

Guidance for Stream Restoration and Rehabilitation

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Top-right: Illinois River, North Park, Colorado.

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Bottom-left: Whychus Creek, Oregon.

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ABSTRACT

A great deal of effort has been devoted to developing guidance for stream restoration and rehabilitation. The available resources are diverse, reflecting the wide ranging approaches used and expertise required to develop stream restoration projects. To help practitioners sort through all of this information, a technical note has been developed to provide a guide to the wealth of information available. 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. The primary topics incorporated into this guidance include general methods, an overview of stream processes and restoration, case studies, and methods for 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 and rehabilitation projects.

ADVISORY NOTE

Techniques and approaches contained in this handbook 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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INTRODUCTION

Nationally, more than \$1 billion is spent each year on stream restoration and rehabilitation projects (Bernhardt et al. 2005). To support this investment, a great deal of effort has been devoted to developing guidance for these projects. These resources are diverse, which reflects the wide ranging approaches used and expertise required in the practice of stream restoration. Substantial guidance is available to assist practitioners with restoration projects, with tens of thousands of pages of relevant material available. The USDA Natural Resources Conservation Service's (NRCS) Stream Restoration Design manual (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.

It is important to not interpret this document structure as a philosophical framework for restoration design; that effort is left to other references. Additionally, this guidance is not limited to only what are currently 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). Taking the approach of restoration or rehabilitation is decided at the project inception, as goals and objectives are defined.

Table 1: Quick reference guide.

Technical Need	Page
Define goals and objectives for stream restoration and rehabilitation projects	2
General methods for developing alternative restoration strategies	3
Overview of stream system processes and restoration practices	8
Learn from past restoration projects, through case studies	10
Resources for collecting existing background data	11
What should be considered when evaluating condition? What preliminary assessment tools can be applied?	14
What is the Channel Evolution Model?	17
Methods for field data collection (surveying, discharge, water quality, sediment, vegetation, aquatic life)	18
How is bankfull stage determined?	19
What analyses are performed for stream restoration and rehabilitation designs?	25
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This document is organized in the typical sequence for assessing, analyzing, and designing stream restoration and rehabilitation projects. Additionally, 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.

GOALS AND OBJECTIVES

One of the most important steps in a stream restoration or rehabilitation 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.

For example, in a habitat enhancement for native cutthroat trout where excessive peak summertime temperatures is the primary impairment, a goal of increasing fish abundance needs to be clarified with such objectives as decreasing the channel width/depth ratio, increasing pool depth and frequency, and increasing shade and terrestrial food input to the stream through revegetation of channel banks and riparian zone.

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

- Prevent streambank erosion, to protect properties and infrastructure
- Provide habitat enhancement for native or sport fishes, to increase abundance and age class diversity
- 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, such as excessive temperature, nutrients, sediment, salts, and metals
- Remove non-native riparian vegetation, replacing with more desirable species
- Reestablish a sinuous channel, from a straight or braided form
- Establish stream reaches capable of transporting 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 the process of adaptive management. In any case, documentation of project performance needs to be maintained, for communication with stakeholders and adding to the knowledge base of the individual professional 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

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.

Interdisciplinary Team

Stream corridor restoration and rehabilitation 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 engineering, hydrology, fluvial geomorphology, 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.

Planning Process

Stream corridor restoration and rehabilitation 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 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?

