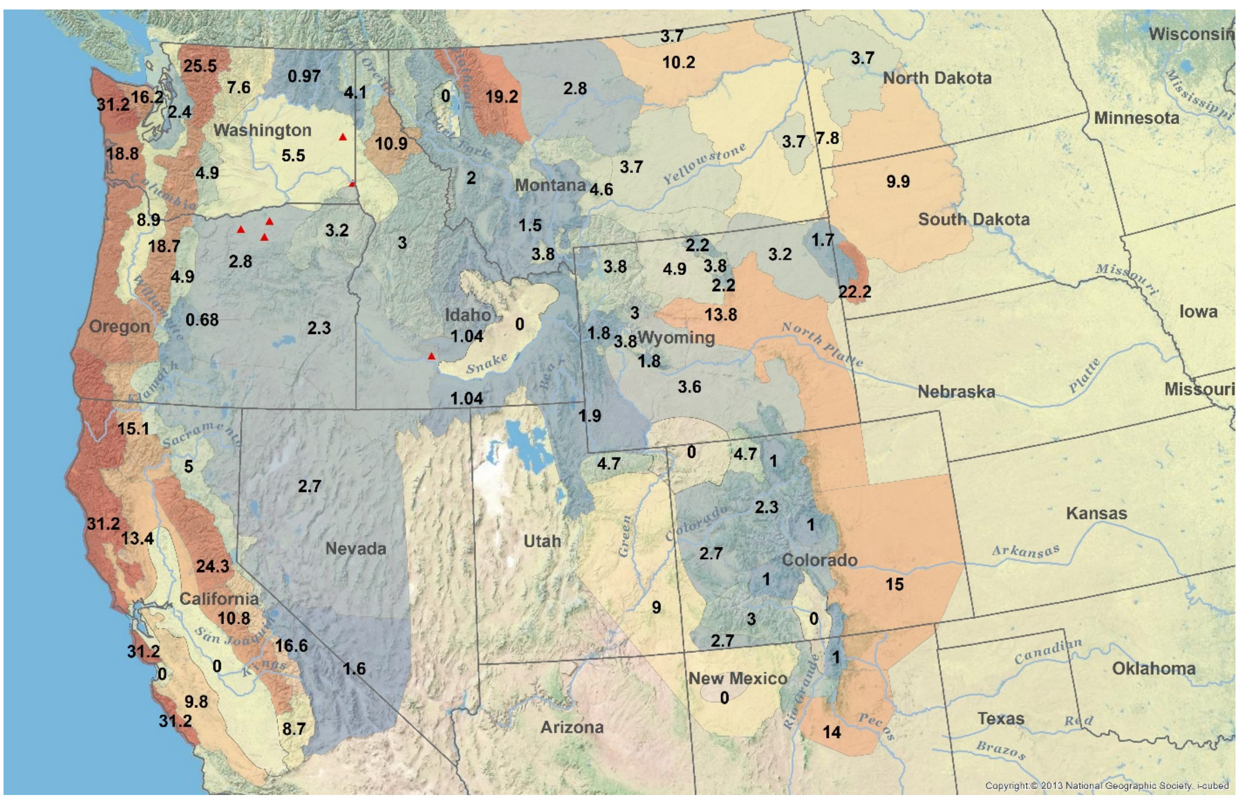


Figure 24: Flood potential zones and index values for a portion of the Western United States. The warmer colors and higher values indicate larger historic (and expected) flood magnitudes.

11.4 Process-Based Restoration

A process-based restoration approach develops the baseline conditions that allow (or encourage) the stream channel(s) and floodplains to evolve through fluvial processes and riparian succession towards more complex and dynamic habitats. Restoration project approaches high on the process spectrum (Figure 19) may be more suitable for projects where ecological-focused goals and objectives area dominant and where infrastructure conflicts are minimal.

A number of tools and technical guidance documents for processed based approaches to restoration are being developed, including the Stage 0 method (Figure 25) and the Stream Evolution Triangle. Available guidance includes:

- Castro and Thorne 2020 The Stream Evolution Triangle (StreamNotes)
- Wheaton et al. 2019 Low-Tech Process-Based Restoration of Riverscapes
- Castro and Thorne 2019 The stream evolution triangle: Integrating geology, hydrology, and biology
- Thorne et al. 2019 Partnering with Nature's River Restorers for Sustainable River Management (SEDHYD-2019)
- Castro and Thorne 2019 The stream evolution triangle: Integrating geology, hydrology, and biology (SEDHYD-2019)
- Shields et al. 2019 A Tool for Beaver Dam Analog Design (SEDHYD-2019)
- Powers et al. 2018 A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network
- Stage 0 Workshop 2019, videos and resources
- Pope et al. 2015 Habitat Conditions of Montane Meadows associated with Restored and Unrestored Stream Channels of California
- Wohl et al. 2015 The Science and Practice of River Restoration
- Palmer et al. 2014 Ecological Restoration of Streams and Rivers: Shifting Strategies and Shifting Goals
- Cluer and Thorne 2013 A stream evolution model integrating habitat and ecosystem benefits
- Beechie et al 2010: Process-Based Principles for Restoring River Ecosystems
- Kodolf et al. 2006 Process-Based Ecological River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages

Figure 25: Stage 0 restoration on the South Fork McKenzie River, just after phase 1 construction (8/7/2018).

11.5 Natural Channel Design

The natural channel design method, developed by Dave Rosgen, uses measurements of morphological relations associated with bankfull flow, geomorphic valley type, and geomorphic stream type to develop channel designs (NRCS 2007, Ch11). This technique combines reference reaches, hydraulic geometry relationships, and simple hydraulic modeling to develop design specifications for establishing a reach with appropriate channel dimension, planform pattern, and longitudinal profile. Figure 26 provides a conceptual outline of this design approach.

Various tools are available for the application of this design method. FLOWSED and POWERSED are relatively simple sediment supply and transport models that can predict total annual suspended and bedload sediment yield, as well as the potential for aggradation or degradation (NRCS 2007, Ch11). Additionally, the BANCS model (Bank Assessment for Non-point Consequences of Sediment), which uses the BEHI (Bank Erosion Hazard Index) and NBS (Near-Bank Stress) bank erosion estimation tools, is also available. This model estimates annual bank erosion rates, providing estimates of annual sediment yield (Rosgen et al. 2008; Bigham et al. 2018).

The availability of a reference reach is fundamental for the application of this methodology. This reference reach is a stable stream that indicates the potential of the design reach (Rosgen 2011). However, considering the wide ranging historic anthropogenic disturbances in streams, such as excessive livestock grazing in riparian zones, the removal of instream wood, and the conversion of channels from multi-thread to single-thread form, it can be difficult or impossible to find a local reference reach that represents full stream potential. Instead, the reference reach is often selected to represent a condition where the stream has adjusted to driving variables and boundary conditions to be self maintaining, in the same stream type, valley type, flow regime, sediment regime, stream bank type, and vegetative community as the design reach (Rosgen 2011).

Regional curves, relationships between bankfull discharge and dimensions with drainage area, are simple linear regressions also used to develop the design. Prediction based on only drainage area can be problematic in regions where precipitation varies substantially (such as mountainous watersheds) and where there are substantial flow diversions.

Tools and references available for stream restoration designs based on the natural channel design method include:

- Bigham et al. 2018 Repeatability, Sensitivity, and Uncertainty Analyses of the BANCS Model Developed to Predict Annual Streambank Erosion Rates
- Rosgen 2013 Natural Channel Design – Fundamental Concepts, Assumptions, and Methods
- Rosgen et al. 2008 River Stability Field Guide
- NRCS 2007, Ch11 Rosgen Geomorphic Channel Design
- NRCS 2007, TS3E Rosgen Stream Classification Technique: Supplemental Materials
- Rosgen 2007 Watershed Assessment of River Stability and Sediment Supply (WARSSS)
- Doll et al. 2003 Stream Restoration: A Natural Channel Design Handbook
- Rosgen 1996 Applied River Morphology
- Harrelson et al. 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique
- Regional Hydraulic Geometry Curves: NRCS Repository of regional curves relating bankfull dimensions with drainage area.
- Rivermorph: Stream restoration software developed for application of the Rosgen geomorphic channel design method.
- Lessons Learned from Natural Stream Restoration/Enhancement: Insight on Natural Channel Design 2013 (Dick Everhart, Angela Greene)

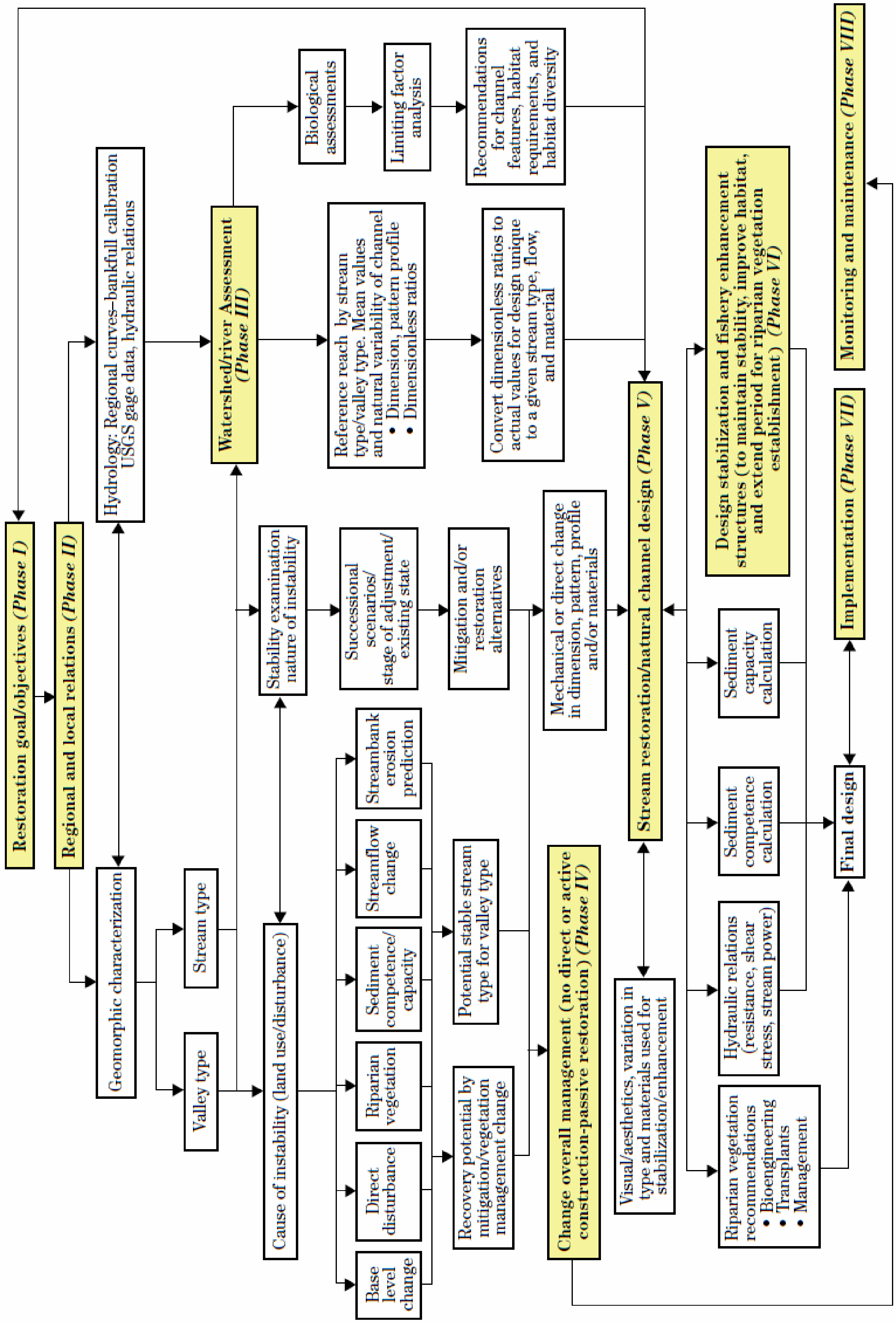


Figure 26: Schematic illustrating the Natural Channel Design method (NRCS 2007, Ch11).

11.6 River Styles

River Styles® (Figure 27) is a fluvial geomorphic approach for assessing river form, condition, and recovery potential. This method provides a physical template for stream management. As discussed on the method website, this approach was developed around four fundamental principles:

1. Respect stream diversity
2. Work with stream dynamics and change
3. Work with linkages to biophysical processes
4. Use geomorphology as an integrative physical template for river management activities

Tools and references available for stream assessment and management based on the River Styles approach include:

- Fryirs and Brierley 2013 Geomorphic Analysis of River Systems: An Approach to Reading the Landscape.
- Brierley and Fryirs 2008 River Futures: An Integrative Scientific Approach to River Repair.
- Brierley and Fryirs 2005 Geomorphology and River Management: Applications of the River Styles Framework.

- **Works with the natural diversity of river forms and processes.** Due recognition is given to the continuum of river morphology, extending from bedrock-imposed conditions to fully alluvial variants (some of which may comprise unincised valley floors). The River Styles framework can be applied in any environmental setting.
- **Is framed in terms of generic, open-ended procedures that are applied in a catchment-specific manner.** Reaches are not 'pigeon-holed' into rigid categories; rather, new variants are added to the existing range of River Styles based on a set of discrete attributes (i.e. the valley setting, geomorphic unit assemblage, channel planform, and bed material texture).
- **Evaluates river behavior, indicating how a river adjusts within its valley setting.** This is achieved through appraisal of the form-process associations of geomorphic units that make up each River Style. Assessment of these building blocks of rivers, in both channel and floodplain zones, guides interpretation of the range of behavior within any reach. As geomorphic units include both erosional and depositional forms, and characterize all riverscapes, they provide an inclusive and integrative tool for classification exercises.
- **Provides a catchment-framed baseline survey of river character and behavior throughout a catchment.** Application of a nested hierarchical arrangement enables the integrity of site-specific information to be retained in analyses applied at catchment or regional levels. Downstream patterns and connections among reaches are examined, demonstrating how disturbance impacts in one part of a catchment are manifest elsewhere over differing timeframes. Controls on river character and behavior, and downstream patterns of River Styles, are explained in terms of their physical setting and prevailing biophysical fluxes.
- **Evaluates recent river changes in context of longer-term landscape evolution, framing river responses to human disturbance in context of the 'capacity for adjustment' of each River Style.** Identification of reference conditions provides the basis to determine how far from its 'natural' condition the contemporary river sits and interpret why the river has changed. Analysis of reaches at differing stages of geomorphic adjustment at differing localities (i.e. space-time transformation or ergodic reasoning) is applied to interpret evolutionary pathways for reaches of the same type.
- **Provides a meaningful basis to compare type-with-type.** From this, the contemporary geomorphic condition of the river is assessed. Analysis of downstream patterns of River Styles and their changes throughout a catchment, among other considerations, provides key insights with which to determine geomorphic river recovery potential. This assessment, in turn, provides a physical basis to predict likely future river structure and function.

Figure 27: River Styles framework (extracted from www.riverstyles.com).

11.7 Soar and Thorne Restoration Design

Soar and Thorne (2001) developed a stream restoration design procedure that combines a range of techniques, including field reconnaissance, detailed site survey, discharge-frequency analyses, hydraulic geometry analysis, and analytical modeling, such as the Copeland method (available in HEC-RAS). This design method acknowledges the limitations of analytical methods and assumes the availability of stable reference reaches, to provide such baseline information as the magnitude and frequency of sediment-transporting flow events and the channel-forming discharge. The method is illustrated in Figure 28.

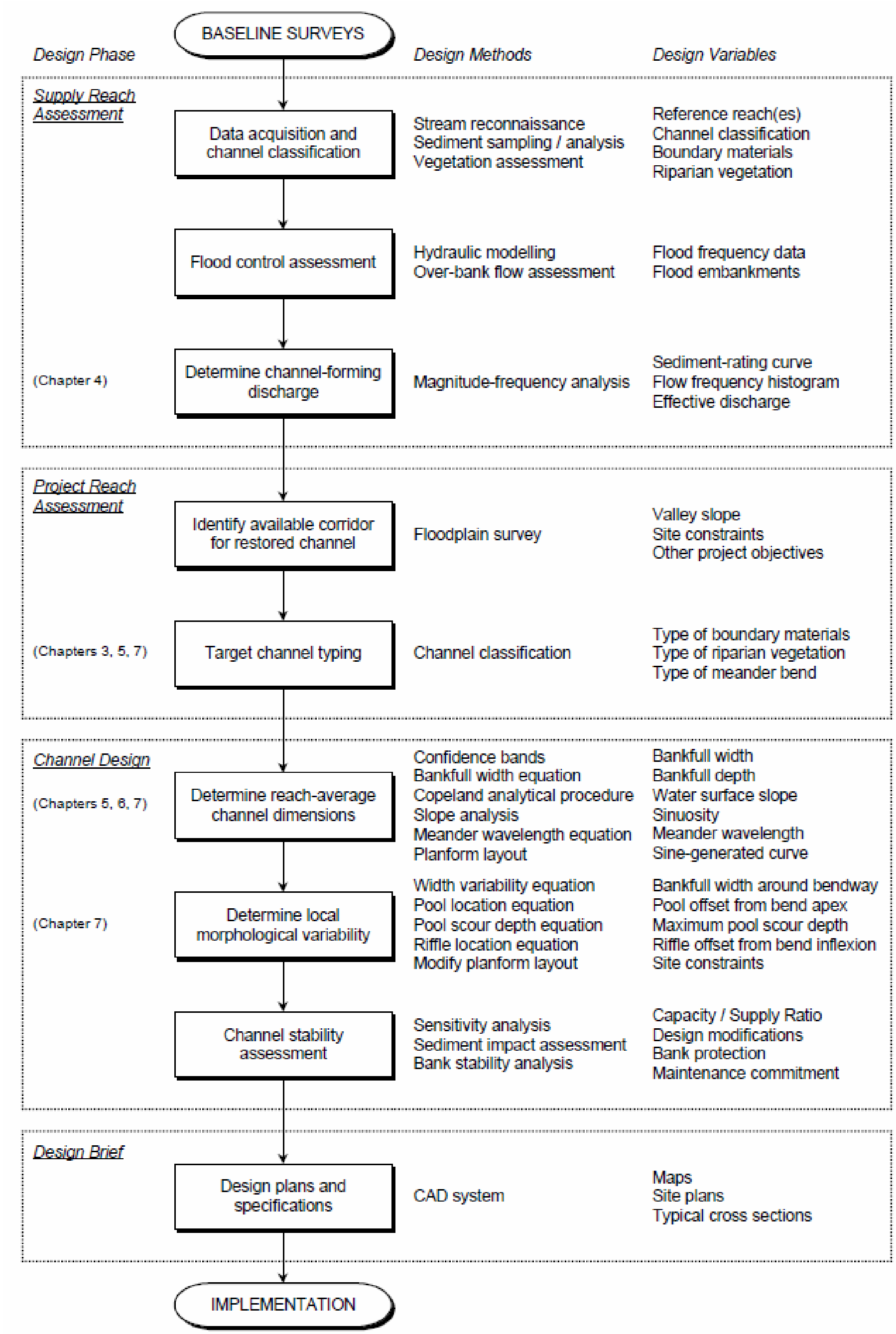


Figure 28: Soar and Thorne (2001) stream restoration design procedure.

11.8 Hydraulic Modeling Overview

Since the variability between stream reaches can be substantial and unforeseen circumstances can lead to unintended consequences, hydraulic modeling can be an important component of a restoration design. An appropriate hydraulic model can reduce the potential for the project to cause undesirable outcomes.

Hydraulic computational modeling in support of stream designs can consist of a wide range of approaches, from a simple normal depth computation using the Manning's equation, to a 3-dimensional finite element model. Some degree of hydraulic modeling is typically required for all restorations that employ engineering practices, with the degree of model complexity defined by the magnitude and objectives of the project. For example, a short bank stabilization project may only require normal depth and incipient motion computations, while a channel relocation may require at least a one-dimensional finite difference model (such as HEC-RAS) to assess the potential for unintended consequences that could result in project failure. Complicating circumstances, such a project in the vicinity of a confluence, need to be considered while judging the need for more advanced modeling. In this example, the confluence may result in unexpected flow and sediment dynamics during high flow. Even when a reference reach approach is being implemented in a design, the analogous stream reach is very rarely a perfect match; sufficient hydraulic modeling is often needed to assess unintended consequences of extrapolating reference geometry to the target reach.

It is necessary to weigh the additional data needs for the development of more complex models, as well as the time required to assemble the model. Additionally, the interactions of 3-dimensional flow, sediment mechanics, erodible banks, and riparian vegetation all interact in complex ways that can often be beyond modeled mechanisms. Hence, models are simplifications that are developed to provide some answers to specific questions that arise when developing restoration designs. They can be most useful in combination with other analysis techniques. Despite these limitations, it may be best to err on the side of caution and opt for the development of more complex modeling if there is reasonable doubt regarding the modeling needs for a particular project, and if the modeling is achievable.