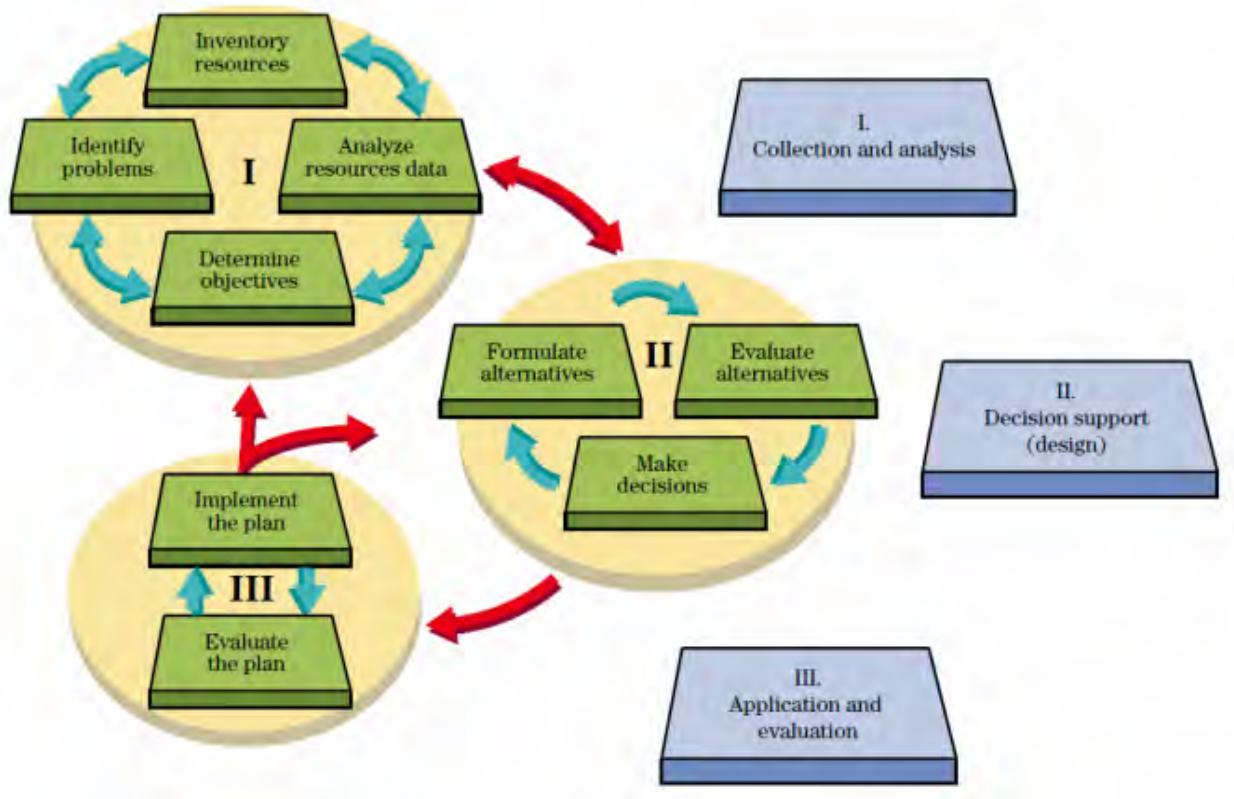


Figure 1: The NRCS planning process (NRCS 2007, Ch. 2).

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, impacts on water quality, and 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 and revise practices.

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

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 publically available so that the restoration community as a whole can benefit from knowledge learned.

Watershed Approach

While technical assistance is typically requested 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 or rehabilitation may not be the wisest 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
- How are flow diversions 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, such as Salt Cedar (*Tamarix spp.*) or Russian Olive (*Elaeagnus angustifolia*)? What are the ramifications?
- Are landslides 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 request for technical assistance?
- 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.

Riparian Management

Effective riparian management is fundamental for supporting proper stream corridor function, to develop a fully functioning stream system. A summary providing a scientific assessment of the effectiveness of riparian 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 or rehabilitation is often not needed to fulfill stakeholders objectives, with livestock management being all that is required in some situations. In other situations, riparian management is used in combination with engineered practices to satisfy project objectives in the desired timeframe. In some of the most disturbed stream systems, where channelization or incision has occurred and water surface elevations and groundwater table elevations have been substantially reduced, resulting in the shifting of former floodplain plant communities to upland terrace species, more intensive restoration may be needed to raise the channel back to the pre-disturbance elevations and restore 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 alternatives do not satisfy project objectives, then more complex engineered 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.

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 process of adaptive management can be an essential method 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:

- [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).

Practice name	Code	Ecosystem services				
		Wildlife habitat	Water quality and quantity	Stable stream banks and soils	Carbon storage	Diverse plant and animal communities
Animal trails and walkways (feet)	575		X	X		
Brush management (acres)	314	X	X	X		X
Channel bank vegetation (acres)	322	X	X	X		
Conservation cover (acres)	327	X	X	X		
Critical area planting (acres)	342			X		
Fence (feet)	382	X	X	X		X
Filter strip (acres)	393		X			
Pest management (acres)	595	X	X			
Prescribed burning (acres)	338	X				X
Prescribed grazing (acres)	528	X	X	X		X
Range planting (acres)	550	X	X	X	X	X
Riparian forest buffer (acres)	391	X	X	X	X	X
Riparian herbaceous cover (acres)	390	X	X	X	X	X
Stream crossing	578		X	X	X	
Stream habitat improvement and management (acres)	395	X	X	X		
Stream bank and shoreline protection (feet)	580	X		X		
Tree/shrub establishment (acres)	612	X	X	X	X	X
Upland wildlife habitat management (acres)	645	X				
Use exclusion (acres)	472		X	X		X
Watering facility (no.)	614		X	X		

Extent of 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 2) 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](#) (River Restoration Analysis Tool) was developed by the NOAA National Marine Fisheries Service to walk reviewers through key questions that help assess if fundamental considerations have been addressed in a project.