Various types of hydraulic modeling options, in increasing order of complexity, are listed below:

1. Normal depth velocity computations, with material entrainment computations (example model: WinXSPro). This method is often used for such applications as rip rap sizing for bank stabilization and in the Rosgen geomorphic channel design methodology.
2. 1-D steady flow modeling (example model: HEC-RAS)
   a. Shear stress and stream power modeling, to assess sediment conveyance continuity and existing versus proposed conditions. For example, locations of reduced shear stress indicates reaches where aggradation is most likely.
   b. Sediment transport capacity modeling, to locate reaches where aggradation or degradation are most likely. In general, if sediment supply is in excess of sediment transport capacity, the channel will aggrade, and if capacity is greater than supply, the channel will degrade or armor. This analysis can be part of a sediment impact assessment, as discussed in Copeland et al. (2001) and NRCS (2007) Ch13.
   c. Sediment transport modeling, to simulate expected channel variability (i.e. scour and deposition). This analysis can be part of a sediment impact assessment, as discussed in Copeland et al. (2001) and NRCS (2007) Ch13.
   d. Stable channel design analysis, through use of the Copeland method (Figure 29), as well as the Regime and Tractive Force methods. Subroutines for these methods are provided in HEC-RAS.
   e. Water quality modeling, to simulate such constituents as temperature. For example, reductions in stream temperature from channel narrowing and shading can be simulated.

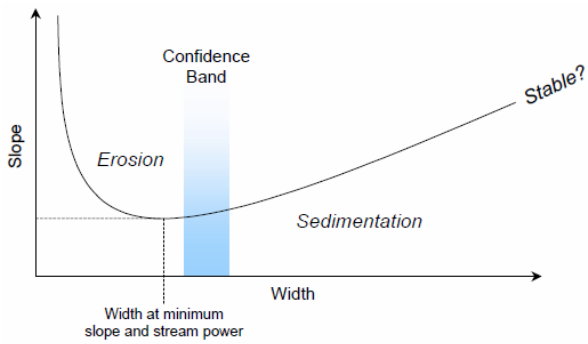


Figure 29: Analytical channel design using the Copeland method (Soar and Thorne 2001).

3. 1-D finite difference unsteady flow modeling, to assess the impacts of a hydrograph on hydraulic and sediment transport characteristics.
4. 2-D finite element steady- and unsteady flow modeling, to assess 2-dimensional flow characteristics.
5. 3-D finite element steady- and unsteady flow modeling, to assess 3-dimensional flow characteristics.

General information regarding hydraulic modeling for stream restoration projects is provided in:

- Fischenich and McKay 2011 Hydrologic Analyses for Stream Restoration Design
- Brunner 2016 HEC-RAS Hydraulic Reference Manual
- NRCS 2007, Ch6 Stream Hydraulics
- NRCS 2007, Ch9 Alluvial Channel Design
- NRCS 2007: Ch13 Sediment Impact Assessments
- Soar and Thorne 2001 Channel Restoration Design for Meandering Rivers
- Copeland et al. 2001 Hydraulic Design of Stream Restoration Projects

11.9 Bankfull Characteristics

Alluvial streams oftentimes develop a characteristic form, with a bankfull channel (or channels) formed by the dominant channel-forming discharge. Large floods, which transport a great deal of sediment, happen very infrequently, while small events, even though they happen frequently, move much less sediment, leading to a logical conclusion that there is a moderate magnitude and frequency flood event, the channel forming flow, that dominates sediment transport and is responsible for creating the bankfull channel (Wolman and Miller 1960). This flow rate is the channel forming discharge, which is commonly referred to as bankfull discharge.

However, it has been argued that, due to difficulties associated with proper bankfull identification as well as a consequence of unstable channels and nonstationarity, that channel-forming discharge should not be considered the same as bankfull discharge (Copeland et al. 2001). Additionally, appropriate bankfull channel geometry can be complicated by project objectives, such as hydraulic conditions that balance overall sediment conveyance with conditions that can retain spawning gravels. In any case, bankfull characteristics may only be expected in perennial or ephemeral alluvial streams in humid environments, and perennial alluvial streams in semiarid or arid environments. In flashy, arid, intermittent streams, or highly-urbanized watersheds, other mechanisms can be dominant and the bankfull discharge concept may not be applicable (Copeland et al. 2001).

When good indicators of channel-forming flow are present, the most reliable method for determining bankfull discharge is to measure the discharge when the project stream is flowing at or near this level. This method is most viable in snowmelt-dominated streams, where the annual flow peak can be more easily predicted. Alternatively, bankfull discharge can be estimated at several stable cross sections by a normal depth assumption, though this method requires an accurate estimate of Manning's *n* for bankfull flow. However, the accurate identification of bankfull may be difficult or impossible in highly disturbed reaches.

Bankfull discharge and geometric characteristics can also be estimated using regional regressions based on drainage area and, possibly, other watershed characteristics. However this method can be problematic in mountainous areas where precipitation varies substantially, resulting in drainage area alone being insufficient for prediction. Additionally, stream diversions and reservoirs also alter bankfull characteristics, complicating or prohibiting the development of regional relationships. It has been found that, on a continental scale, that watershed area alone is insufficient for regional bankfull width estimation and that precipitation variability should also be included (Wilkerson et al. 2014). This study also indicates that differing width regional curve relationships may occur as watershed area (A) increases ($A < 1.9$ mi^2, $1.9 < A < 130$ mi^2, $A > 130$ mi^2).

The regional approach for developing bankfull discharge estimates is described in:

- NRCS 2007, TS5 Developing Regional Relationships for Bankfull Discharge Using Bankfull Indices

Typically, bankfull flow corresponds to a 1 to 2.5-year return interval flood, with an average of about 1.5 years (Leopold 1994). Alternatively, it has been argued that bankfull flow occurs less frequently for many streams (Williams 1978). Davidson and Eaton (2018) performed biogeomorphic modeling which indicated that streams with greater interannual flow variability express more variable channel variability, with return intervals of formative flow increasing from about 2 years for low variability streams to 8 years for high-variability streams. With a range of return intervals associated with bankfull flow, basing bankfull discharge on only a specific return interval event may be inappropriate. Instead, another method should be used to compute bankfull discharge and these results compared to the flow-frequency estimates, for quality assurance. For example, if the return interval of a predicted bankfull discharge is greater than 2 or 2.5 years, than the bankfull channel may have been overestimated (i.e., a terrace feature mistaken for an active floodplain) in streams with lesser interannual flow variability.

Where discharge and sediment transport data are available (or can be reliably simulated), channel forming flow can be computed through use of the effective discharge methodology (Figure 30). This method has been argued to be more reliable and appropriate than assuming that bankfull discharge is equivalent to the channel-forming discharge (Soar and Thorne 2001, Copeland et al. 2001, Soar and Thorne 2011). However, research indicating that effective discharge in some mountain streams is more related to maximum discharge rather than bankfull discharge (Bunte et al. 2014) complicates standard approaches for implementing an effective discharge approach in high-gradient streams. Additionally, Sholtes and Bledsoe (2016) found that the discharge aligned with 50% of the cumulative sediment yield, referred to as the half-yield discharge, predicts bankfull discharge well.

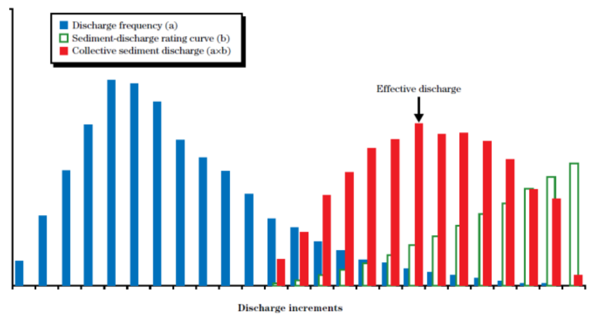


Figure 30: Effective discharge computation (NRCS 2007, Ch5).

The methodology for computing effective discharge is described in:

- Soar and Thorne 2011 Design Discharge for River Restoration
- NRCS 2007, Ch5 Stream Hydrology
- Soar and Thorne 2001 Channel Restoration Design for Meandering Rivers
- Copeland et al. 2001 Hydraulic Design of Stream Restoration Projects

11.10 Modeling Tools

Numerous modeling tools have been developed for performing hydrologic and ecologic analyses, including tools for the assessment of environmental flows and instream habitat. Examples are provided in the following sections.

11.10.1 Hydraulic Analysis and Aquatic Habitat

- iRIC: 1-, 2-, and 3-D river flow and riverbed variation analysis software package
- DSS-WISE: 2-D hydraulic analyses, with GIS-based decision support tools
- FishXing: Evaluation and assessment tool for fish passage through culverts
- FLO-2D: 2-D mobile bed hydraulic modeling
- FLOW-3D: 1-, 2- and 3-D steady flow simulation
- HEC-RAS: Steady and unsteady 1-D hydraulic modeling of stream systems, including water quality simulations and temperature modeling
- D-Claw: Depth-averaged debris flow modeling using adaptive mesh refinement
- FaSTMECH: quasi-steady 2-D and 3D river flow and morphodynamics solver
    - USGS MD_SWMS: Multidimensional Surface-Water Modeling System
- i-Tree Cool River: Mechanically simulates river temperatures
    - Abdi et al. 2020 A model to integrate urban river thermal cooling in river restoration
- InSTREAM: an individual-based model of trout in a stream environment; predictions of how trout populations respond to many kinds of environmental and biological change
- MIKE 11: 1-D modeling for simulating sediment transport and fluvial morphology, as well as ecological and water-quality assessments
- MIKE 21C: 2-D modeling for simulating bed and bank erosion, scouring, and sedimentation
- Nays2DH 2-D model for simulating unsteady horizontal 2D flow, sediment transport, and morphological changes of bed and banks in rivers.
- PHABSIM: Physical Habitat Simulation. Suite of programs designed to simulate habitat characteristics (depth, velocity, channel indices) in streams as a function of streamflow, and assess suitability for aquatic life
- RHABSIM: Riverine Habitat Simulation. River hydraulics and aquatic habitat modeling using IFIM
    - IFIM: Instream Flow Incremental Methodology. An analysis method that associates fish habitat, recreational opportunity, and woody vegetation response to alternative water management schemes (Bovee et al. 1998). See SEFA
- River2D: 2-D depth-averaged finite element model customized for fish habitat evaluation. Performs PHABSIM-type fish habitat analyses
- Rivermorph: Stream restoration software developed for application of the Rosgen geomorphic channel design method
- SEFA: System for Environmental Flow Analysis. Implements the substance of the Instream Flow Incremental Methodology
- Sim-Stream: Physical habitat simulation model that describes the utility of instream habitat conditions for aquatic fauna, to simulate changes in habitat quality and quantity in response to flow alterations or changes in stream morphology
    - Impliments the Mesohabitat Simulation Model (MesoHABSIM)
- SRH-2D: 2-D hydraulic, sediment, temperature, and vegetation modeling
- SNTEMP: Stream Network and Stream Segment Temperature Model
- WinXSPro: Channel cross-section analysis

11.10.2 Bank/Bed Stability and Sediment

- BANCS: tool for the prediction of bank erosion rates (Rosgen et al. 2008)
- BSTEM: spreadsheet tool for bank erosion simulation, including the affects of riparian vegetation (Simon et al. 2011)
- CONCEPTS: model for the simulation of incised channel evolution, the evaluation of the long-term impacts of rehabilitation measures, and the reduction of sediment yield (Langendoen 2011)
- WARSSS: Watershed Assessment of River Stability and Sediment Supply, a web-based assessment tool for evaluating suspended and bedload sediment in streams impaired by excess sediment
- FLOWSED: modeling tool for the prediction of total annual sediment yield
- POWERSED: modeling tool to estimate sediment transport capacity
- RUSLE2: Revised Universal Soil Loss Equation
- UBCRM: tools that quantifies the effect of bank vegetation on bank strength, and the resulting effects on channel geometry (Miller and Eaton 2011)

11.10.3 Environmental Flows

- ELOHA: Ecological Limit of Hydrologic Alteration. Provides a framework for assessing and managing environmental flows across regions, when resources are not available to evaluate individual streams (Poff et al. 2010). A Colorado pilot study was performed on the Roaring Fork and Fountain Creek (Sanderson et al. 2011).

- HEC-EFM: Ecosystem Function Model, to help determine ecosystem responses to changes in flow regime of rivers and wetlands

- HIP: Hydroecological Integrity Assessment Process. A suite of software tools for conducting hydrologic classification of streams, assessing instream flow needs, and analyzing historical and proposed hydrologic alterations
- IHA: Indicators of Hydrologic Alteration. Facilitates hydrologic analysis for environmental flows in an ecologically meaningful manner
- NATHAT: National Hydrologic Assessment Tool. Used to establish a hydrologic baseline, environmental flow standards, and evaluate past and proposed hydrologic modifications

11.9.4 Watershed Modeling

- AGWA: Automated Geospatial Watershed Assessment Tool (SWAT, KINEROS2)
- BASINS: Better Assessment Science Integrating Point & Non-point Sources. Provides access to water quality databases, applies assessment and planning tools, and runs non-point loading and water quality models within a GIS format
- HEC-HMS: Hydrologic Engineering Center – Hydrologic Modeling System. Simulates precipitation-runoff processes, from small agricultural or urban watersheds to large river basins
- PRMS: Precipitation Runoff Modeling System. A rainfall-runoff watershed model developed by the USGS.
- SWAT: Soil and Water Assessment Tool. River basin scale model for assessing the impact of land management practices in large, complex watersheds
  - HAWQS: Hydrologic and Water Quality System, a web-based water quantity and quality modeling system that employs SWAT.
- SWMM: Storm Water Management Model. Software for rainfall-runoff simulation in primarily urban watersheds
- VIC: Variable Infiltration Capacity macroscale hydrologic model.
- WEAP: Water Evaluation and Planning. GIS-based modeling, with subroutines for rainfall-runoff, infiltration, evapotranspiration, crop requirements and yields, surface water/groundwater interactions, and water quality
- WEPP: Water Erosion Prediction Project, a process-based erosion prediction model
  - Forest Service WEPP provides such tools as peak flow estimates for burned areas and erosion prediction from forest roads.
  - WEPPcloud is also available, which automatically utilizes preloaded elevation, soils, landcover, climate datasets.
- WinTR20: NRCS software for single event, watershed scale, rainfall-runoff modeling

11.11 Flow Resistance Estimation

Fundamental in hydraulic modeling is flow resistance prediction. In-channel resistance is the result of roughness due to the bed and bank grain material, bedforms (such as dunes and step pools), sinuosity, vegetation, streambank variability, instream wood, and other obstructions (Figure 31). Floodplain flow resistance is primarily due to vegetation. In-channel resistance typically decreases as stage and discharge increase; resistance coefficients should be selected for the discharge of interest. Inaccurate resistance coefficients can result in inaccurate prediction of flow velocities and travel times, the miscategorization of flow regime, inaccurate design parameters for hydraulic structures, and unnecessary instability in computational modeling.

Manning's n is the most common resistance coefficient used in the United States, however Darcy Weisbach f and Chezy C are sometimes used. These resistance coefficients can be converted from one form to the other using

$$V = \frac{R^{2/3} S_f^{1/2}}{n} = \sqrt{\frac{8gRS_f}{f}} = C\sqrt{RS_f}$$

where V is the average velocity (m/s), R is the hydraulic radius (m) = A/P_w, A is the flow area (m^2), P_w is the wetted perimeter (m), S_f is the friction slope, g is acceleration due to gravity (m/s^2), n is the Manning's coefficient, f is the Darcy-Weisbach friction factor, and C is the Chezy coefficient.

Flow resistance prediction is inexact, with varying results often obtained by different methodologies and practitioners. Experience is fundamental for the selection of the most appropriate resistance coefficient.

To address this potential variability, multiple methods should be used and the results compared for consistency. To facilitate this, a spreadsheet tool (Figure 32) has been developed to assist practitioners with flow resistance coefficient selection (Yochum 2018).

Figure 31: Milk Creek on the White River National Forest (7/1/2015). Flow resistance is due to roughness from bed material (gravel dominated), streambank variability and vegetation, riffle-pool bedforms, large instream wood, and sinuosity.

Stream Channel Flow Resistance Coefficient Computation Tool (version 1.1, 2-2018) Page 2 of 2

Stream Name: First Creek **Reach:** Restoration Reach 2
Slope, S (m/m): 0.01000 **Date:** 4/27/2017
Practitioner: Yochum

D_{50}, D_{84}, $D_{84, step}$ (m):	0.06	0.12	----
R (ft, m):	1.44	0.44	
d (ft^2, m^2):	1.48	0.45	
σ_z (ft, m):	----	----	
h_m (ft, m):	----	----	

Overall Average n:	0.046
f:	0.224
Quantitative Average n (1):	0.045
f (1):	0.217
Arcement and Schneider (1989) n:	0.052
f:	0.276

3 Quantitative Prediction

Quasi-Quantitative:

	n_b (2)	n_1	n_2	n_3	n_4	m	**Estimate**	**Use in Average? Enter "y"**
Arcement and Schneider (1989) $n = (n_b + n_1 + n_2 + n_3 + n_4)m$	0.035	0.005	0	0	0.005	1.15	0.052	y
	Base	Degree of Irrigularity	Variation in X-S	Effect of Obstruction	Amount of Vegetation	Degree of Meandering		

Fully Quantitative:

Method [Fit]	Relative Submergenc	Estimate n	f	# Data Points	Applicable Range Slope (ft/ft)	Relative Sub.(3)	Use in Average ? Enter
Yochum et al. (2012) [R^2 = 0.78; f: R^2 = 0.82]	----	----	----	78	0.02 to 0.20	h_m/σ_z = 0.25 to 12	
Rickenmann and Recking (2011)	3.75	0.040	0.163	2890	0.00004 to 0.03	d/D_{84} = 0.18 to ~100	y
Aberle and Smart (2003); in flume	----	----	----	94	0.02 to 0.10	d/σ_z = 1.2 to 12	
Lee and Ferguson (2002)(4) [RMS error = 19%]	----	----	----	81	0.027 to 0.184	R/D_{84} (step) = 0.1 to 1.4	
Bathurst (1985) [RMS error = ~34%]	3.75	0.039	0.153	44	0.00429 to 0.0373	d/D_{84} = 0.71 to 11.4	y
Jarrett (1984) [ave. std. error = 28%]	n/a	0.064	0.421	75	0.002 to 0.039	n/a	y
Griffiths (1981); rigid bed [R^2=0.59]	7.3	0.042	0.180	84	0.000085 to 0.011	R/D_{50} = 1.8 to 181	y
Hey (1979); a = 12.72	3.7	0.043	0.192	30	0.00049 to ~0.01	R/D_{84} = 0.8 to 25	y
Limerinos (1970) [R^2=0.77]	3.7	0.043	0.191	50	0.00038 to 0.039	R/D_{84} = 1.1 to 69	y

Notes:
(1) Quantitative average excludes the Arcement and Schneider (1989) method.
(2) In some situations it can be appropraite to assume that the quantitative average n is n_b., though this may result in overestimated flow resistance.
(3) Relative submergence is computed using either R (hydraulic radius) or d (mean depth) and the D_{50} (median bed material size) or D_{84} (84% of bed material smaller); or computed using either h_m (median thalweg depth) or d and σ_z (standard deviation of residuals of a thalweg longitudinal profile regression). For σ_z computation, see "S>0.03, Sigma z" tab of this spreadsheet.
(4) This method can substantially underestimate flow resistance in steeper streams (slope>0.03) where large wood is

This spreadsheet has been reviewed for accuracy. However, the ultimate responsibility for flow resistance estimates remains with the user.
U.S. Forest Service
National Stream and Aquatic Ecology Center

Figure 32: Flow resistance coefficient estimation tool.

It is recommended that the following steps are followed when predicting flow resistance:

1. **Consult a tabular guide** that provides a range of potential resistance values (Brunner 2010; NRCS 2007, Ch 6; Fischenich 2000; Arcement and Schneider 1989).
2. **Consult photographic guidance** (Barnes 1967; Aldridge and Garrett 1973; Hicks and Mason 1998; Yochum et al. 2014).
3. **Apply a quantitative prediction methodology**
   a. Implement a quantitative prediction method appropriate for your stream type – see Yochum (2017) spreadsheet tool. These approaches typically only include roughness due to bed and bank grain material or bedforms (in higher-gradient streams).
   b. Implement a quasi-quantitative approach (Cowan 1956; Arcement and Schneider 1989) that takes into account roughness due to sinuosity, instream large wood, streambank vegetation, bank irregularities, and obstructions.

Various tools are available for estimating flow resistance, with methods varying by channel type. The most relevant prediction methodologies are provided in the following sections.

11.11.1 General Guidance and Tools

- Yochum 2018 Flow Resistance Coefficient Selection in Natural Channels: A Spreadsheet Tool (Figure 32, NSAEC TS-103.1).
- USGS: Verified Roughness Characteristics of Natural Channels (online photo guide)
- Brunner 2016 HEC-RAS Hydraulic Reference Manual
- NRCS 2007, Ch6 Stream Hydraulics
- Fischenich 2000 Resistance Due to Vegetation.
- Arcement and Schneider 1989 Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains

11.11.2 Low-Gradient Channels

(clay-, silt- and sand-bed channels)

In sand-bed channels, bedforms should initially be predicted, using such guidance as Brownlie (1983) and van Rijn (1984). Flow resistance varies by bedform type, as indicated in Table 6.

- Arcement and Schneider 1989 Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains
- van Rijn 1984 Sediment Transport, Part III: Bedforms and Alluvial Roughness

Table 6: Manning's *n* in sand-bed channels (compilation provided by Bledsoe 2007).

	bedform	**range of Manning's *n***
Subcritical	plane bed	0.012 - 0.014
	ripples	0.018 - 0.03
	dunes	0.02 - 0.04
Transitional	plane bed	0.01 - 0.013
Supercritical	antidune	0.012 - 0.020
	chutes/pools	0.018 - 0.035

- Brownlie 1983 Flow Depth in Sand-Bed Channels
- Aldridge and Garrett 1973 Roughness Coefficients for Stream Channels in Arizona
- Barnes 1967 Roughness Characteristics of Natural Channels

11.11.3 Mid-Gradient Channels

(~0.2% < slopes < ~3%, gravel- and cobble-bed, riffle-pool and plane bed channels)

- Rickenmann and Recking 2011 Evaluation of flow resistance in gravel-bed rivers through a large field data set
- Hicks and Mason 1998 Roughness Characteristics of New Zealand Rivers
- Bathurst 1985 Flow Resistance Estimation in Mountain Rivers
- Jarrett 1984 Hydraulics of High-Gradient Streams
- Griffiths 1981 Flow resistance in coarse gravel bed rivers
- Hey 1979 Flow Resistance in Gravel-Bed Rivers
- Aldridge and Garrett 1973 Roughness Coefficients for Stream Channels in Arizona

- Limerinos 1970 Determination of Manning's Coefficient from Measured Bed Roughness in Natural Channels.
- Barnes 1967 Roughness Characteristics of Natural Channels

11.11.4 High-Gradient Channels

(slopes > ~3%, cobble- and boulder-bed, step pool and cascade channels)

- Yochum et al. 2014 Photographic Guidance for Selecting Flow Resistance Coefficients in High-Gradient Channels.
- Yochum et al. 2012 Velocity Prediction in High-Gradient Channels
- Rickenmann and Recking 2011 Evaluation of flow resistance in gravel-bed rivers through a large field data set
- Aberle and Smart 2003 The influence of roughness structure on flow resistance in steep slopes
- Lee and Ferguson 2002 Velocity and flow resistance in step-pool streams
- Jarrett 1984 Hydraulics of High-Gradient Streams
- Barnes 1967 Roughness Characteristics of Natural Channels

The method described in Yochum et al. (2012) implements the variable σ_z, the standard deviation of the residuals of a bed elevation regression. An illustration of how this variable is computed from a longitudinal profile is shown (Figure 33). Yochum (2017) provides a spreadsheet tool for computing σ_z.

11.11.5 Floodplains

- Arcement and Schneider 1989 Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains.

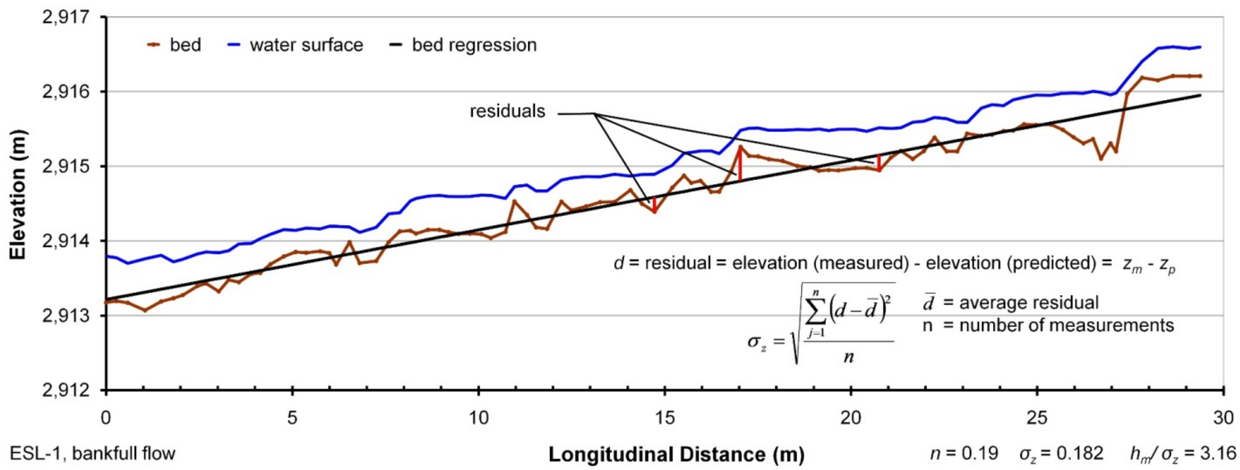


Figure 33: Computation methodology for σ_z (Yochum et al. 2014).

11.12 Groundwater

Riparian areas and streams interact with groundwater. The restoration potential of stream and riparian systems frequently depend on local groundwater conditions and groundwater-surface water interactions along the reach. In some stream reaches, the water in the stream feeds the local groundwater aquifer (losing stream) and in other stream reaches groundwater discharges to the stream channel (gaining stream; Figure 34). Understanding groundwater dynamics and interactions between groundwater and the stream channel(s) is often important for understanding and restoring stream and riparian ecosystem potential and riparian vegetation-hydrology relationships.

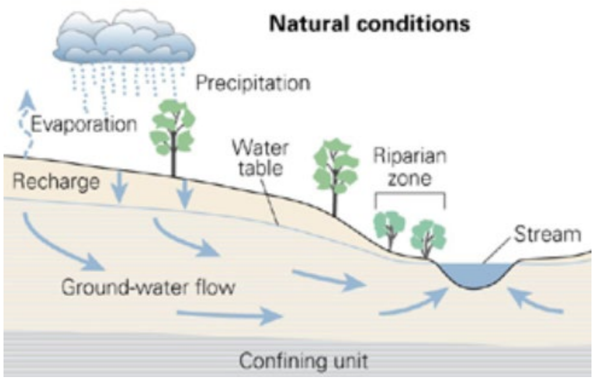


Figure 34: Schematic illustrating a valley cross section for a gaining stream reach (USDA Forest Service, 2007)

Hyporheic exchange, the flow of water into and out of the streambed, is an important stream process that serves a critical role in naturally functioning streams. Movement of stream water into and out of high-porosity alluvial deposits can have an important influence on surface water quality and aquatic habitat. Important functions of hyporheic exchange include water temperature moderation, recycling of carbon, energy, and nutrients, natural attenuation of pollutants, a sink/source of sediment for the channel, and habitat for benthic and interstitial organisms (Bakke et al. 2020).

Hyporheic flowpaths are altered by the transport of fine sediment through the stream bed and are thus susceptible to changes in sediment regime and hydraulics, as well as the changes produced during construction of a restoration project (Fernald et al. 2000). Kasahara et al. (2009) lists the following approaches for restoring hyporheic exchange and sediment structure at the stream-reach scale:

- Introduction of small-scale obstructions (wood, boulders)
- Construction of step-pool and riffle-pool sequences
- Introduction of large obstructions (e.g. wood dams, protruding sediment bars)
- Channel widening
- Promotion of multi-thread channels
- Re-meandering
- Increasing flow fluctuation by dam operations (e.g. restoration of peak flow)
- Reduction of fine sediment input
- Selective removal of fines (managed sand traps, floodplain inundation)
- Sustainable de-siltation by increasing frequency of sediment re-deposition and breaking up of armored layers by flushing flows
- Augmentation of coarse sediments (to increase bed mobility in sediment-deficit reaches)
- Reducing channel cross-sectional area
- Increasing structural heterogeneity of the bed to promote small-scale patches of bed mobility at medium peak flows

With the use of these techniques, monitoring of stream restorations have shown significant increases in streamflow during the summer recession period, decreased groundwater table depths across a wide range of streamflow conditions (Tague et al. 2008), and increased groundwater–surface water interactions (Kurth et al. 2015). Some restoration designs have proven capable of maintaining natural scour and fill processes which slow or reverse embedded conditions and may improve hyporheic exchange over time through natural stream evolution, including processes of large-wood recruitment and associated accumulation of more diverse and extensive alluvial streambed material (Bakke et al. 2020).

Incision of a channel leads to lower groundwater levels that extend laterally away from the channel. In general, restoration of an incised channel will cause the water table adjacent to the stream to rise to roughly the level of the restored stream water surface. The elevation of the water table farther from the stream may also rise but the magnitude is dependent on the distance from the stream, hydraulic conductivity of the valley fill materials, gaining/losing characteristics of the stream reach, frequency of overbank flows, and the influx of groundwater from surrounding bedrock.

Wells or piezometers can be used to track the change in water table elevation before and after restoration. If the project objective is to promote groundwater levels that are supportive of the establishment of native wetland herbaceous ground cover and potentially suppressing invasive species, the target water table depth should be less than a meter below the ground surface, and ideally less than 20 cm (Aldous and Bach 2014). Rooting depths for many groundwater dependent plant species are available on the GDE Rooting Depth Database (The Nature Conservancy 2020).

12. RESTORATION FEATURES

This section provides guidance for specific planning and design features that are relevant when developing stream restoration projects. These include ecological and engineered approaches and structures as well as riparian corridor management. Guidance is provided for vegetation, livestock grazing, instream wood, stream habitat and environmental flows, fish passage and screening, beavers, bank stabilization, bed stabilization and stream diversions, planform design, and dam removal. Maintenance of restoration features is typically needed with lack of maintenance frequently being a substantial challenge for the longterm effectiveness of restoration projects (Moore and Rutherford 2017).

General references for the design of stream restoration features are provided in the Overview of Stream Processes and Restoration section.

Stream restoration projects are subject to various regulatory programs. An overview of permitting requirements is provided in:

- NRCS 2007, Ch17 Permitting Overview

12.1 Vegetation

Riparian vegetation offers a great variety of benefits to stream channels and riverine ecosystems, including binding soil together to reduce erosion rates and increase bank stability; increasing bank and floodplain flow resistance, reducing near-bank velocities and erosive potential; inducing sediment deposition to support stabilizing fluvial processes; providing shade to decrease solar radiation and stream temperatures, cover for hiding opportunities for fish, and sources of coarse instream wood to the stream channel, for habitat; and feeding energy input to streams in the form of dropped leaves and terrestrial insects. A key difference between braided and non-braided streams is the dominance of bank stabilizing vegetation (Braudrick et al. 2009; Crosato and Saleh 2011; Li and Millar 2011). Well vegetated stream channels with substantial quantities of in-channel wood can, in some cases, lead to stability measured in millennia (Brooks and Brierley 2002); the benefits of vegetation to bank stability should not be underestimated.

Additionally, at a watershed scale there are flood-reduction benefits to well-vegetated riparian corridors. While increases in riparian vegetation typically increase water surface stages along downstream higher-order streams, increased riparian vegetation along headwater streams can decrease flood discharges and stages on the higher-order streams, decreasing flood risk (Anderson 2006). In these situations, the increased roughness of the upstream riparian corridors increases flow resistance and flood attenuation, reducing discharges and depths downstream while increasing flood duration.

In most streams, both woody and herbaceous wetland species are important for bank stabilization (Figure 35), with the combination being substantially more effective at bank stabilization than woody species alone (Hoag et al. 2011). A willow and sedge assemblage forms a highly-reinforced streambank, with the larger-size willow roots behaving like rebar and the very large quantity of fine sedge roots acting like netting throughout the soil material (Polvi et al. 2014).

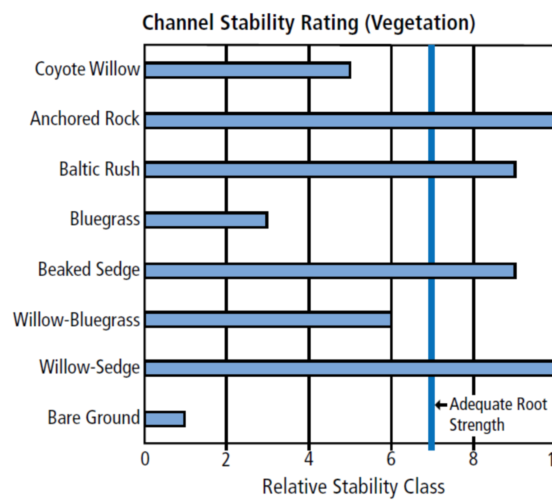


Figure 35: Channel stability ratings for various vegetative compositions (Wyman et al. 2006).

Since vegetation is an integral part of stream ecosystems, a revegetation component should be included in stream restoration projects. Where grazing exists, livestock management should also be included; otherwise the investment into riparian vegetation and benefits to a project can be lost to grazing. Additionally, previous channelization projects or channel incision may impact appropriate species in some locations – this should be a consideration. The vegetation used in stream corridor projects should typically be native, with the source material collected as close to the project site as possible, to assure inclusion of locally adapted plants, ensure the best chance of plant survival, and reduce costs. The use of such tools as a stinger (Figure 36) or an electric hammer drill to dig planting holes can be valuable for willow pole and bundle plantings, especially in riparian areas with substantial amounts of underlying gravels and cobbles. In addition to willows and other shrubs, it is equally important to establish herbaceous plants, including forbs, grasses, sedges, and rushes in the riparian zone. Riparian trees can also provide substantial amounts of bank stabilization (Polvi et al. 2014), though take considerably longer to colonize. Ecological site descriptions and historic photographs are valuable for assessing what vegetative communities to restore.

Figure 36: The use of a stinger for vegetative plantings (nativerevegetation.org).

References and tools helpful for understanding the role of plants for bank stabilization, as well as for planning and designing vegetation aspects of projects, include:

- Hausner et al. 2018 Assessing the effectiveness of riparian restoration projects using Landsat and precipitation data from the cloud-computing application ClimateEngine.org
- MacFarland et al. 2017 Riparian Forest Buffers: An Agroforestry Practice
- Successful Buffer Restoration: Initial Establishment Methods and Post-Planting Care (NRCS webinar)
- Hoag 2016 Developing a Riparian Planting Plan (StreamNotes)
- Polvi et al. 2014 Modeling the functional influence of vegetation type on streambank cohesion.
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Cooper and Merritt 2012 Assessing the water needs of riparian and wetland vegetation in the western United States
- Caplan et al. 2012 Growth Response of Coyote Willow (*Salix exigua*) Cuttings in Relation to Alluvial Soil Texture and Water Availability
- Hoag et al. 2011 Description, Propagation, and Establishment of Wetland-Riparian Grass and Grass-Like Species in the Intermountain West
- Hoag & Ogle 2011 The Stinger – A Tool to Plant Unrooted Hardwood Cuttings (Figure 36)
- Quistberg and Stringham 2010 Sedge Transplant Survival in a Reconstructed Channel: Influences of Planting Location, Erosion, and Invasive Species
- Dosskey et al. 2010 The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams
- Dreenen and Fenchel 2010 Deep-Planting Techniques to Establish Riparian Vegetation in Arid and Semiarid Regions
- Hoag & Ogle 2010 Willow Clump Plantings

- Stromberg et al. 2009 Influence of Hydrologic Connectivity on Plant Species Diversity Along Southwestern Rivers – Implications for Restoration.
- Dreesen and Fenchel 2009 Revegetating Riparian Areas in the Southwest “Lessons Learned”
- Hoag 2009 Vertical Bundles: A Streambank Bioengineering Treatment to establish willows and dogwoods on streambanks
- Hoag et al. 2008 Field guide for Identification and Use of Common Riparian Woody Plants of the Intermountain West and Pacific Northwest Regions.
- Conservation Buffer Economic Analysis Tool An Excel-based tool for analyzing the economic benefits of riparian conservation buffers.
- Sotir and Fischenich 2007 Live Stake and Joint Planting for Streambank Erosion Control.
- NRCS 2007, TS-14I Streambank Soil Bioengineering
- Hoag 2007 How to Plant Willows and Cottonwoods for Riparian Restoration
- Hoag and Sampson 2007 Planting Willow and Cottonwood Poles under Rock Riprap
- Fischer 2004 Using Soil Amendments to Improve Riparian Plant Survival in Arid and Semi-arid Landscapes.
- Steed and DeWald 2003 Transplanting Sedges (Carex spp.) in Southwestern Riparian Meadows
- Shafer and Lee 2003 Willow Stake Installation – Example Contract Specifications
- Hoag & Fripp 2002 Streambank Soil Bioengineering Field Guide for Low Precipitation Areas
- Hoag et al. 2001 Users Guide to Description, Propagation, and Establishment of Wetland Plant Species and Grasses for Riparian Areas in the Intermountain West.
- Fischenich 2001c Plant Material Selection and Acquisition.
- Sotir and Fischenich 2001 Live and Inert Fascine Streambank Erosion Control.
- Goldsmith et al. 2001 Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity
- Fischenich 2000 Irrigation Systems for Establishing Riparian Vegetation

For additional publications and information, please refer to the following websites:

- Riparian Publications: NRCS
- Wetland Publications: NRCS
- Potential Seed and Plant Sources: NRCS
- Ecological Site Descriptions: NRCS
- Revegetation Resources: RiversEdge West

Along urban streams with banks hardened by steel or concrete, floating riverbanks are available for providing, according to their manufacturer Biomatrix Water, “attractive waterscape aesthetic, improved water quality, biodiversity and habitat benefits.” More information is available here.

12.2 Livestock Grazing Management

Livestock grazing in riparian zones can negatively influence herbaceous species composition, productivity, and commonly modifies the structure and composition of woody plant communities (George et al. 2011). The result is often destabilized streambanks and reduced channel cover and shading. The decreased stability leads to overwidened channels, decreased flow depth and, in combination with the decreased shading, substantial increases in water temperatures. Temperature increases are a substantial concern with cold water fishes and are especially problematic for native endangered, threatened, or species of concern. Additionally, stream access paths and loafing areas (shaded areas) within riparian zones have been found to be the most intensive non-bank sources of sediment and phosphorus in streams (Tufekcioglu et al. 2012); these areas deserve special attention in livestock grazing mitigation efforts. Consequently, exclusion, rest, and deferment (Table 7), are typically critical components of stream restoration projects in grazed areas. Livestock exclusion along streams has been shown to increase population-level (abundance) trout responses (Sievers et al. 2017).

As discussed in George et al. (2011), altered grazing practices designed for maintaining or rehabilitating riparian zone health include:

1) controlling the timing and duration of riparian grazing by fencing riparian pastures within existing pastures
2) fencing riparian areas to exclude livestock
3) change the kind and class of livestock
4) reducing grazing duration
5) reducing grazing intensity
6) controlling season of use

Table 7: Evaluation and rating of grazing strategies for stream-riparian-related fisheries values, based on observations by Platts (1990). (George et al. 2011)

Strategy	Level to which riparian vegetation is commonly used	Control of animal distribution (allotment)	Stream bank stability	Brushy species condition	Seasonal plant regrowth	Stream–riparian rehabilitative potential	Rating
Continuous season-long (cattle)	Heavy	Poor	Poor	Poor	Poor	Poor	1[1]
Holding (sheep or cattle)	Heavy	Excellent	Poor	Poor	Fair	Poor	1
Short duration–high intensity (cattle)	Heavy	Excellent	Poor	Poor	Poor	Poor	1
Three herd–four pasture (cattle)	Heavy to moderate	Good	Poor	Poor	Poor	Poor	2
Holistic (cattle or sheep)	Heavy to light	Good	Poor to good	Poor	Good	Poor to excellent	2–9
Deferred (cattle)	Moderate to heavy	Fair	Poor	Poor	Fair	Fair	3
Seasonal suitability (cattle)	Heavy	Good	Poor	Poor	Fair	Fair	3
Deferred rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Stuttered deferred rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Winter (sheep or cattle)	Moderate to heavy	Fair	Good	Fair	Fair to good	Good	5
Rest–rotation (cattle)	Heavy to moderate	Good	Fair to good	Fair	Fair to good	Fair	5
Double rest–rotation (cattle)	Moderate	Good	Good	Fair	Good	Good	6
Seasonal riparian preference (cattle or sheep)	Moderate to light	Good	Good	Good	Fair	Fair	6
Riparian pasture (cattle or sheep)	As prescribed	Good	Good	Good	Good	Good	8
Corridor fencing (cattle or sheep)	None	Excellent	Good to excellent	Excellent	Good to excellent	Excellent	9
Rest–rotation with seasonal preference (sheep)	Light	Good	Good to excellent	Good to excellent	Good	Excellent	9
Rest or closure (cattle or sheep)	None	Excellent	Excellent	Excellent	Excellent	Excellent	10

[1]Rating scale based on 1 (poorly compatible) to 10 (highly compatible) with fishery needs.