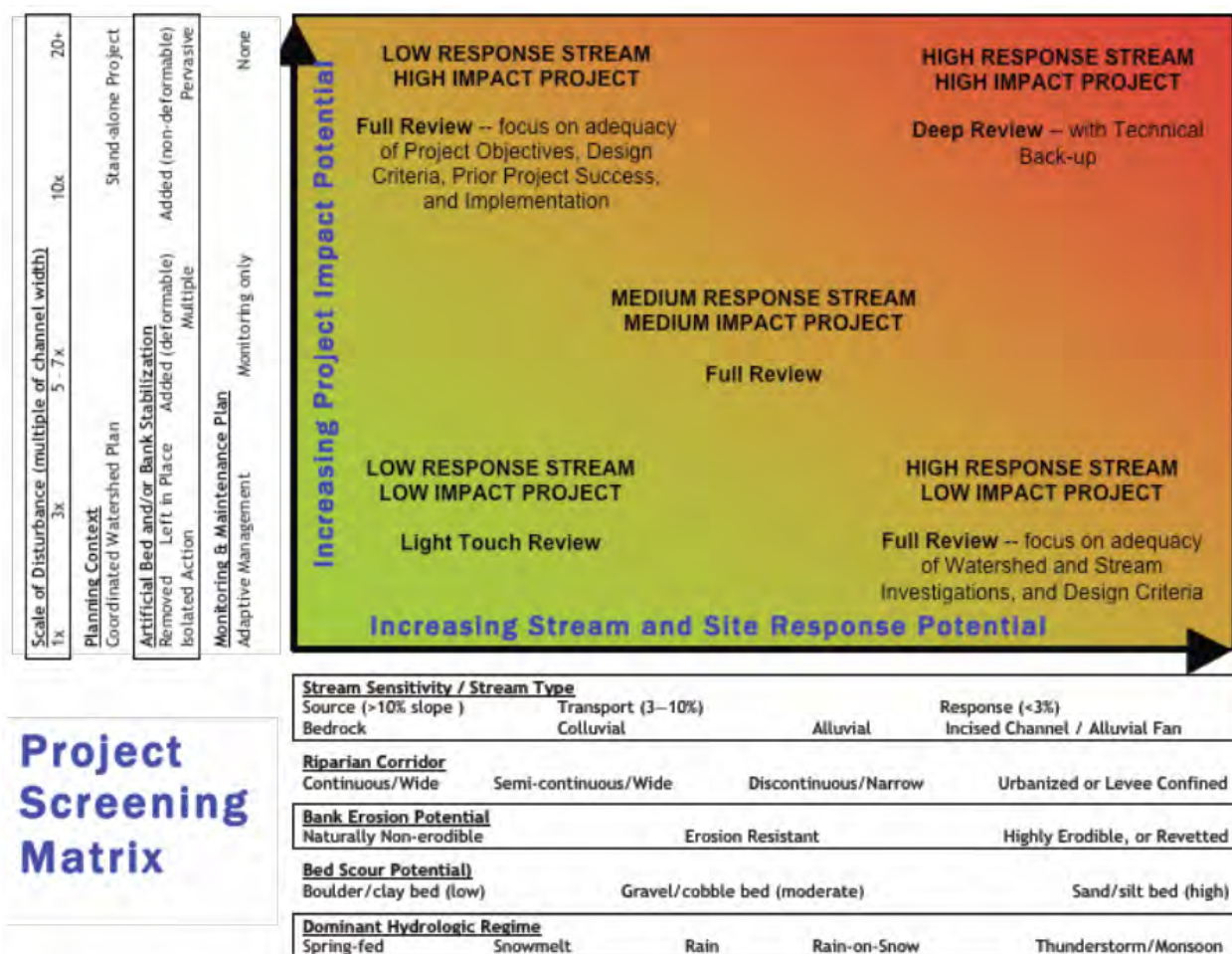


Figure 2: Project screening matrix (Skidmore et al. 2011).

OVERVIEW OF STREAM PROCESSES and RESTORATION

There are a wide variety of approaches implemented in stream projects, with this variety a function of the goals and objectives, setting (urban vs. rural, private vs. public lands), 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, 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:

- [EPA 2015](#) Connectivity of Streams & Wetlands to Downstream Waters: A Review & Synthesis of the Scientific Evidence
- [Niezgoda et al. 2014](#) Defining a Stream Restoration Body of Knowledge as a Basis for National Certification
- [How to do River Restoration](#) Step-By-Step Guidance (from the European Union Environment Agency)
- [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
- [Burton et al. 2011](#) Multiple Indicator Monitoring of Stream Channels and Streamside Vegetation
- [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
- Julien 2002 River Mechanics
- [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
- Knighton 1998 Fluvial Forms and Processes: A New Perspective
- [FISRWG 1998](#) Stream Corridor Restoration: Principles, Processes and Practices
- [Biedenham et al. 1997](#) The Waterways Experiment Station Stream Investigation and Streambank Stabilization Handbook
- [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:

- [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)
- [Undamming the Elwha](#) The Documentary, 2012 (Katie Campbell and Michael Werner)
- [Recipe for a River](#) NPR Science Friday video illustrating dominant mechanisms in meandering streams, 2009 (Christian Braudrick and Bill Dietrich)
- [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)

CASE STUDIES

Case studies can be very valuable for understanding lessons learned from previous projects and to provide ideas for projects currently being planned. 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.

- [Pollock et al. 2015](#) The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains
- [East et al. 2015](#) Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change.
- [Powers 2015](#) Case Study: Restoration of the Camp Polk Meadow Preserve on Whychus Creek
- [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
- [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.
- [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.

Videos illustrating case studies are provided at:

- [Whychus Creek, Oregon](#) Camp Polk Meadow Preserve restoration, 2011 & 2012.

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 (including LiDAR). A Geographic Information System (GIS) is typically the most appropriate method for viewing and analyzing spatial data.

Data Sources

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

Water Quantity

- [USGS water data](#): real-time and historical streamgauge 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.
- [USGS station statistics](#): available through the national StreamStats page.
- [BOR water data](#): water data in the Pacific Northwest, from the Bureau of Reclamation
- [FEMA floodplain mapping](#): 100-year flood inundation boundaries, from the Federal Emergency Management Agency.

Water Quality

- [USGS water quality data](#): real-time field parameter data, such as temperature, conductivity, and pH, as well as historical data for many constituents.
- [NorWeST Stream Temp](#): stream temperature data and geospatial map outputs from a regional temperature model for the Northwest United States

- [USGS SPARROW Decision Support Systems](#): map based 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 WQIC](#): National Agricultural Library Water Quality Information Center, for agricultural-related water quality information.

GIS Data and Mapping

- [USFS Geospatial Service and Technology Center](#): provides the Forest Service with a range of geographic information products and related technical and training services.
- [NRCS Geospatial Data Gateway](#): GIS data, such as ortho imagery, topographic images and hydrologic unit boundaries.
- [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.” (Other basemap layers are also available from ArcGIS online.)
- [National Map](#): Visualize, inspect and download topographic base data, elevation data, orthoimagery, landcover, hydrography, and other GIS products. From the 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 of U.S. Forest Service managed lands.
- [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.

Climate Data

- [National Climatic Data Center](#): climate 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.

Vegetative Information

- [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).
- [Tamarisk Coalition](#): education and technical assistance for the restoration of riparian lands.