A grazing management planning process is presented (Figure 37). Since willows are some of the most common vegetation types implemented in streambank stabilization, it is especially important to provide grazing practices that encourage willow growth. Different geomorphic stream types and channel evolution phases have varying sensitivities to grazing practices. Guidance for grazing systems that are compatible with willow-dominated plant communities is provided (Table 8).

Table 8: Grazing system compatibility with willow-dominated plant communities, as developed by Kovalchik and Elmore (1991), (George et al. 2011).

Grazing practice	Compatibility with willows
Corridor fencing	Highly
Riparian pasture	Highly
Spring (early-season) grazing	Highly
Winter grazing	Highly
Two-pasture rotation	Moderately
Three-pasture rest rotation	Moderately
Three-pasture deferred rotation	Moderately
Spring–fall pastures	Incompatible
Deferred grazing	Incompatible
Late-season grazing	Incompatible
Season-long grazing	Incompatible

Available information and guidance for riparian grazing management includes:

- To Fence or Not to Fence (Out a Stream): Planning Considerations and Design Options for Prescribed Grazing Systems and Functional Riparian Buffers (NRCS Conservation Webinar, 2017-9)
- Livestock & Grazing Management; Riparian Restoration Resource Center RiversEdge West
- Swanson et al. 2015 Practical Grazing Management to Maintain or Restore Riparian Functions and Values
- Wyman et al. 2006 Grazing Management Processes and Strategies for Riparian-Wetland Areas
- Leonard et al. 1997 Riparian Area Management – Grazing Management for Riparian-Wetland Areas
- Ehrhart and Hansen 1997 Effective Cattle Management in Riparian Zones: A Field Survey and Literature Review

Excessive ungulate (hooved mammal) wildlife browsing can cause negative riparian impacts similar to the impacts of domestic livestock grazing. In some locations, a mechanism allowing excessive browsing by elk and deer may be the elimination of large predators, such as cougars and wolves. Additionally, the elimination of beavers has also had substantial negative influences on riparian vegetation. In areas that have had top predator extirpations, increased browsing intensity by native ungulates in combination with altered hydrology with lack of beavers and beaver ponds has been shown to have long-term negative impacts on vegetative recruitment and extent, resulting in increased bank erosion, decreased channel depths, and increased channel widths, incision, and braiding (Bilyeu et al. 2008, Beschta and Ripple 2012, Marshall et al. 2013).

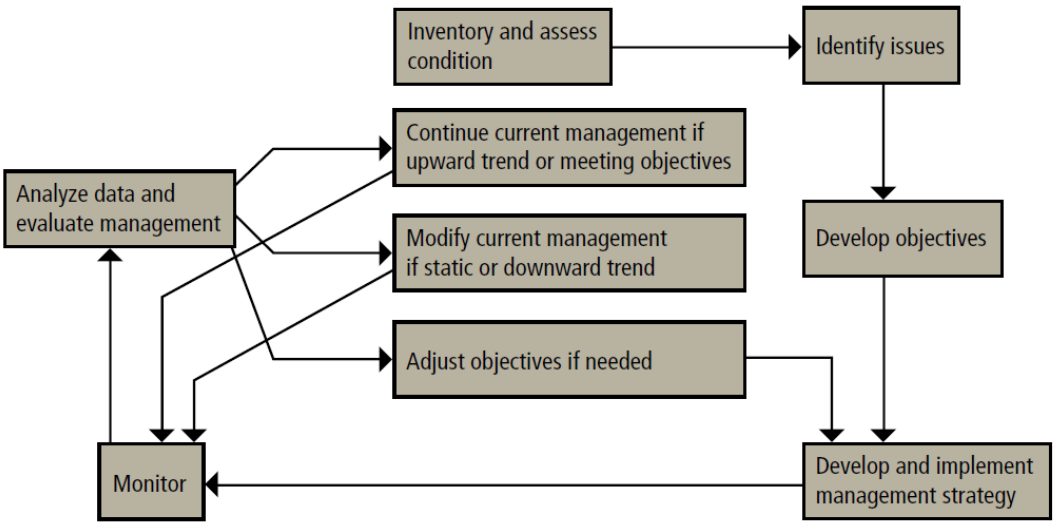


Figure 37: A grazing management planning process (Wyman et al. 2006).

12.3 Large Wood

Streams in forested areas had large wood (also known as large woody debris [LWD], Figure 38) present within the channel and floodplain prior to anthropogenic manipulation, but such wood has been frequently removed. This removal has disturbed the natural wood regime, the third leg (with flow and sediment) of the triad of physical transport processes that streams support (Wohl et al. 2019). Objectives of such removal include increasing flow conveyance, removing hazards to infrastructure and navigation, and (controversially) improving fish migration in streams with debris jams along the Pacific Coast of North America (1950s through early 1970s, Reeves at al. 1991).

Removal of large wood reduces bedform variability (Brooks et al. 2003), with the lack of pools resulting in ecological consequences of reduced hyporheic exchange, increased water temperatures, and fewer available refugia for aquatic life from peak temperatures and winter ice. The presence of instream wood can be a primary driver of the physical heterogeneity in stream channels (Livers and Wohl 2016), with this complexity often considered a surrogate for ecological health. Additionally, increased amounts large wood in streams due to restoration projects has been shown to increase population-level (abundance) trout responses (Sievers et al. 2017).

Figure 38: Substantial wood loading in a high-gradient stream channel (Fraser Experimental Forest, Colorado).

Large wood, in combination with streambank and floodplain vegetation, help to increased riparian and channel roughness, which substantially impacts flood wave celerity, and hydrograph dispersion and skew. Larger and more dense vegetation results in higher Manning's *n* values, lower velocities, and lower peak discharges as floodwaves disperse downstream (Anderson et al. 2006). This effect is moderated by flood magnitude, with smaller-magnitude floods more impacted by vegetation than larger floods.

The presence of substantial amounts of in-channel large wood can increase lateral connectivity with the floodplain while decreasing sediment and nutrient transport downstream, temporarily retaining this material within the riparian zone as opposed to "leaking" this material downstream through a stream system largely devoid of wood and in a potentially alternative stable state (Wohl and Beckman 2014). The presence of large wood can mitigate, to an extent, the impacts of the greatly-increased release of sediment into smaller stream channels after wildfires through the accumulation of sediment behind jams (Short et al. 2015).

Velocity increases resulting from channel clearing activities have been found to lead to channel widening, reduced sinuosity, increased slope, channel incision, reduced groundwater levels, bed material coarsening, and increased rates of lateral migration (Brooks et al. 2003). Large wood, when present, provides more frequent, larger, and deeper pools (Richmond and Fausch 1995), accumulation of finer sediment (Buffington and Montgomery 1999; Klaar et al. 2011; Jones et al. 2011), increased flow resistance (Shields and Gippel 1995; David et al. 2011), and diversity in hydraulic gradients (Klaar et al. 2011). These morphological and hydraulic adjustments can provide substantial ecological benefits, through increased pool refugia from high flows, summertime temperatures and winter ice, increased cover, accumulation of spawning gravels, and nutrient enrichment.

For example, large wood removal was a consequence of such extensive anthropogenic disturbances in Rocky Mountain streams as railroad tie drives (Figure 39) and placer mining.

With tie drives, cut ties were driven downstream during peak snowmelt to railroad construction sites, requiring the removal of all large wood to allow passage of the ties and severely altering the natural geomorphic channel features (Ruffing et al. 2015). The similar practices of log drives and splash damming were utilized to transport logs to downstream mills along the West Coast of the

United States, as well as in other areas of North America (Higgins and Reinecke 2015).

Figure 39: Railroad tie drives in the Rocky Mountains resulted in instream wood removal and reduction in channel variability (courtesy of the American Heritage Center).

A summary of the ecological benefits of instream wood is provided in the following reports and sites:

- Herdrich et al. 2018 The loss of large wood affects rocky mountain trout populations
- Fish of the Forest: Large Wood Benefits Salmon Recovery: Blog article by Emily Howe, of The Nature Conservancy (2016)
- BBC Radio4: Nature – Wood and Water (2012)
- Maser and Sedell 1994 From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans

12.3.1 Management for Large Wood Recruitment and Retention

Retaining dead wood in stream corridors has been suggested as a key passive restoration approach (Livers and Wohl 2016). However, passive recovery of natural wood loads after desnagging can take centuries (Stout et al. 2018). Key mechanisms for large wood recruitment to stream channels include recruitment from riparian tree fall from mature riparian and upland forests, recruitment from transport of downed wood through ephemeral channels during floods, and landslides and debris flows that deliver large slugs of large wood to stream corridors for transport downstream. For streams to maintain large wood recruitment, they must have adequate nearby riparian and upland forests, thus a stream with a diversity of woody riparian age classes from seedlings to mature shrubs and trees, will have a long-term source of large wood input. Large wood recruitment from mass wasting (landslides and debris flows) can dominate in headwater streams while recruitment from lateral bank erosion can dominate in higher-order streams (Figure 40; Steeb et al. 2017). Retention of large wood in higher-gradient streams is more likely in multi-thread channels as opposed to channelized single-thread streams, due to lesser mean flow depths and velocity, and shear stress and unit stream power (Wyżga et al. 2017).

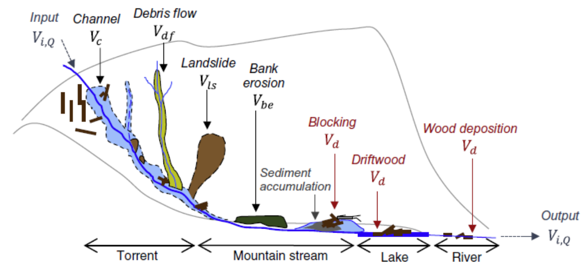


Figure 40: Conceptual visualization of large wood recruitment, transport, and deposition (Steeb et al. 2017).

Guidance for managing riparian areas for large wood recruitment and retention in stream channels include:

- Wohl et al. 2019 Managing for Large Wood and Beaver Dams in Stream Corridors (RMRS GTR)
- Wohl et al. 2019 The Natural Wood Regime in Rivers
- MacFarlane et al. 2017 Riparian Forest Buffers: An Agroforestry Practice
- USBR and ERDC 2016 National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure
- Wohl et al. 2016 Management of Large Wood in Streams: An Overview and Proposed Framework for Hazard Evaluation
- Bentrup 2008 Conservation Buffers: Design Guidelines for Buffers, Corridors, and Greenways.

12.3.2 Large Wood Structures

The inclusion of large wood into stream designs can be fundamental for satisfying project objectives focused on habitat restoration, since the associated increase in geomorphic and hydraulic variability benefits ecological diversity. Wood structures include many types, including: self-stabilizing wood pieces dropped into stream channels, windthrow emulation (Figure 41, Figure 42), single-piece log structures and small wood complexes, log vanes (Figure 57), toe wood bench (Figure 63), log jams and complexes (Figure 65), and other large wood features (Figure 43; Figure 44). These structures can provide benefits in the short to medium term while, in the long term, proper management of riparian zones for wood production is needed for providing sustainable wood recruitment.

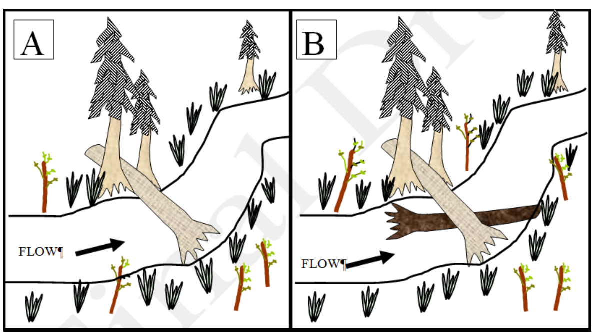


Figure 41: Windthrow emulation, with a single log placed between two standing trees to create a pivot and lock point (A), and with the addition of a second log with root wad attached to create an X pattern (B). To increase stability, logs should be ≥1.5 times the bankfull width (with attached rootwad) or ≥2 times the bankfull width (without an attached rootwad). (Graphic and guidance from ODF ODFW 2010).

The use of unanchored, strategically-placed large wood, such as windthrow emulations, cost substantially less than anchored wood augmentation. In small- and medium-sized streams in Northern California it was found that unanchored wood projects cost only 22% of the average cost of anchored wood augmentation (Carah et al. 2014), which can allow watershed-scale implementation. Unanchored wood can also more-closely mimic natural wood-loading processes, leading to greater effectiveness. However, large wood movement can be a risk to bridge and culvert infrastructure. Large wood can also be a recreational hazard. Wohl et al. (2016) and Wohl et al. (2019) provide a framework for managing such risks.

Limited information is available regarding wood decay rates for instream structures, though wood has been documented as being relatively functional in streambank structures for as long as 70 years (Thompson 2002). Decay rates vary as a function of surface area and water quality. Larger-diameter logs (which have less surface area per wood volume) decay at lower rates (Diez et al. 2002; Spanhoff and Meyer 2004) while wood in streams with higher nutrient levels decay at higher rates (Diez et al. 2002; Gulis et al. 2004; Spanhoff and Meyer 2004). Differing rates of decay can also be expected by species and amount of wet/dry cycling. Estimated wood decay rates are provided in USBR and ERDC (2016).

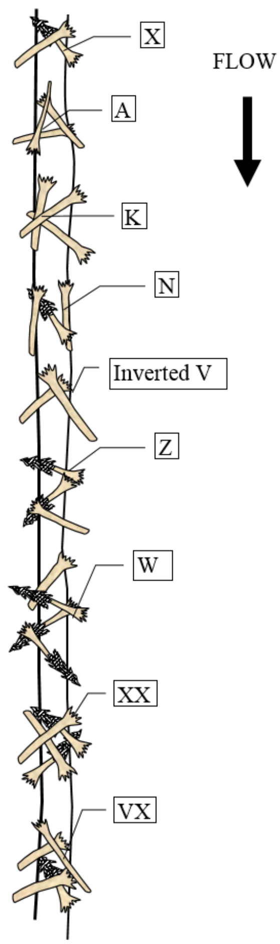


Figure 42: Typical plan view illustrating windthrow emulations orientations (Graphic from ODF ODFW 2010).

Figure 43: Introduced large wood (photo credit: Paul Powers).

Figure 44: Complex timber revetment (photo credit: Tim Abbe, USBR and ERDC 2016).

References and tools helpful for the incorporation of large wood into stream and riparian restoration projects include:

- Wheaton et al. 2019 Low-Tech Process-Based Restoration of Riverscapes
- Schalko et al. 2018 Backwater Rise due to Large Wood Accumulations
- Watts, A. 2018 River Food Webs: Incorporating Nature's Invisible Fabric into River Management (Science findings, USFS Pacific Northwest Research Station)
- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- USBR and ERDC 2016 National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure
- Rafferty 2016 Computational Design Tool for Evaluating the Stability of Large Wood Structures (NSAEC TN-103). Tool.
- Use of Wood in Stream Restoration NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- Carah et al. 2014 Low-Cost Restoration Techniques for Rapidly Increasing Wood Cover in Coastal Coho Salmon Streams
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- USBR 2014a Improving Public Safety of Large Wood Installations: Designing and Installing Safer large Wood Structures
- USBR 2014b Modeling How Large Woody Debris Structures Affect Rivers: Modeling River Changes from Large Wood Structures and Other Instream Structures
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Wohl, E. 2011 (in Simon et al. 2011): Seeing the Forest and the Trees – Wood in Stream Restoration in the Colorado Front Range, United States
- Abbe and Brooks 2011(in Simon et al. 2011) Geomorphic, Engineering, and Ecological Considerations When Using Wood in River Restoration.
- ODF ODFW 2010 Guide to Placement of Wood, Boulders and Gravel for Habitat Restoration
- FEMA 2009 Engineering With Nature: Alternative Techniques to Riprap Bank Stabilization
- NRCS 2007, TS14J Use of Large Woody Material for Habitat and Bank Protection
- NRCS 2007, TS14H Flow Changing Techniques
- Shields et al. 2004 Large Woody Debris Structures for Sand-Bed Channels
- NRCS 2001 Incorporation of Large Wood Into Engineered Structures
- D'Aoust and Millar 2000 Stability of Ballasted Woody Debris Habitat Structures
- Hilderbrand et al. 1998 Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects
- Gippel et al. 1996 Hydraulic Guidelines for the Re-Introduction and Management of Large Woody Debris in Lowland Rivers
- Reeves at al. 1991 Rehabilitating and Modifying Stream Habitats (in Influences of Forest Rangeland Management on Salmonid Fishes and Their Habitats)

12.4 Stream Habitat and Environmental Flows

In general, fish and other aquatic and riparian corridor species need appropriate and sufficient physical habitat, water quality, and instream flows to thrive. Channelized and incised streams, as well as streams without connections to their floodplains, are fundamental impairments along many stream corridors. The lack of thalweg longitudinal profile complexity is a common physical impairment for cold-water fishes. The removal of instream wood, through channel clearing and snagging activities, has contributed substantially to the lack of cover and complexity. One of the most common water quality impairments is excessive peak summer temperatures, which can be related to flow depletions associated with reservoirs and stream diversions. With substantial competition for water in the semi-arid and arid West, and increasing pressure on water resources in other parts of the United States, sufficient discharge to maintain habitat extent and quality is an ongoing challenge.

The desired biologic response from water quality and riparian management improvements can be substantially delayed behind the time of implementation. For example, macroinvertebrate recovery was found to lag 6 years behind water quality improvements in a stream impacted by coal mine drainage (Walter et al. 2012), and the diversity of macroinvertebrates and fish have been found to be better predicted by watershed land use characteristics from 40 years ago rather than contemporary characteristics (Harding et al. 1998). An extended monitoring program (and patience) may be required to assess the ultimate success of a project.

Fundamental for instream fish habitat is sufficient flow to support natural stream function. Competing water needs often minimizes instream flow for supporting ecologic function and sufficient water availability is an ongoing problem for providing habitat for all aquatic life. Reservoir regulation, irrigation withdrawals, urbanization, and groundwater depletion alter the magnitude, frequency, duration, timing, and rate of change of the natural flow regime, impairing stream function (Bunn and Arthington 2002; Poff et al. 1997; Poff 2018). Similarly, a natural (or balanced) sediment regime is also required for proper ecosystem function (Wohl et al. 2015).

To improve riparian ecologic function in areas of altered streamflow, methods have been developed for defining natural flow regimes and applying them the stream systems (Tharme 2003; Olden and Poff 2003; Arthington et al. 2006; Hall et al. 2009; Bartholow 2010; Poff et al. 2010; Richter et al. 2011; Sanderson et al. 2012; Chen and Olden 2017 Lytle et al. 2017). However, competing uses for limited water resources will be an ongoing problem for stream restoration projects.

Instead of relying upon geomorphological design approaches to restoration, it has been proposed that restoration design be based on ecohydraulic-based mesohabitat classification and fish species

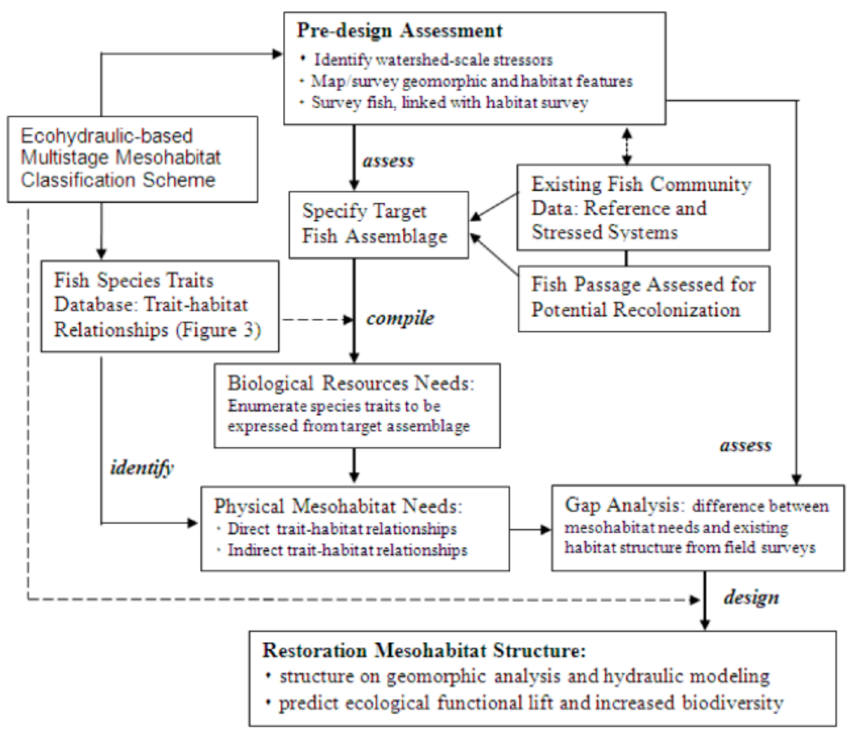


Figure 45: Proposed restoration design strategy utilizing ecohydraulic principles and species functional traits (Schwartz 2016).

traits (Schwartz 2016; Figure 45). Such an approach could better reflect goals and objectives commonly elucidated during restoration planning. This approach requires the selection of a target fish community as an initial step, with available knowledge of functional traits and physical habitat needs.

Structures such as deflectors, boulder placements, riprap bank protection, cover structures, and log grade control structures have been used since at least the 1930s to enhance instream habitat by creating pools, cover, and bed stabilization. Reeves at al. (1991) provides a historic overview of habitat enhancement. In an evaluation of 70-year-old structures, Thompson (2002) found a mix of successes and failures of such structures for providing preferred habitat conditions, with deterioration or failure of the structures, variable pool depths that are not as deep as natural pools in adjacent reaches, and rip rap that impaired vegetative growth. However, some habitat benefits are still being realized by 70% of the surviving structures, despite wood logs being extensively implemented in their construction and a greater than 100-year flood experienced. While structures can be beneficial in the shorter term for providing habitat enhancement, natural geomorphic mechanisms are likely more enduring for providing narrowed channels, undercut banks, and instream wood recruitment. Hence, habitat enhancement can be viewed as two pronged, with structures that do not inhibit vegetative growth used to provide shorter term habitat improvements, and vegetative planting and livestock (and wildlife) management used to provide favorable habitat for the longer term.

The following structures and techniques have been used to enhance habitat for fish and other aquatic species:

- Provision of sufficient instream flows.
- Channel modification and reconstruction: Alteration of the channel planform, cross section, and profile, including channel realignment and riparian meadow restoration from incised or channelized conditions (Figure 46).
- Stage 0 restorations.
- Levee modification or removal: Floodplain connectivity reestablishment by modifying or removing levees.
- Side channel and off-channel habitat establishment or enhancement: Construction, restoration, or reconnection of side channels to the main stream channel.

Figure 46: Meadow restoration of Whychus Creek, Oregon (photo credit: Russ McMillian).

- Aquatic organism passage restoration: Reestablishing upstream and downstream passage blocked by culverts, flow diversions weirs, and other artificial obstructions (discussed in the following section).
- Toe wood: Wood armoring of streambanks to provide cover, refuge from high velocities, and bank stabilization (Figure 63).
- Beaver reintroduction: Use of reintroduced beaver colonies to recover degraded stream corridors (Figure 47; discussed in the Beavers section).

Figure 47: Beaver dam in a previously-incised stream channel (Trout Creek, Colorado; photo credit: Barry Southerland).

- Spawning gravel cleaning and placement: techniques to increase the quantity and quality of spawning habitat.
- Large wood complexes and log jams: Adding or trapping large wood in stream channels to provide improved morphological and biological conditions and to replace historical wood that was removed (Figure 65).
- Cross vane and W-weirs: Rock weirs installed to maintain pool habitat and channel grade control (Figure 67).
- Log or rock bank vane: Bank vane installed to narrow channels, provide bank stabilization, and to maintain pool habitat (Figure 56, Figure 57, Figure 58).
- Bank-attached boulders, mid-channel boulders, and boulder clusters: Placement of large boulders (>3 ft in diameter), to produce more heterogeneous stream channel morphology and provide refuge from high velocities for fish (Reeves at al. 1991, Shen and Diplas 2010).
- Excavated pools in armored beds on meander bends, with helical flow providing pool maintenance.
- Constructed riffles: Engineered riffles designed to increase hydraulic complexity and habitat, restore fish passage, and stabilize mobile bed streams (Newbery et al. 2011).
- LUNKERS (Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids): Provide cover, refuge from high velocities, and bank stabilization; NRCS 2007, TS14O).
- Drop structures: Engineered structures to prevent upstream migration of non-native fish. Gabion and log weir structures need to be avoided, due to poor effectiveness (Thompson and Rahel 1998) and shorter longevity.

Guidance for some of these habitat-enhancing features is provided in the following sections, as well as in the Large Wood section above. Additional guidance and background material with respect to aquatic habitat enhancement and environmental flows are provided in:

- Wheaton et al. 2019 Low-Tech Process-Based Restoration of Riverscapes
- Watts, A. 2018 River Food Webs: Incorporating Nature's Invisible Fabric into River Management (Science Findings)
- Glenn et al. 2017 Effectiveness of environmental flows for riparian restoration in arid regions: A tale of four rivers
- Chen and Olden 2017 Designing flows to resolve human and environmental water needs in a dam-regulated river
- Schwartz 2016 Use of Ecohydraulic-Based Mesohabitat Classification and Fish Species Traits for Stream Restoration Design
- McKay and Fischenich 2016 Development and Application of Flow Duration Curves for Stream Restoration
- Fish Habitat Decision Support Tool: provides access to data, models, and prioritization tools for use with multiple fish habitat assessments (funded by the U.S. Fish and Wildlife Service)
- Novak et al. 2016 Protecting Aquatic Life from Effects of Hydrologic Alteration
- Pierce et al. 2013 Response of Wild Trout to Stream Restoration over Two Decades in the Blackfoot River Basin, Montana.
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Biron et al. 2011 (in Simon et al. 2011): Combining Field, Laboratory, and Three-Dimensional Numerical Modeling Approaches to Improve Our Understanding of Fish Habitat Restoration Schemes
- Newberry et al. 2011 (in Simon et al. 2011) Restoring Habitat Hydraulics with Constructed Riffles
- ODF ODFW 2010 Guide to Placement of Wood, Boulders and Gravel for Habitat Restoration
- Flosi et al. 2010 California Salmonid Stream Habitat Restoration Manual.

- Saldi-Caromile et al. 2004 Stream Habitat Restoration Guidelines (Washington State)
- Stewardson et al. 2004 Evaluating the Effectiveness of Habitat Reconstruction in Rivers.
- Sylte and Fischenich 2000 Rootwad Composites for Streambank Erosion Control and Fish Habitat Enhancement
- Fischenich and Morrow 2000 Streambank Habitat Enhancement with Large Woody Debris
- Fischenich and Seal 2000 Boulder Clusters
- Morrow and Fischenich 2000 Habitat Requirements for Freshwater Fishes
- Reeves at al. 1991 Rehabilitating and Modifying Stream Habitats (in Influences of Forest Rangeland Management on Salmonid Fishes and Their Habitats)

12.5 Longitudinal Connectivity

Fish and other aquatic organism passage is often included as an objective for stream restoration work, with road crossings and irrigation diversion weirs being common barriers. Passage is important, since anadromous fish require passage to complete their lifecycles and freshwater fish populations need habitat diversity to flourish, with isolated populations more vulnerable to disturbances, such as drought, fire, debris flows, and floods.

Studies have shown that fish often have extensive ranges. For example, cutthroat trout have been observed moving downstream during the onset of winter in the Middle Fork Salmon River by an average of 57 miles (91 km), have been found to migrate 1 to 45 miles (2 to 72 km) on the Blackfoot River on spawning runs, and, on smaller streams, migrations of 1.1 miles (1.8 km) have been measured (Young 2008). Short, isolated reaches often lack critical resources, such as deep pools for refuge from peak summer temperatures and winter refuge from ice. Fish passage allows populations to move to locations where conditions are most suitable.

Longitudinal disconnections in flow can occur where streams dry in reaches along their length, especially in arid and semi-arid ecosystems (intermittent and ephemeral streams). Additionally, some regions may be subject to drying climates with climate change, which may cause an increase in the number and length of dry reaches and could be a concern for longitudinal connectivity throughout a watershed (Jaeger and Olden, 2014). The availability of continuous water along a restoration reach, especially for fish habitat restoration, is an important component of environmental flows (See above section).

Fish passage barriers also result from a variety of proximate anthropogenic causes. *Road crossings* provide substantial and numerous barriers to fish

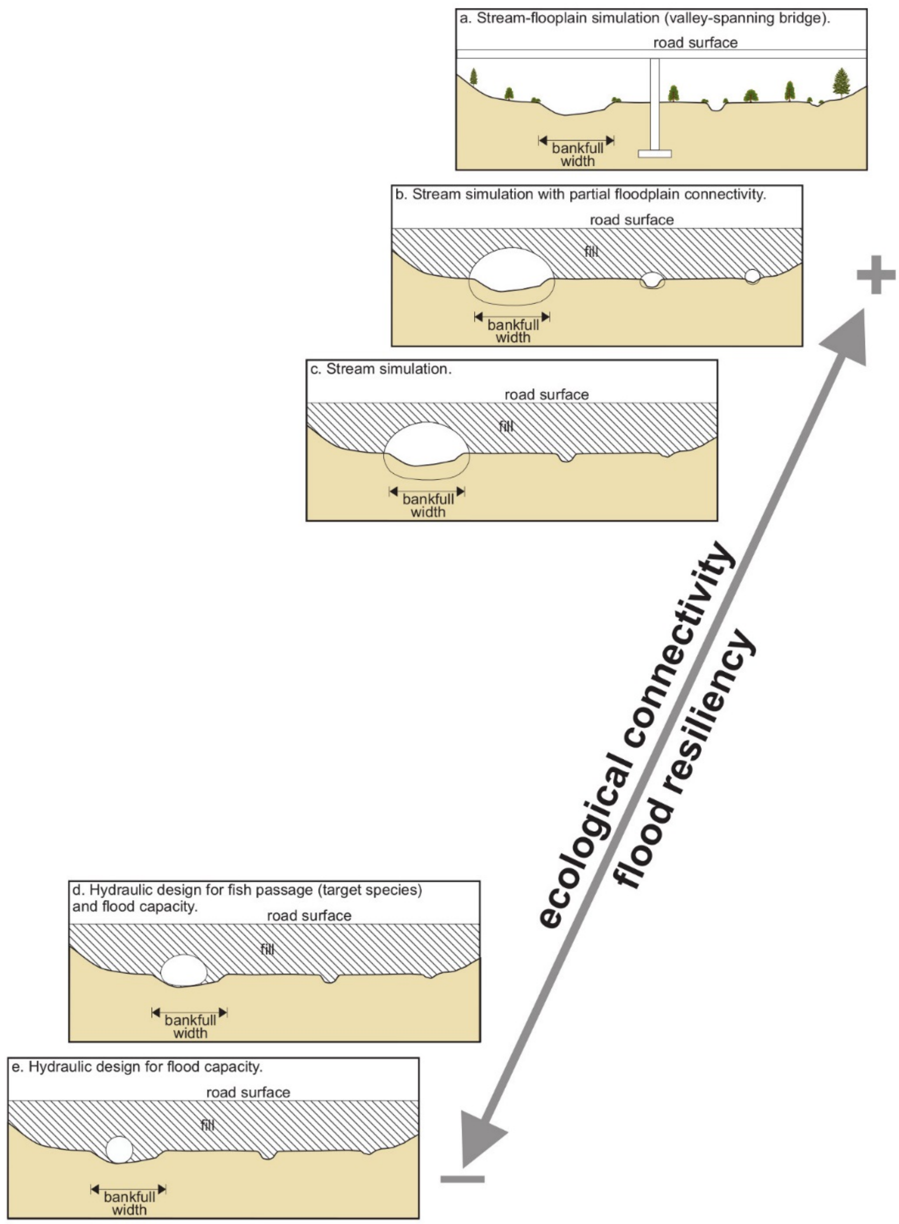


Figure 48: Spectrum of road crossing impacts upon aquatic organism passage and flood resiliency (graphic courtesy of Dan Cenderelli).

connectivity. The primary barrier mechanism to upstream passage is high velocity, though shallow depth is also relevant (Warren and Pardew 1998). Crossings that most substantially alter flow from natural conditions may cause the most substantial barriers, which provides a conceptual model for passage design. Figure 48 provides examples of a spectrum of impacts of various types of road crossings upon stream channels, from both aquatic organism passage and flood resiliency perspectives.

Fish passage barriers from *irrigation diversion dams* can also be pervasive. For example, the upper Rio Grande between Del Norte and Alamosa has 23 diversions, at a spacing of 2 miles (3 km) on average. This is typical for many Rocky Mountain streams. Additionally, *whitewater parks*, for instream kayaker recreation, feature constricted flow and high velocities that can induce a partial barrier (by size class) to fish passage (Fox et al. 2016).

To gain understanding of how fish attempt to cope with barriers and use fish passage structures, it can be helpful to "think like a fish." As discussed in Williams et al. 2012, in slow flowing streams migrating fish may likely distribute across the channel. However, as velocity in flowing streams increases, due to increased gradient or obstructions, upstream migrants tend to swim in the vicinity of the channel edges, near the bank or bed. These upstream-migrating fish hence seek areas with higher velocity gradients. In contrast, downstream migrants tend to swim in regions with the highest channel velocities, with the lowest velocity gradients. Different species have different swimming capabilities, leading to different design requirements for passage structures.

To reduce road crossing barriers, the replacement of traditional culverts with open-bottom arches and box structures, and bridges is recommended. When culverts are necessary, velocity and length are both relevant (Warren and Pardew 1998), with higher velocities mitigated to an extent by shorter culverts (Belford and Gould 1989). Additionally, elimination of outlet drops (Figure 49), the installation of a removable fishway (Clancy and Reichmuth 1990) or baffles (MacDonald and Davies 2007), and non-circular or open-bottom culverts with wide and natural bed conditions can all be helpful in reducing barriers. The stream simulation method, a procedure for providing natural-bed channel conditions through culverts, was developed by the USFS to provide aquatic organism passage (USFS 2008).

Figure 49: Culvert outlet drop, with Coho.

To reduce the impact of diversion barriers, several options are available including diversion consolidation; construction of a diversion weir type that reduces velocity and rate of water surface drop, such as a cross-vane; the installation of a bypass structure when the diversion is not needed; the use of an infiltration gallery or pumped diversion; and the addition of a properly-maintained fish passage structure (Figure 50; Schmetterling et al. 2002).

Figure 50: Pool and weir fishway.

Helpful references discussing barriers and methods for establishing longitudinal connectivity include:

- Martin 2018 Assessing and Prioritizing Barriers to Aquatic Connectivity in the Eastern United States
- Dodd et al. 2018 Win, win, win: Low cost baffle fish pass provides improved passage efficiency, reduced passage time and broadened passage flows over a low head weir
- Baki et al. 2016 Flow Simulation in a Rock-Ramp Fish Pass
- Barnard et al. 2013 Water Crossing Design Guidelines (Washington State)
- Axness and Clarkin 2013 Planning and Layout of Small Stream Diversions (USFS)
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Bunt et al. 2012 Performance of Fish Passage Structures at Upstream Barriers to Migration
- Newberry et al. 2011 (in Simon et al. 2011) Restoring Habitat Hydraulics with Constructed Riffles
- Flosi et al. 2010 California Salmonid Stream Habitat Restoration Manual.
- FishXing: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings
- Mooney et al. 2007 Rock Ramp Design Guidelines (USBR)
- Ficke and Myrick 2007 Fish Barriers and Small Plains Fishes – Fishway Design Recommendations and the Impact of Existing Instream Structures
- NRCS 2007, TS-14N Fish passage and screening design
- MacDonald and Davies 2007 Improving the upstream passage of two galaxiid fish species through a pipe culvert
- Clarkin et al. 2005 National Inventory and Assessment Procedure For Identifying Barriers to Aquatic Organism Passage at Road-Stream Crossings
- Saldi-Caromile et al. 2004 Stream Habitat Restoration Guidelines (Washington State)
- Bates et al. 2003 Design of Road Culverts for Fish Passage
- DVWK 2002 Fish Passes – Design, Dimensions and Monitoring.
- Bates 2000 Fishway Guidelines for Washington State.
- Clay 1995 Design of Fishways and Other Fish Facilities
- Clancy and Reichmuth 1990 A detachable fishway for steep culverts

Tutorials and webinars discussing road crossing barriers and mitigation:

- Restoring river continuity: methods and open challenges (Wetlands International, 12/2017-2/2018)
- Stream Simulation Culvert Design and Performance – A USFS Perspective (Dan Cenderelli, Mark Weinhold, Paul Anderson, 2013)
- RESTORE (Episode 10): Aquatic Organism Passage Restoration USFS Region 5 (California) summary of barrier removal
- A Tutorial on Field Procedures for Inventory and Assessment of Road-Stream Crossings for Aquatic Organism Passage (Michael Love, Ross Taylor, Susan Firor, Michael Furniss)
- Culvert Case Studies: From here and there (Mark Weinhold)
- The Biology of Culvert Barriers: The Biology of Assessment, Monitoring, and Research of Aquatic Organism Passage at Culverted Road-Stream Crossings (8 presentations; 2003)

In situations where species isolation is necessary, for example to isolate cutthroat trout from introduced species, fish passage barriers are required. In a study of the success and failure of Greenback Cutthroat trout translocations, almost half of the failed projects were unsuccessful due to reinvasions by non-native salmonids (Harig et al. 2000). For barriers to be effective, they must prevent species from jumping over the obstacle, from swimming around the obstacle during high flows, or from swimming through the obstacle, through interstitial spaces (such as in gabions). A key component of an effective barrier includes a splash pad, to minimize fish acceleration.

12.6 Fish Screening

In addition to diverting water, stream diversions can also divert a substantial amount of adult and juvenile fish, resulting in high mortality (Burgi et al. 2006; Roberts and Rahel 2008). This is especially problematic with threatened and endangered fish. Fish screens (Figure 51) allow the diversion of water without the accompanying fish and allow the safe return of the fish to their stream of origin.

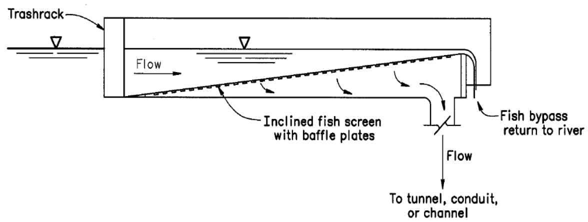


Figure 51: Fixed, inclined fish screen (courtesy Burgi et al. 2006).

Types vary substantially and include vertical fixed plate screens, non-vertical fixed plate screens, vertical traveling screens, rotary drum screens, pump intake screens, and infiltration galleries.

Resources available for designing fish screening facilities for stream diversions include:

- Ercan et al. 2016 Hydraulics Near Unscreened Diversion Pipes in Open Channels: Large Flume Experiments
- Befford 2013 Pocket Guide for Screening Small Water Diversions
- Axness and Clarkin 2013 Planning and Layout of Small Stream Diversions (USFS)
- Mesa et al. 2010 Biological Evaluations of an Off-Stream Channel, Horizontal Flat-Plate Fish Screen: The Farmers Screen.
- NRCS 2007, TS-14N Fish Passage and Screening Design
- Burgi et al. 2006 Fish Protection at Water Diversions: A Guide for Planning and Designing Fish Exclusion Facilities
- Nordlund and Bates 2000 Fish Protection Screen Guidelines for Washington State

Vendors of fish screening equipment include:

- Farmers Screen (FCA)
- Hydrolox traveling fish screens
- Intake Screen Inc (ISI)

12.7 Beavers and Beaver Dam Analogs

Through their dam-building activities, North American beavers (*Castor canadensis*) can cause a great deal of morphological and ecological changes in riparian corridors (Figure 52). The conversion of single thread channels to multi-thread within beaver-meadow complexes can reflect a stable state that has been frequently dominant within the historical range of variability of many stream valleys. For millions of years beaver played a major role as a geomorphic agent in floodplain development and salmonid evolution. However, beavers were extirpated from many watersheds across North America by trapping activities in the 17th, 18th and 19th centuries.

The conversion of land from terrestrial to wetland behind beaver ponds alters sediment transport, nutrient cycling, and vegetative succession (Westbrook et al. 2011). These changes can be to the benefit of the riparian ecosystem, potentially supporting stream restoration project objectives. Specifically, beavers ponds can increase baseflow, reduce bank erosion, collect sediment, reduce phosphorus levels, reduce daily temperature fluctuations, and increase mean temperature (potentially increasing temperature to more optimal levels in high-elevation streams). Beaver activity can also increase willow cover; beaver introduction and dam building activities increase water table elevations, create side channels, and distribute willow cuttings that can then propagate asexually throughout the expanded willow-favored landscape (Burchsted et al. 1010, McColley et al. 2012). Additionally, the construction and failure of beaver dams, which promote geomorphic diversity, has been associated with increased cutthroat trout redd construction (Bennett et al. 2014) Beaver ponds can also provide overwinter habitat by providing refugia from winter ice (Collen and Gibson 2001).

However, the potential negative consequences of beaver ponds include increased mean temperatures (potentially displacing salmonids in lower-elevation streams), reduced dissolved oxygen, increased evaporation, loss of spawning sites (in the ponds), and possibly causing barriers to some species of fish during low flow (Collen and Gibson 2001). Additionally, there is concern by some regarding negative impacts on water rights, with the State of Utah limiting beaver dam analog implementation over such concerns.

Considering disturbed landscapes and the historic extirpation of beavers from their pre-trapping range, it can be challenging to understand potential favorable habitat of beavers across large landscapes. To assist with this issue, a framework for understanding the capacity of riverscapes to support beaver dams has been developed (Macfarlane et al. 2017). Such modeling can be valuable for land management purposes.

Figure 52: Beaver-dominated stream corridor (photo credit: Barry Southerland).

Background information and guidance for the incorporation of beavers and beaver-like structures into stream restoration projects include:

- ASWM Beaver Webinar Series 2020: The History of Beaver and the Ecosystem Service They Provide
- Wheaton et al. 2019 Low-Tech Process-Based Restoration of Riverscapes
- Shields et al. 2019 A Tool for Beaver Dam Analog Design
- Pollock et al. 2017 The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains
- Cheap and Cheerful Stream and Riparian Restoration: Beaver Dam Analogues as a Low-cost Tool (NRCS webinar)
- Hafen and Macfarlane 2016 Can Beaver Dams Mitigate Water Scarcity Caused by Climate Change and Population Growth? (StreamNotes)
- Macfarlane et al. 2014 The Utah Beaver Restoration Assessment Tool: A Decision Support and Planning Tool

- Beaver Dam Flow Device Training Training video, by Animal Protection of New Mexico
- The Beaver Solution, by the Lands Council
- Beavers: Wetlands and Wildlife Educational not-for-profit for educating people about beavers
- Beaver Wiki Shared information on the impacts and benefits of beavers in streams
- Bring Back the Beaver Campaign Occidental Arts and Ecology Center
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- DeVries et al. 2012 Emulating Riverine Landscape Controls of Beaver in Stream Restoration
- Burchsted et al. 1010 The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters
- Saldi-Caromile et al. 2004 Stream Habitat Restoration Guidelines (Washington State)

While oftentimes beneficial to riparian ecosystems, beaver can be frustrating for landowners and agricultural producers. Beavers' instinctual tendency to block trickling water is often in conflict with such structures as irrigation diversions and road culverts. Additionally, while sub-irrigation of meadows by beaver activity can be highly beneficial for hay production, pond and associated groundwater levels need to be limited, and often reduced for harvest.

Beaver deceivers, a fence that discourages damming due to its large perimeter (Figure 53), and beaver bafflers, a cylindrical wire mesh or perforated pipe device that provides stage control (Figure 54) can be valuable methods for inhibiting dam construction and maintaining or altering water levels. They function by eliminating the trickling sound that beavers instinctually block, or by preventing beaver access. Beaver deceivers need to have a substantial perimeter length; otherwise they will still be blocked, while beaver bafflers can require high maintenance in streams with substantial amounts of fine sediment that can block the inlet perforations.

References helpful for designing such structures include:

- Pollock et al. 2017 The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains
- Boyles and Savitzky 2008 An Analysis of the Efficacy and Comparative Costs of Using Flow Devices to Resolve Conflicts with North American Beavers Along Roadways in the Coastal Plain of Virginia.
- Simon 2006 Solving Beaver Flooding Problems through the Use of Water Flow Control Devices.
- Langlois and Decker 2004 The Use of Water Flow Devices in Addressing Flooding Problems Caused by Beaver in Massachusetts.
- Brown et al. 2001 Control of Beaver Flooding at Restoration Projects
- Fentress 1997 An Improved Device For Managing Water Levels in Beaver Ponds
- Clemson University 1994 The Clemson Beaver Pond Leveler

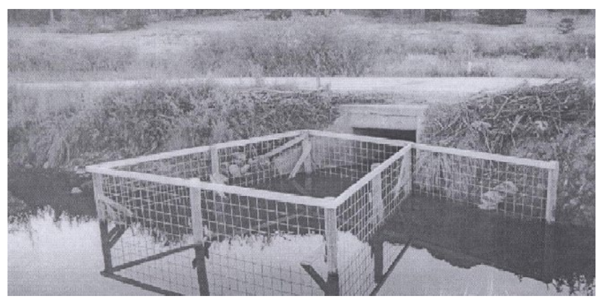


Figure 53: Beaver deceiver (Brown et al. 2001).

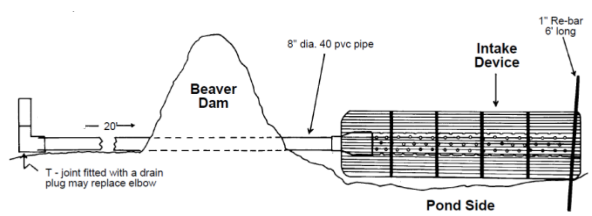


Figure 54: Beaver baffler (Clemson University 1994).

12.8 Bank Stabilization

Excessive bank erosion is a stream impairment that practitioners are oftentimes asked to address, with bank stabilization being a fundamental treatment for reducing excessive erosion rates and resulting sediment loads. However, bank erosion is a normal process in alluvial streams and fixing a stream in place so that it can no longer migrate can have undesirable consequences. Rather than fixing a stream in place, substantial reduction in banks erosion rates is oftentimes the most realistic and appropriate focus of bank stabilization projects. To this end, defining the acceptable rates of bank erosion is an important consideration when setting objectives and developing project designs.

There are two primary processes involved in bank erosion: hydraulic force and geotechnical failure. Hydraulic force is erosion induced by near-bank shear and steep velocity gradients, as is found at the outer banks of meander bends, while geotechnical failure is often caused by reduced bank strength, soil piping, and undercutting (Knighton 1998). The primary bank instability mechanism involved in a project needs to be identified to assure the most appropriate remediation measure is implemented. Streambank stratigraphy, including the relationship between textural changes in the bank profile and cohesive properties of the soil layers, will help the designer plan more effective bank stabilization measures. This principle applies to both vegetative and structural stabilization measures.

There are numerous types of protruding streambank stabilization structures, including stream barbs, vanes, bendway weirs, spur dikes, and log jams. Description of the various types of structures are included in NRCS (2007) TS-14H, Radspinner et al. (2010), and Biedenharn et al. (1997). In general, they act as deflectors, in that they deflect flow velocities and sediment. Through this deflection, they induce flow resistance and energy dissipation. Stream barbs, vanes, and bendway weirs tend to shift the secondary currents in channel bends (helicoidal flow patterns) away from the banks by forcing overtopping flow perpendicular to the structure alignment, decreasing near-bank flow velocity. These reduced velocities allow planting and recruitment of bank vegetation, enhancing bank stability. However, a common unintended consequence of protruding streambank stabilization structures is shifts in the channel thalweg causing altered downstream meander translation. Hence, the use of streambank stabilization structures may force the need for additional structural streambank stabilization downstream, which in turn can induce additional bank erosion even further downstream.

Besides protruding streambank stabilization measures, longitudinal bank stabilization features are also commonly implemented. Such structures include toe wood and soil bioengineering practices, as well as rock walls and rip rap.

Bank stabilization structures can have direct negative impacts on recreational water users. Guidance for addressing recreational boating needs is provided in Colburn 2012.

A principle cause of streambank instability is insufficient vegetative cover. Root systems can reinforce bank material up to 20,000 times more than equivalent sediment without vegetation (Knighton 1998), with vegetative condition explaining much of the variability in bank erosion rates.

Reflecting this natural process, bank stabilization can be most affectively addressed through a combination of both structures and vegetation. Structures can provide immediate relief to excessive erosion rates while vegetation can be more enduring for bank stabilization in the longer term. Hence, a bank stabilization strategy can be viewed as two pronged, with structures that minimize impairments to vegetative growth used to provide shorter term stabilization and vegetative planting implemented to provide minimized erosion rates for the longer term. Such a method also provides greater aquatic habitat benefits.

Bank stabilization structures are most-commonly constructed primarily of rock or wood, though various engineered products are also available. Both rock and wood have advantages and disadvantages. Rock is more enduring but susceptible to shifting and resulting loss of function, and can impair growth of riparian vegetation. Wood can be more native to a project site, can be more beneficial to aquatic biota, and can be a more flexible material to work with during construction, but is susceptible to buoyant forces and decay.

Both rock and log bank protection measures can require the use of filters, such as geotextile filter fabric, to reduce structural porosity and material piping through the structure. Cable and rebar are also incorporated into structures in places. However, there are legacy issues that can arise when introducing synthetic geotextiles, cable, and rebar into a fluvial setting. The long-term fate of such materials should be a consideration.

When planning the use of any structural measures in stream restoration projects, it is essential that geomorphic processes and project objectives are first considered before specific structural measures are planned. Oftentimes, professionals have a tendency to default to specific structure types without full consideration of the geomorphic context and suitability for a specific project. Additionally, this tendency can lead to bias for or against specific features, potentially excluding the best remediation practice for a specific circumstance. This practice has led to many inappropriate or less effective designs being implemented.

Terminology describing the various types of deflectors can be confusing and, sometimes, conflicting. Additionally, other types of bank stabilization methods are used in stream restoration projects, including woody armoring revetments, such as root wads, toe wood, and logs; soil bioengineering; log jams, rock walls; and rip rap. Descriptions and references for the various types of bank stabilization methods are discussed in the following sections.

General guidance for bank protection measures are provided below:

- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Colburn 2012 Integrating Recreational Boating Considerations Into Stream Channel Modification & Design Projects
- NCHRP 2004: Environmentally Sensitive Channel- and Bank-Protection Measures.

12.8.1 Stream Barbs

Stream barbs are low dike structures (Figure 55), with tops surfaces that slope from the bank into the channel and extend from the bank no more than 1/3 of the channel width. They are typically angled into the oncoming flow, which diverts flow away from the bank as the flow passes over the structure. Barbs can be constructed of graded riprap (solid) or arrangement of individual boulders (porous). Besides the benefit of reducing near-bank velocities, they can also enhance habitat through creating and maintaining scour pools immediately downstream of the structures. Design guidance for stream barbs is provided in:

- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- NRCS 2007, TS-14H Flow Changing Techniques
- NRCS 2007, TS-14C Stone Sizing Criteria
- Welch and Wright 2005 Design of Stream Barbs
- Castro and Sampson 2001 Design of Stream Barbs

Figure 55: Stream barb (courtesy Jon Fripp).

12.8.2 Vanes

Vanes are a subcategory of barbs. Vanes (Figure 56, Figure 57, Figure 58) are implemented with an upstream orientation of 20 to 30 degrees from the tangent to the bank line, have a crest elevation at or just below the bankfull level of the bank, and slope at 2 to 7 degrees dip towards the tip. Dip angle increases with increasing stream slope and bed material size. Vanes can be constructed of either rock or logs, or a combination. Design guidance for vanes is provided in:

- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- Bhuiyan et al. 2010: Bank-Attached Vanes for Bank Erosion Control and Restoration of River Meanders
- Bhuiyan et al. 2009 Effects of Vanes and W-Weir on Sediment Transport in Meandering Channels
- NRCS 2007, Chapter 11 Rosgen Geomorphic Channel Design
- NRCS 2007, TS-14G Grade Stabilization Techniques
- NRCS 2007, TS-14H Flow Changing Techniques
- NRCS 2007, TS-14C Stone Sizing Criteria
- NRCS 2007, TS-14J Use of Large Woody Material for Habitat and Bank Protection
- Johnson et al. 2001 Use of Vanes for Control of Scour at Vertical Wall Abutments

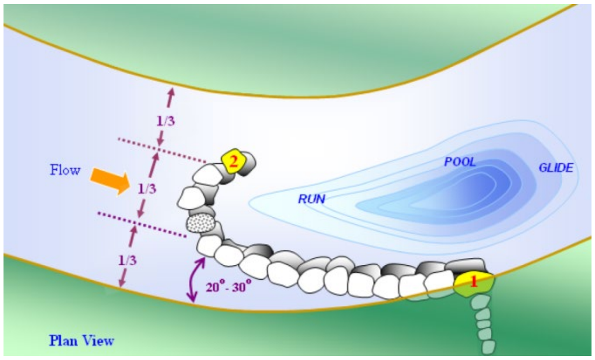


Figure 56: J-hook vane (NRCS 2007).

Figure 57: Log vanes at low flow providing bank stabilization and channel narrowing 2 years after construction (Milk Creek, Colorado).

Figure 58: Log J-hook vane providing bank stabilization and pool scour 4 years after construction (Pisgah National Forest, North Carolina; photo credit: Brady Dodd).

12.8.3 Bendway Weirs

Bendway weirs are rock structures with flat to slightly sloped surfaces (from the bank towards the thalweg) that generally extend from 25% to 50% of the channel width from the bank into the channel (Figure 59; Radspinner et al. 2010). Since these structures protrude further into the channel than barbs, their spacing tends to be further apart. Due to their longer lengths, they are less appropriate than barbs in small radius bends (Radspinner et al. 2010). Bendway weirs are oriented upstream at angles typically between 50 and 80 degrees to the bank tangent (NRCS 2007, TS14H). Design guidance is provided in:

- Abt et al. 2016: Bendway Weir Riprap Sizing Criteria
- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Kinzli and Thornton 2009 Predicting Velocity in Bendway Weir Eddy Fields
- NRCS 2007, TS-14H Flow Changing Techniques
- NRCS 2007, TS-14C Stone Sizing Criteria
- Julien and Duncan 2003 Optimal Design Criteria of Bendway Weirs from Numerical Simulations and Physical Model Studies
- Winkler 2003 Defining Angle and Spacing of Bendway Weirs

Figure 59: Bendway weir (Lagasse et al. 2009).

12.8.4 Spur Dikes

A spur dike is a protruding feature from the stream bank out into the channel, with a horizontal top surface that is typically above the high-flow water level. They are typically oriented perpendicular to the bank but can also be angled either upstream or downstream (Figure 60). Flow patterns and scour pool development in the vicinity of spur dikes, as well as other information relevant for design, are provided in:

- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Lagasse et al. 2009 Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance
- Kuhnle et al. 2008 Measured and Simulated Flow near a Submerged Spur Dike
- Fazli et al. 2008 Scour and Flow Field Around a Spur Dike in a 90° Bend
- NRCS 2007, TS14B Scour Calculations
- Kuhnle et al. 2002 Local Scour Associated with Angled Spur Dikes
- Kuhnle et al. 1999 Geometry of Scour Holes Associated with 90° Spur Dikes
- Copeland 1983 Bank Protection Techniques Using Spur Dikes

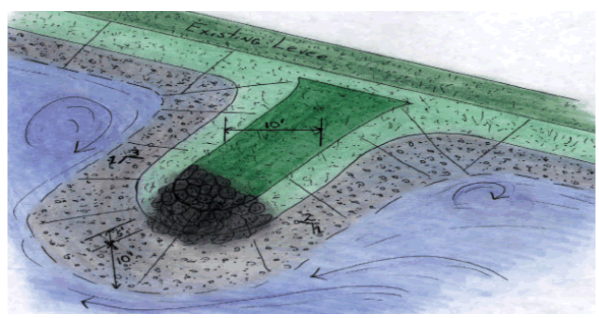


Figure 60: Spur dike (Walla Walla District USACE via Google Images).

12.8.5 Bioengineering

Streambank soil bioengineering (Figure 61, Figure 62) is a technology that uses engineering practices combined with ecological principles to assess, design, construct, and maintain living vegetative systems (NRCS 2007, TS14I). Bioengineering can be considered a good compromise between streambank erosion control and riparian biodiversity (Janssen et al. 2019), compared to more traditional civil engineering practices (riprap). A related methodology that uses similar approaches to stabilization is *Induced Meandering* (Zeedyk 2009; Zeedyk and Clothier 2009), which provides riparian restoration techniques for addressing incised stream channels.

In addition to the previous references provided for vegetation, references for the use of soil bioengineering in stream restoration projects include:

- Janssen et al. 2019: Soil Bioengineering Techniques Enhance Riparian Habitat Quality and Multi-Taxonomic Diversity in the Foothills of the Alps and Jura Mountains
- Recking et al. 2019 Design of Fascines for Riverbank Protection in Alpine Rivers: Insight from Flume Experiments
- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Giordanengo et al. 2016 Living Streambanks: A Manual of Bioengineering Treatments for Colorado Streams
- Rafferty 2016 Computational Design Tool for Evaluating the Stability of Large Wood Structures (NSAEC TN-103). Tool.
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- Soil Bioengineering Washington State Department of Transportation
- FEMA 2009 Engineering With Nature: Alternative Techniques to Riprap Bank Stabilization
- Zeedyk and Clothier 2009 Let the Water do the Work – Induced Meandering, and Evolving Method for Restoring Incised Channels
- NRCS 2007, TS-14I Streambank Soil Bioengineering
- Eubanks and Meadows 2002 A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization
- Hoag & Fripp 2002 Streambank Soil Bioengineering Field Guide for Low Precipitation Areas
- Sotir and Fischenich 2003 Vegetated Reinforced Soil Slope Streambank Erosion Control
- Allen and Fischenich 2001 Brush Mattresses for Streambank Erosion Control
- Allen and Fischenich 2000 Coir Geotextile Roll and Wetland Plants for Streambank Erosion Control

Figure 61: Installation of coir fascines (NRCS 2007, TS14I).

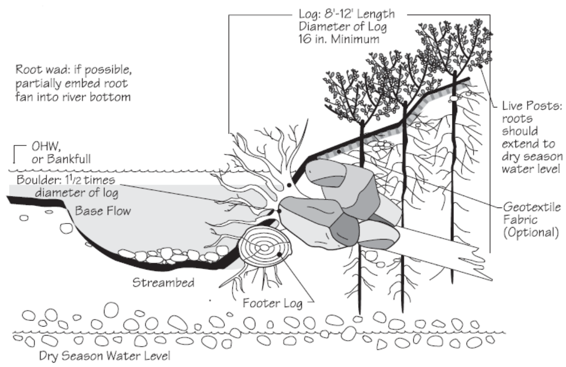


Figure 62: Rootwad with footer section (Eubanks and Meadows 2002).

12.8.6 Toe Wood

Toe wood is a method for constructing a bankfull bench or floodplain surface using primarily un-milled wood as the structural component, soil lifts to create the bankfull surface, and vegetation (Figure 63, Figure 64). These materials act in unison to create a stable matrix that provides a well armored constructed floodplain surface using natural materials. After vegetation is well established, toe wood will eventually degrade allowing for natural fluvial processes to continue at a slower rate. Toe wood can provide a substantial quantity of high-quality cover for fish.

The following references can be helpful for toewood design:

- USBR and ERDC 2016 National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure
- Rafferty 2016 Computational Design Tool for Evaluating the Stability of Large Wood Structures (NSAEC TN-103). Tool.
- Use of Wood in Stream Restoration NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Abbe and Brooks 2011(in Simon et al. 2011) Geomorphic, Engineering, and Ecological Considerations When Using Wood in River Restoration
- MN DNR 2010 Stream Restoration – Toe Wood-Sod Mat
- Sotir and Fischenich 2003 Vegetated Reinforced Soil Slope Streambank Erosion Control
- NRCS 2007, TS14J Use of Large Woody Material for Habitat and Bank Protection
- Shields et al. 2004 Large Woody Debris Structures for Sand-Bed Channels
- NRCS 2001 Incorporation of Large Wood Into Engineered Structures
- D'Aoust and Millar 2000 Stability of Ballasted Woody Debris Habitat Structures

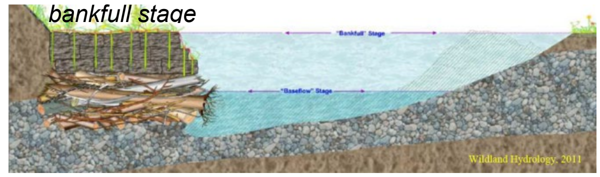


Figure 63: Toe wood cross section (Wildland Hydrology).

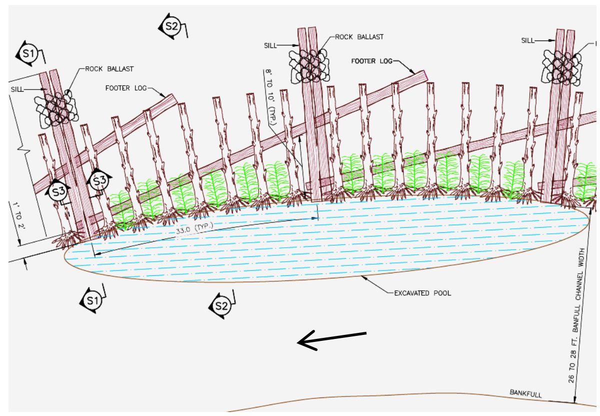


Figure 64: Two cells of a toe wood plan view. This configuration is intended for high-bank locations, with rock-ballasted sills embedded in the bank.

12.8.7 Log Jams

Log jams (Figure 65; similar to structures known as engineered log jams, large woody debris structures, and wood complexes) are log structures that deflect erosive flows, increase flow resistance, and promote sediment deposition. These structures also provide habitat for aquatic organisms. They compensate for stream reaches that are deficient of instream wood due to past practices. The large wood used in these structures includes whole trees with attached rootwads, pieces of trees with or without rootwads, and cut logs. Unlike many rock structures, such as stream barbs (Figure 55), log jams are permeable to flow.

In some situations, these structures can significantly raise local water surface elevations (especially if more debris is caught during a flood); this can be problematic or prohibited in some situations. These structures can cause unanticipated local bank erosion and shifts in the river thalweg (which may or may not be a problem), and may encourage avulsions in some situations. They can also be hazardous for recreational river users. If the material in these structures is mobilized, the wood can block downstream bridge or culvert openings.

Figure 65: Log jam (photo credit: Paul Powers).

The following references and tools can be helpful for the design of log jams:

- USBR and ERDC 2016 National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure
- Rafferty 2016 Computational Design Tool for Evaluating the Stability of Large Wood Structures (NSAEC TN-103). Tool.
- Bouwes et al. 2016 Adapting Adaptive Management for Testing the Effectiveness of Stream Restoration: An Intensely Monitored Watershed Example
- Use of Wood in Stream Restoration NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- Cramer 2012 Washington State Stream Habitat Restoration Guidelines
- Abbe and Brooks 2011 (in Simon et al. 2011) Geomorphic, Engineering, and Ecological Considerations When Using Wood in River Restoration
- Southerland 2010 Performance of Engineered Log Jams in Washington State: A Post-Project Appraisal
- NRCS 2007, TS14J Use of Large Woody Material for Habitat and Bank Protection
- Saldi-Caromile et al. 2004 Stream Habitat Restoration Guidelines (Washington State)
- Shields et al. 2004 Large Woody Debris Structures for Sand-Bed Channels
- NRCS 2001 Incorporation of Large Wood Into Engineered Structures
- D'Aoust and Millar 2000 Stability of Ballasted Woody Debris Habitat Structures

12.8.8 Rock Walls

Rock walls (Figure 66) can be an effective practice for toe armoring as well as high bank stabilization in constrained locations. References for the design of such structures include:

- NRCS 2007, TS-14K Streambank Armor Protection with Stone Structures
- NRCS 2007, TS-14M Vegetated Rock Walls

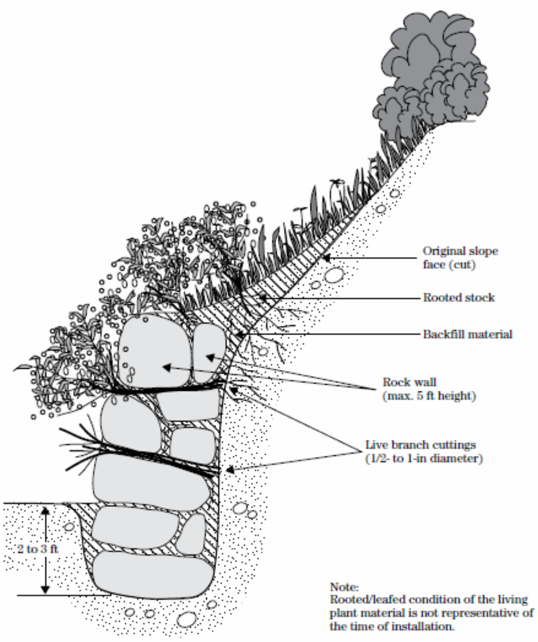


Figure 66: Vegetated rock wall (NRCS 2007, TS-14M).

12.8.9 Riprap

Riprap is a basic bank protection tool that can be used alone or in combination with other structural methods. Riprap is a needed bank stabilization tool in some situations, such as where infrastructure protection is required. The use of riprap should be minimized, since riprap has been found to decrease riparian tree species richness and simplify aquatic microhabitats (Janssen et al. 2019), and can impair vegetative growth and eliminate ecologically-important undercut banks for many decades (Thompson 2002). Generally, riprap is an ecological impairment in streams, by locally reducing sediment and wood input to stream channels, simplifying geomorphic complexity, and potentially causing local incision, bed material coarsening, and reduction in hyporheic exchange (Reid and Church 2015). However, riprap has been noted to be beneficial to some species in degraded systems or where little bank complexity already exists. Additionally, the negative impacts of riprap can be mitigated by burying the rock in an embankment and creating a floodplain and streambanks within a riparian zone beyond this line of riprap protection.

References available for designing and sizing riprap bank stabilization include:

- Baird et al. 2016: Bank Stabilization Design Guidelines (Bureau of Reclamation)
- Froehlich 2011 Sizing loose rock riprap
- Lagasse et al. 2009 Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance
- NRCS 2007, TS-14C Stone Sizing Criteria
- NRCS 2007, TS-14K Streambank Armor Protection with Stone Structures

12.9 Bed Stabilization and Stream Diversions

Grade control is a frequently-used component of stream restoration projects, to provide for bed stabilization. Incising streams can often lead to increased bank destabilization, since the incised streams increase bank height and lower water tables, changing the plant community composition to a type that provides lower bank stability. This mechanism is inherent in the channel evolution model, as described in the Preliminary Assessment section.

Channel spanning vanes and weirs are common grade control structures, with cross vanes (Figure 67) and large wood (Figure 68; Figure 69) structures provided as examples. Cross vane structures are also useful component for gravity-fed stream diversions. Bed stabilization structures can act as substantial barriers to some types of aquatic life passage; this should be accounted for in their application.

The development of step-pool bedforms in channels, through construction of steps or provision of armoring material, can also be an effective method of channel bed stabilization in small high-gradient channels, such as urbanizing watersheds with altered flow regimes. Additionally, bed stabilization in wet meadows has been successfully performed using riffle construction with heterogeneous-sized alluvial material as well as limited quantities of larger angular rock material (Figure 71; Medina and Long 2004).

A common task when using a cross vane or similar structure for a flow diversion is setting the elevation of the structure. It is necessary to build sufficient head to allow a stream diversion during low flow while, at the same time, minimizing drop that could cause barriers to aquatic life. A method to address this need is to select a minimum streamflow at which a specific diversion amount is needed and use a flow rating curve to set a vane elevation that allows the permitted diversion.

Figure 67: Cross vane on the Rio Blanco, CO (NRCS 2007, Ch11).

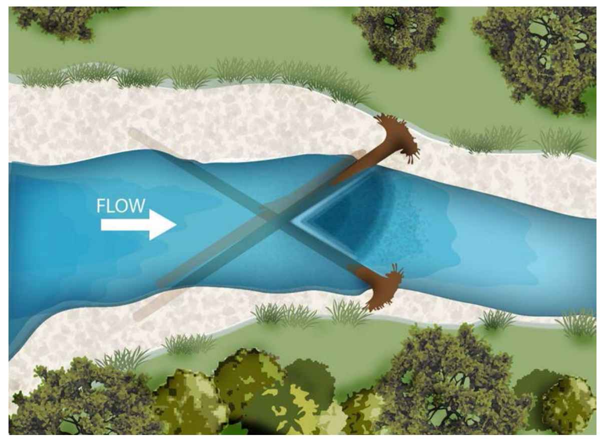


Figure 68: Large wood grade-control structure (Knutson and Fealko 2014).

Figure 69: Log "rock and roll" channel in the Trail Creek watershed, Colorado (USFS 2015).

For a U-type cross vane structure, the upstream water surface elevation can be estimated using a method developed by Holmquist-Johnson (2011) for discharges less than 2/3 bankfull:

$$h_{weir} = \left[\frac{Q}{4.386\sqrt{2g}\left(\frac{2}{3}W_u\right)\left(\frac{W_u}{Z_u}\right)^{-0.601}\left(\frac{L_t}{T_w}\right)^{-0.429}} \right]^{2/3}.$$

where h_{weir} is the depth of water over the weir (m) relative to the throat crest, Q is the discharge over the weir (m^3/s), g is acceleration due to gravity (m/s^2), and T_w is the channel top width (m, Figure 36). Z_u, the effective weir height (m), is computed as:

$$Z_u = \frac{1}{3}\left(\frac{(T_w - W_t)}{2}\frac{\tan\phi}{\sin\theta}\right) + Z_d$$

where W_t is the throat width (m), Z_d is the upstream drop height (m), θ is the arm angle, and ϕ is the arm slope (Figure 70). Also, L_t is the effective weir length along the structure crest (m), can be computed as:

$$L_t = W_t + 2\left(\frac{(T_w - W_t)}{2}\frac{1}{\sin\theta\cos\phi}\right)$$

and W_u, the effective weir width (m), is computed as:

$$W_u = W_t + 2\left(\frac{(Z_u - Z_d)\sin\theta}{Tan\phi}\right)$$

For discharges greater than 2/3 bankfull, the following equation was developed:

$$h_{weir} = \left[\frac{Q}{9.766\sqrt{2g}\left(\frac{2}{3}W_u\right)\left(\frac{W_u}{Z_u}\right)^{-0.73}\left(\frac{L_t}{T_w}\right)^{-0.359}} \right]^{2/3}.$$

These equations were developed using the results of 3-dimensional computational modeling and verified using both laboratory and field data.

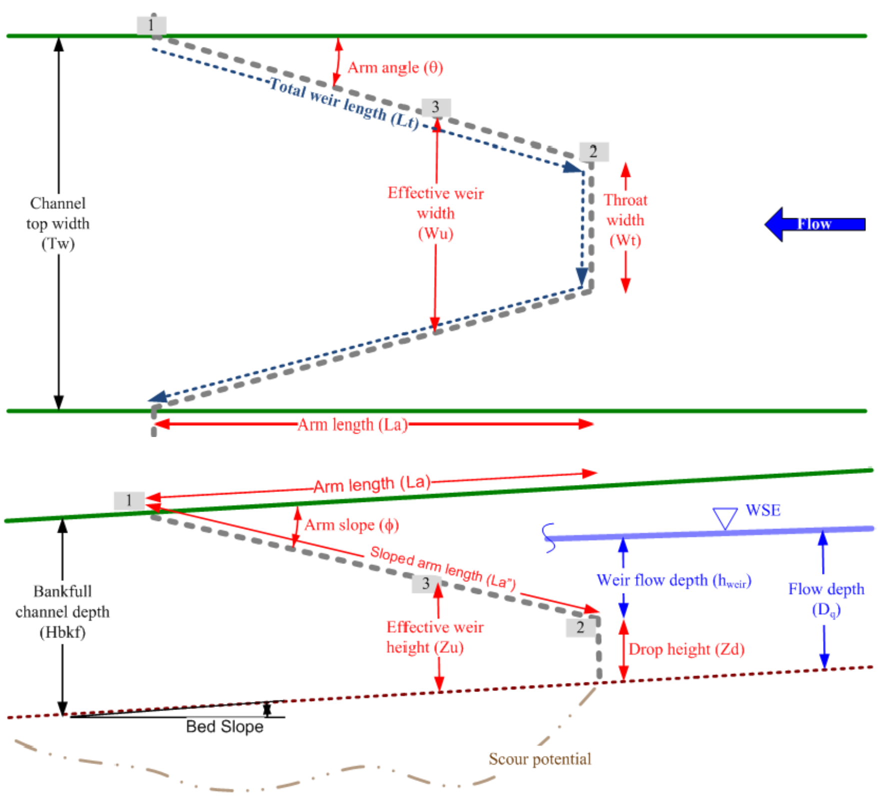


Figure 70: Variable descriptions for U-vane stage-discharge rating (Holmquist-Johnson 2011).

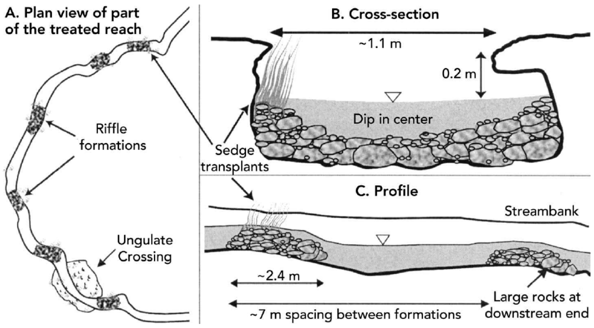


Figure 71: Bed stabilization in a wet meadow using constructed riffles (Medina and Long 2004).

References helpful for stream diversion structures and bed stabilization (including the development of step-pool channels) include:

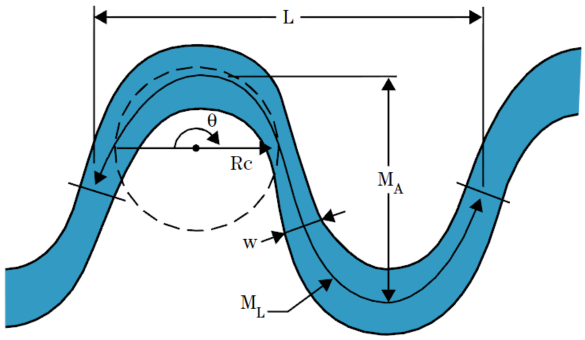
- Norman et al. 2017 Quantifying geomorphic change at ephemeral stream restoration sites using a coupled-model approach
- Knutson and Fealko 2014 Large Woody Material – Risk Based Design Guidelines
- Axness and Clarkin 2013 Planning and Layout of Small Stream Diversions (USFS)
- Colburn 2012 Integrating Recreational Boating Considerations Into Stream Channel Modification & Design Projects
- Scurlock et al. 2012 Equilibrium Scour Downstream of Three-Dimensional Grade-Control Structures
- Thomas et al. 2011 Effects of Grade Control Structures on Fish Passage, Biological Assemblages and Hydraulic Environments in Western Iowa Streams – A Multidisciplinary Review
- Thornton et al. 2011 Stage-Discharge Relationships for U-, A-, and W-Weirs in Un-Submerged Flow Conditions
- Zimmermann et al. 2010 Step-pool stability – Testing the jammed state hypothesis
- Chin et al. 2009 Linking Theory and Practice for Restoration of Step-pool Streams
- Holburn et al. 2009 Quantitative Investigation of the Field Performance of Rock Weirs
- Zeedyk and Clothier 2009 Let the Water do the Work – Induced Meandering, and Evolving Method for Restoring Incised Channels
- Vuyovich et al. 2009 Physical Model Study of Cross Vanes and Ice
- Bhuiyan et al. 2009 Effects of Vanes and W-Weir on Sediment Transport in Meandering Channels
- NRCS 2007, Ch11 Rosgen Geomorphic Channel Design
- NRCS 2007, TS14B Scour Calculations
- NRCS 2007, TS14G Grade Stabilization Techniques
- NRCS 2007, TS 14P Gullies and Their Control
- Chin and Phillips 2006 The Self-Organization of Step-Pools in Mountain Streams
- Medina and Long 2004 Placing Riffle Formations to Restore Stream Functions in a Wet Meadow
- Saldi-Caromile et al. 2004 Stream Habitat Restoration Guidelines
- Castro and Sampson 2001 Design of Rock Weirs

Additionally, the following website provides information on research performed on river-spanning rock structures in coordination with the U.S. Bureau of Reclamation:

- USBR: River-Spanning Rock Structures Research

12.10 Planform Design

Natural channels are inherently sinuous. Hence, channel relocations require the design of planform characteristics (Figure 72).



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

Figure 72: Schematic illustrating variables describing channel planform characteristics (NRCS 2007, Ch12).

Design guidance for developing appropriate planform geometry is provided in:

- NRCS 2007, Ch12 Channel Alignment and Variability Design.
- Soar and Thorne 2001 Channel Restoration Design for Meandering Rivers

12.11 Dam Removal

Dam removal (Figure 73) is increasingly being implemented as a primary approach for addressing such impairments as the lack of longitudinal connectivity for aquatic organisms, sediment, large wood, and particulate organic matter. Dams are commonly removed due to their age, loss of function, and obsolescence. Removals are often motivated by concerns (and Endangered Species Act listings) for anadromous fish, such as in the Pacific Northwest. Frequently the greatest concern (and expense) regarding removals is the fate of reservoir sediment, nutrients, contaminants, and organic matter after the dam breach.

Based on available studies on dam removals, a summary review by Foley et al. (2017) reached the following conclusions:

> *1) physical responses are typically fast, with the rate of sediment erosion largely dependent on sediment characteristics and dam-removal strategy; (2) ecological responses to dam removal differ among the affected upstream, downstream, and reservoir reaches; (3) dam removal tends to quickly reestablish connectivity, restoring the movement of material and organisms between upstream and downstream river reaches; (4) geographic context, river history, and land use significantly influence river restoration trajectories and recovery potential because they control broader physical and ecological processes and conditions; and (5) quantitative modeling capability is improving, particularly for physical and broad-scale ecological effects, and gives managers information needed to understand and predict long-term effects of dam removal on riverine ecosystems.*

Figure 73: Removal of the lower portion of Glines Canyon Dam, Washington, 7/1/2012 (photo courtesy of the National Park Service).

Bellmore et al. (2019) developed conceptual models that elucidate key physical and ecological responses to dam removals, upstream, at, and downstream of a removed dam and reservoir (Figure 74). They illustrate causal pathways and feedback loops among physical and biological mechanisms at play during recovery, to assist with project planning.

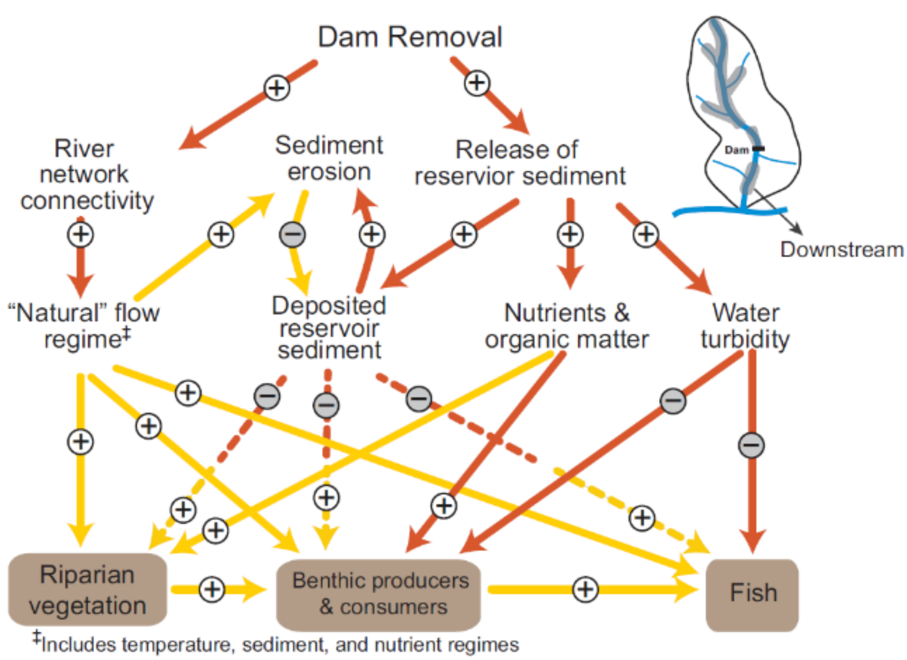


Figure 74: Causal loop diagram illustrating mechanistic links and feedback loops for locations downstream of a dam removal (Belmore et al., 2019).

The following websites have information of value when planning a dam removal project:

- Restoring river continuity: methods and open challenges Dam Removal Step by Step, Wetlands International (12/2017-2/2018)
- Dam Removal Information Portal U.S. Geological Survey
- Clearinghouse of Dam Removal Information Online repository for documents about proposed and completed dam removal projects (University of California at Riverside)
- Database of U.S. Dams Removed American Rivers
- Undamming the Elwha The Documentary, 2012 (Katie Campbell and Michael Werner)

Additionally, the following references provide information on dam removals for stream restoration:

- Bellmore et al. 2019 Conceptualizing Ecological Reponses to Dam Removal: If You Remove It, What Will Come?
- Randle and Bountry 2018 Dam Removal Analysis Guidelines for Sediment (Advisory Committee for Water Information, Subcommittee on Sedimentation)
- Foley et al. 2017 Dam removal: Listening in
- Oliver 2017 Liberated Rivers: Lessons From 40 Years of Dam Removal
- EPA 2016 Frequently Asked Questions on Removal of Obsolete Dams
- U.S. Society on Dams 2015 Guidelines for Dam Decommissioning Projects
- Graber et al. 2015 Removing Small Dams: A Basic Guide for Project Managers (American Rivers)
- FAQ on Dam Removal Frequently asked questions on the removal of obsolete dams, from the Environmental Protection Agency
- The Geomorphic Response of Rivers to Dam Removal (Gordon Grant)
- East et al. 2015 Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change.
- Wilcox et al. 2014 Rapid Reservoir Erosion, Hyperconcentrated Flow, and Downstream Deposition Triggered by Breaching of 38 m Tall Condit Dam, White Salmon River, Washington.
- Cannatelli and Curran 2012 Importance of Hydrology on Channel Evolution Following Dam Removal: Case Study and Conceptual Model
- Pearson et al. 2011 Rates and Processes of Channel Response to Dam Removal with a Sand-Filled Impoundment.
- Science Findings 2009 A Ravenous River Reclaims its True Course: The Tale of Marmot Dam's Demise.
- Hoffert-Hay 2008 Small Dam Removal in Oregon: A Guide for Project Managers
- EOEEA 2007 Dam Removal in Massachusetts: A Basic Guide for Project Proponents.
- Lenhart 2003 A preliminary Review of NOAA's Community-Based Dam Removal and Fish Passage Projects.
- Bednarek 2001 Undamming Rivers: A Review of the Ecological Impacts of Dam Removal.
- Smith et al. 2000 Breaching a Small Irrigation Dam in Oregon: A Case History.

13. SUMMARY

Guidance for stream restoration projects has been developed by a wide variety of practitioners and academics. This material is so extensive that it can be difficult for professionals to find the most relevant references available for specific projects. To assist practitioners sort through this extensive literature, this technical note has been developed to provide a guide to the guidance. Through the use of short literature reviews and hyperlinked reference lists, this technical note is a bibliographic repository of information available to assist professionals with planning, analyzing, and designing stream restoration projects.

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APPENDIX A: Table of Contents for NRCS Stream Restoration Design, NEH Part 654

NRCS 2007

Chapter:

APPENDIX B: Glossary of Fluvial Geomorphology Terms

Adapted from a compilation developed by Janine Castro, Paul Bakke, Rob Sampson, and others.

Aggradation: A persistent rise in the elevation of a streambed caused by sediment deposition.

Alluvial Fan: A gently sloping, usually convex landform shaped like an open fan or a segment of a cone, composed predominately of coarse-grained soils deposited by moving water. The stream deposits a fan wherever it flows from a narrow mountain valley onto a plain or broad valley, or wherever the stream gradient suddenly decreases. Being constructed of sediment transported by the stream, alluvial fans tend to be highly dynamic, with high rates of channel avulsion and rapid responses to channel obstructions or man-made alterations.

Alluvial Stream: Self-formed channels composed of clays, silts, sand, gravel, or cobble and characterized by the ability to alter their boundaries and their patterns in response to changes in discharge and sediment supply.

Anastomosing Channel: A channel that is divided into one or more smaller channels, which successively meet and then redivide. This channel type differs from a braided channel in that the islands separating sub-channels are relatively stable and well vegetated.

Anthropogenic: caused or influenced by human actions.

Armoring: The development of a coarse surface layer in a stream bottom. The gradual removal of fines from a stream, leaving only the large *substrate* particles, caused by a reduction in the sediment load. This is sometimes referred to as pavement.

Avulsion: A significant and abrupt change in channel alignment resulting in a new channel across the floodplain. Channel straightening or relocating, as well as the construction of dikes or levees, are common contributing factors in channel avulsions.

Bankfull Discharge: Sometimes referred to as the effective flow or ordinary high water flow. It is the channel forming flow. For most streams the bankfull discharge is the flow that has a recurrence interval of approximately 1.5 years in the annual flood series. Most bankfull discharges range between 1.0 and 1.8, though in some areas it could be lower or higher than this range. It is the flow that transports the most sediment for the least amount of energy.

Bar: Accumulation of sand, gravel, cobble, or other alluvial material found in the channel, along the banks, or at the mouth of a stream where a decrease in velocity induces deposition.

Attached – diamond-shaped bar with flow on one side and remnants of a channel on the floodplain side.

Diagonal – Elongated bodies with long axes oriented obliquely to the flow. They are roughly triangular in cross-section and often terminate in riffles.

Longitudinal – Elongated bodies parallel to local flow, of different shape, but typically with convex surfaces. Common to gravelly braided streams.

Point – Found on the inside of meander bends. They are typically attached to the streambank and terminate in pools.

Transverse – Typically solitary lobate features that extend over much of the active stream width but may also occur in sequence down a given reach of river. They are produced in areas of local flow divergence and are always associated with local deposition. Flow is distributed radially over the bar. Common to sandy braided streams.

Baseflow: Flow in a channel during periods between the runoff events, generated by moisture in the soil or groundwater.

Base Level of a Stream: The elevation below which a river can no longer erode, i.e. the level of its mouth.

Bedload: The part of a stream's sediment load that is moved on or immediately above the stream bed, such as the larger or heavier particles (boulders, cobbles, gravel) rolled along the bottom. The part of the load that is not continuously in suspension or solution.

Bed Material: The material of which a streambed is composed.

Bioengineering: An approach to strengthening the streambank soil or improving its erosion resistance by utilizing live plant materials, mostly woody shrubs and trees. Although non-living materials such as wood or fabric may also be part of the design, bioengineering technique relies mostly on the long-term integrity of the live plants and their rooting systems for its streambank stabilization function.

Braided Channel: A stream characterized by flow within several channels which successively meet and redivide, which are divided by unvegetated islands. Braiding may be an adjustment to a sediment load too large to be carried by a single channel or having insufficient riparian vegetation to maintain stable channel banks. Braided channels often occur in deltas of rivers or in the outflow from a glacier.

Channel: A natural or artificial waterway of perceptible extent that periodically or continuously contains moving water. It has a definite bed and banks which serve to confine the water.

Channel Confinement: Lateral constriction of a stream channel.

Channel Depth: The vertical distance from the bankfull elevation to the channel bed.

Channel Forming Flow: See "Bankfull Discharge."

Channelization: Straightening a stream or dredging a new channel into which the flow of the original channel is diverted.

Channel Scour and Fill: Terms used to define erosion and sedimentation during relatively short periods of time, whereas aggradation and degradation apply to similar processes that occur over a longer period of time. Scour and fill applies to events measures in minutes, hours, days, perhaps even seasons, whereas aggradation and degradation apply to persistent trends over a period of years or decades.

Channel Stability: A relative measure of the resistance of a stream to aggradation or degradation. Stable streams do not change appreciably from year to year. An assessment of stability helps determine how well a stream will adjust to and recover from mild to moderate changes in flow or sediment transport.

Channel Width: The horizontal distance along a transect line from bank to bank at the bankfull elevation, measured at right angles to the direction of flow.

Chute Cutoff: A new channel formed by the truncating of a meander bend across the floodplain. The channel flow bypasses the meander bend by cutting straight through it.

Colluvium: A general term for loose deposits of soil and rock moved by gravity.

Crossover: The point of inflection in a meander where the thalweg intersects the centerline of the stream. A riffle.

Cross-section: A line across a stream perpendicular to the flow along which measurements are taken.

Cross-Sectional Area: The area of a stream channel taken perpendicular to the channel centerline. Often taken at the bankfull elevation or top of bank for channel capacity.

Cubic Foot per Second (cfs): A unit of stream discharge. It represents one cubic foot of water moving past a given point in one second.

D_{50}, D_{84}, D_{100}: The particle size for which 50, 84 and 100 percent, respectively, of the sample is finer. D_{50} is thus the median size, while D_{100} is the maximum size. D_{84} represents one standard deviation above the median in a typical sediment size distribution, and thus is often used in design calculations to represent the population of "large" streambed particles.

Debris Fan: A gently sloping, usually convex landform shaped like an open fan or a segment of a cone, composed predominately of mixed-sized materials deposited by debris flows (landslides). Debris fans tend to form at the junctions of narrow mountain valleys and larger, broader valleys, or wherever the valley gradient suddenly decreases, allowing deposition. Being constructed of debris flow deposits, debris fans can be active or inactive (static), depending on current landslide rates. Inactive fans are characterized by highly incised channels and low avulsion rates. In contrast to alluvial fans, debris fans may be comprised of material too coarse to be readily mobilized by stream flow.

Degradation: The geologic process by which streambeds are lowered in elevation and streams are detached from their floodplains. Also referred to as entrenched or incised streams

Deposition: The settlement or accumulation of material out of the water column and onto the streambed or floodplain. This process occurs when the energy of flowing water is unable to transport the sediment load.

Discharge: Rate of flow expressed in volume per unit of time, for instance, in cubic feet per second or liters per second. Discharge is the product of the mean velocity and the cross-sectional area of flow. One cubic meter per second is equal to 35.3 cubic feet per second (cfs).

Dissolved Load: The chemical load contained in stream water; that acquired by solution or by decomposition of rocks followed by solution.

Drainage Area or Basin: The area so enclosed by a topographic divide that surface runoff from precipitation drains into a stream above the point specified.

Effective Discharge: The discharge responsible for the largest volume of sediment transport over a long period of record. Effective discharge is computed from long-term flow statistics and the sediment transport to discharge relationship. It is typically in the range of a 1- to 3-year flood event, and in many settings has been shown to correspond to the bankfull discharge.

Embeddedness: The degree to which boulders, cobble, or gravel are surrounded by fine sediment. This indicates the suitability of stream substrate as habitat for benthic macroinvertebrates and for fish spawning and egg incubation. Evaluated by visual observation of the degree (percent) to which larger particles are surrounded by fine sediment.

Energy Dissipation: The loss of kinetic energy of moving water due to channel boundary resistance; form resistance around such features as large rock, instream wood, and meanders; and spill resistance from flow dropping from steps.

Entrenchment: The vertical containment of a river and the degree in which it is incised in the valley floor. A stream may also be entrenched by the use of levees or other structures.

Entrenchment Ratio: Measurement of entrenchment. It is the floodprone width divided by the bankfull discharge width. The lower the entrenchment ratio the more vertical containment of flood flows exists. Higher entrenchment ratios depict more floodplain development.

Erosion: A process or group of processes whereby surface soil and rock is loosened, dissolved or worn away and moved from one place to another by natural processes. Erosion usually involves relatively small amounts of material at a time; but, over a long time periods, can involve very large volumes of material.

Fine Sediment: Clay, silt and sand sized particles.

Floodplain: The nearly flat area adjoining a river channel that is constructed by the river in the present climate and overflows upon during events greater than the bankfull discharge.

Floodprone Area: The active floodplain and the low terraces. Using the Rosgen methodology, the elevation of floodprone is qualitatively defined as 2 times the maximum bankfull depth.

Flow: The movement of stream water and other mobile substances from place to place. Syn: Discharge.

> **Baseflow** – see above.
>
> **Hyporheic Flow** – That portion of the water that infiltrates the stream bed and moves horizontally through and below it. It may or may not return to the stream channel at some point downstream. Also known as subsurface flow.
>
> **Instantaneous Flow** – The discharge measured at any instant in time.
>
> **Interstitial Flow** – That portion of the surface water that infiltrates into the stream bed and banks, and moves through the substrate pores.
>
> **Low Flow** – The lowest discharge recorded over a specified period of time; also known as minimum flow.
>
> **Mean Flow** – The average discharge at a given stream location, computed for the period of record by dividing the total volume of flow by the length of the specified period.
>
> **Minimum Flow** – The lowest discharge recorded over a specified period of time.
>
> **Peak Flow** – The instantaneous highest discharge recorded over a specified period of time.

Fluvial: Pertaining to streams or produced by stream action.

Geomorphic Equilibrium: The “sediment-transport continuity” of a stream, wherein the quantity and size of sediment transported into the reach is approximately the same as the quantity and size of sediment transported out of the reach. If a stream is in geomorphic equilibrium, the processes of bank erosion and channel migration will occur only gradually, such that the shape, profile and planform patterns remain similar over time.

Geomorphology: the scientific study of landforms and the processes that shape them.

Gradient (stream): Degree of inclination of a stream channel parallel to stream flow; it may be represented as a ratio, percentage, or angle.

Head Cut: A break in slope along a stream profile which indicates an area of active erosion. Niagara Falls is an example of a very large head cut. Also known as "Nick Point."

Hydraulic Geometry: A quantitative way of describing the channel changes in width, depth, and velocity relative to discharge.

Hydraulic Jump: An abrupt, turbulent rise in the water level of a flowing stream, occurring at the transition from shallow, fast flow to deeper, slower flow.

Hydraulic Radius: The cross-sectional area of a stream divided by the wetted perimeter. In relatively wide channels (width/depth > ~20), it is approximately equal to average depth.

Hydraulics: Refers to water, or other liquids, in motion and their action.

Hydrograph: A curve showing discharge over time.

Hyporheic Zone: The zone of saturated sediment adjacent to and underneath the stream. It is directly connected to the stream, and stream water continually exchanges into and out of the hyporheic zone as hyporheic flow.

Ice Types

Anchor Ice – Ice formed on the stream bed materials when, due to outward radiation in evening, they become colder than the water flowing over them.

Frazil Ice – Needle-like crystals of ice that are slightly lighter than water, but carried below the surface due to turbulence. This causes a milky mixture of ice and water. When these crystals touch a surface that is even a fraction of a degree below freezing, they instantly adhere and form a spongy, often rapidly growing, mass.

Hinge Ice – A marginal sheet of surface ice attached to the bank materials and extending toward the center of a stream but not spanning it completely.

Incised Channel: A stream channel that has deepened and as a result is disconnected from its floodplain.

Instream Wood: Wood material accumulated or placed in a steam channel, providing opportunity for habitat, and enhanced bedforms and flow resistance.

Invert: Refers to the bottom, inside surface of a pipe, log, or other object. Occasionally used to refer to the bottom or base elevation of a structure.

Laminar Flow: A flow, in which all particles or filaments of water move in parallel paths, characterized by the appearance of a flat, ripple free surface. In nature, this is only seen in very thin sheet flow over smooth surfaces (such as in parking lots) or in imperceptibly creeping flow (such as in the Florida Everglades). Opposite of turbulent flow.

Large Woody Debris (LWD): Any large piece of relatively stable woody material having a least diameter greater than 10cm and a length greater than 1 m that intrudes into the stream channel.

Longitudinal Profile: A profile of a stream or valley, drawn along its length from source to mouth; it is the straightened-out, upper edge of a vertical section that follows the winding of the stream or valley. A graph of the vertical fall of the stream bed or water surface measured along the course of the stream.

Manning's Roughness Coefficient: A measure of frictional resistance to water flow. Also called Manning's "n," it is defined by Manning's equation for flow in open channels.

Mean Annual Discharge: Daily mean discharge in units per second averaged over a period of years.

Meander: A reach of stream with a ratio of channel length to valley length greater than 1.5. By definition, any value exceeding unity can be taken as evidence of meandering, but 1.5 has been widely accepted by convention.

Meander Pattern: A series of sinuous curves or loops in the course of a stream that are produced as a stream shifts from side to side over time across its floodplain.

Near Bank Region: Sometimes referred to as the terrace side of the stream or the concave bank side or the top of the meander wave. This bank area is opposite the point bar and most susceptible to erosion. This area is referred to sometimes as the near bank region because it is the location in the channel where the thalweg come closest to the bank.

Neck Cutoff: The loss of a meander resulting from an avulsion across the intervening land separating adjacent meander bends.

Nick Point: See "headcut."

Particle Size Distribution: The composition of the material along the streambed is sampled; from this sample a plot of particle size or weight versus frequency in percent is plotted.

Planform: The characteristics of a river as viewed from above (in an aerial photo, on a map, etc.), which are generally expressed in terms of pattern, sinuosity (channel length/valley length) and individual meander attributes such as amplitude, wavelength and radius of curvature.

Point Bar: Usually the side opposite the concave bank. The point bar is the depositional feature that facilitates the movement of bedload from one meander to the next. The point bar extends at the loss of the near bank region.

Pool: A portion of the stream with reduced current velocity (during base flow), with deeper water than adjacent areas.

Radius of Curvature: radius of a curve fitting a stream channel's thalweg planform.

Reach: (a) Any specified length of stream. (b) A relatively homogeneous section of a stream having a repetitious sequence of physical characteristics and habitat features. (c) A regime of hydraulic units whose overall profile is different from another reach.

Recurrence Interval: Interchangeably used with "return period"; a statistic based on frequency analysis derived from annual or partial duration peak flow series that describes the average interval (in years) between events equaling or exceeding a given magnitude.

Reference Site (Stream Geomorphology Context): The reference site is a stable morphological stream type in the system. This type may- or may not- be in a pristine state. The majority of time it is not pristine; however, the important geomorphologic, and most likely vegetative components, are there to sustain a long-term stable stream type. The reference site would fall within the range of natural variability for geomorphic type and bedload transport.

Riffle: A shallow, rapid section of stream where the water surface is broken into waves by obstructions that are wholly or partly submerged.

Riparian: Relating to or living on or near the bank of a watercourse. These zones range in width from narrow bands in arid or mountainous areas to wide bands which occur in low-gradient valleys and more humid regions.

Roughness Element: Large obstacles in a channel that deflect flow and affect a local increase in shear stress, causing scour and deposition.

Salmonids: a family of ray-finned fish (Salmonidae), including salmon, trout, and chars.

Scour: The process of mobilizing and transporting away material from the bed or banks of a channel through the action of flowing water. Scour can result in erosion if the scoured material is not replaced by material transported in from upstream.

Sediment: Any mineral or organic matter of any size in a stream channel. Sizes:

Name	Size (mm)	Size (inches)
boulder	>256	>10
cobble	64 - 256	2.5 - 10
gravel	2 - 64	0.08 - 2.5
sand	0.062 - 2	
silt	0.004 - 0.062	
clay	<0.004	

Sediment Load: The sum total of sediment available for movement in a stream, whether in suspension in the water column (suspended load) or in contact with the bottom (bedload).

Sediment Transport: The rate of sediment movement through a given reach of stream

Shear Strength: The characteristic of soil that resists internal deformation and slippage. Shear strength is a function of soil cohesion, root structure, water content, rock content, and layering.

Shear Stress: Results from the tangential pull of flowing water on the streambed and banks. The energy expended on the wetted boundary of the stream increases proportionally with the energy slope and water depth.

Sinuosity: The ratio of stream channel length (measured in the thalweg) to the down-valley distance, or is also the ratio of the valley slope to the channel slope. When measured accurately from aerial photos, channel sinuosity may also be used to estimate channel slope (valley slope/sinuosity).

Stage: Elevation of water surface above any chosen reference plane. Also known as water level or gage height.

Stage-Discharge Relationship: The functional (mathematical, or graphical) relationship between water discharge and corresponding stage (water-surface elevation). Also called a stage-discharge "rating curve."

Stationarity: An assumption imbedded in such hydrologic analysis as flood-frequency analysis that annual floods are independent and identically distributed over time. However, cycles and trends in flood and other climatological records indicate nonstationarity can be the norm.

Stream: A natural water course of any scale, from the smallest creek to the largest river.

> **Perennial Stream** – one that flows continuously throughout the year.
>
> **Intermittent or Seasonal Stream** – One that flows only at certain times of the year or along a discontinuous sequence of reaches.
>
> **Ephemeral Stream** – One that flows only briefly, as a direct result of precipitation.

Substrate: Mineral and organic material that forms the bed of a stream.

Suspended Load: That part of the sediment load whose immersed weight is carried by the fluid, suspended above the bed.

Terrace: A previous floodplain which has been disconnected from a stream channel because of channel incision.

Thalweg: The line connecting the lowest points along a streambed, as a longitudinal profile. The path of maximum depth in a river or stream.

Toe: The base of a streambank or terrace slope.

Transport Velocity: The velocity of flow required to maintain particles of a specific size and shape in motion along the streambed. Also known as the critical velocity.

Tributary: Any channel or inlet that conveys water into a stream.

Turbulence: The motion of water where local velocities fluctuate widely in all three dimensions, resulting in abrupt changes in flow directions. It causes surface disturbances and uneven surface levels, and often masks subsurface areas due to the entrainment of air. Virtually all flow in rivers is turbulent flow. Opposite of laminar flow.

Velocity: The distance that water travels in a given direction during a given interval of time.

Wetted Perimeter: The length of the wetted contact between a stream of flowing water and the stream bottom and banks in a vertical plane at right angles to the direction of flow.

Width-to-Depth Ratio: The bankfull width divided by the average bankfull depth.