Literature

- Websites for discovering published texts and journal articles relevant for a restoration project:
 - [Google Scholar](#)
 - [Google](#)
 - [USFS Treesearch](#)
 - [USGS Publications Warehouse](#)
 - [Science.gov](#)
 - [Web of Knowledge](#)
- [DigiTop](#): USDA access to journal articles from principle publishers
- [Scholarly Open Access](#): Critical analysis of scholarly open access publishing (since all journals are not created equal).

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 and rehabilitation 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.

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 or rehabilitation. 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.

PRELIMINARY ASSESSMENT

Before initiating a potentially intensive field data collection effort, a preliminary field-based assessment of the reach in question is necessary to develop initial insights into key impairments and their root causes. This stage of a project serves as a decision point for the technical specialists and stakeholders on if it is desired to proceed with the project and if an active engineering approach or just riparian management is needed to satisfy the project objectives in the desired timeframe.

Physical and biological characteristics to assess are detailed in [NRCS \(2007\), Ch3](#). Potential issues to consider are wide ranging, including: excessive bank erosion; flow modification by infrastructure; channel straitening and incision; discharge modification by reservoir regulation, diversions and urbanization; water quality impairments; lack of geomorphic complexity associated with pools and instream wood; insufficient riparian vegetation, for bank stabilization, cover, shading, and energy input to streams; and excessive fine sediment or sediment transport capacity. Field indicators should be evaluated for evidence of channel degradation, aggradation, or stability (Table 3), as a part of a stability assessment for a stream reach (Figure 3). Importantly, stability may not be a goal; instead, proper stream function may be the goal, depending upon local site conditions. Given this, evidence of degradation or aggradation may still be relevant for assessing general impairments and trends.

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 instream 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 assessment of riparian corridors.

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

- What are the dominant fluvial processes in the stream system?
- What is the equilibrium state of the reach or 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 (Wohl 2011)?
- What are the factors contributing to the problem? What are potential mitigation strategies?

Table 3: Possible field indicators of stream instability and stability (adapted from NRCS 2007, Ch3).

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 upstream
failed revetments due to undercutting

evidence of aggradation

buried culverts and outfalls
reduced bridge clearance
uniform sediment deposition across channel
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 pipeline crossings or bridge footings

To assist with the preliminary assessment, tools have been developed to assist practitioners in performing basic assessments of riparian areas. An overview is provided in:

- [NRCS 2007, TS3A](#): Stream Corridor Inventory and Assessment Techniques.

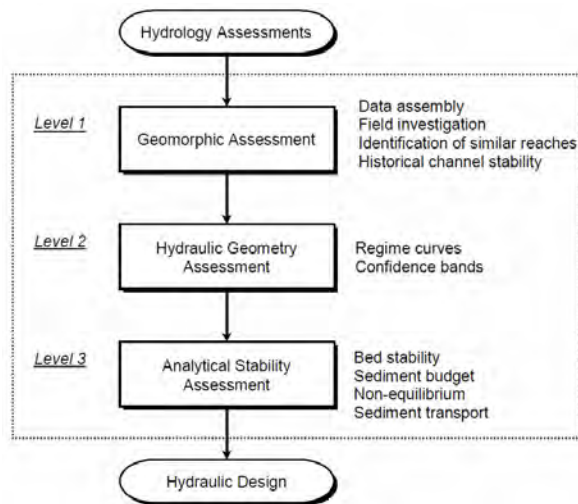


Figure 3: Levels of stability assessments (Copeland et al. 2001).

Basic Assessment Tools

Basic qualitative assessments can be useful tools for providing a structured evaluation of a riparian corridor. These methods evaluate common issues impacting streams, such as channel condition, hydrologic alteration, canopy cover, pools, and nutrient enrichment (NRCS 2009).

These qualitative assessments are typically 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.

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 erosion/deposition characteristics in describing the condition of riparian and wetland areas. Condition is described as proper functioning, functional – at risk, nonfunctional, or unknown. (Prichard et al. 1998)
- [Pfankuch Method](#): Stream Reach Inventory and Channel Stability Evaluation. 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)

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 systems are the Montgomery and Buffington (1997) and Rosgen (1994, 1996) systems. The Montgomery and Buffington system (Figure 4) 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 5) 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](#).

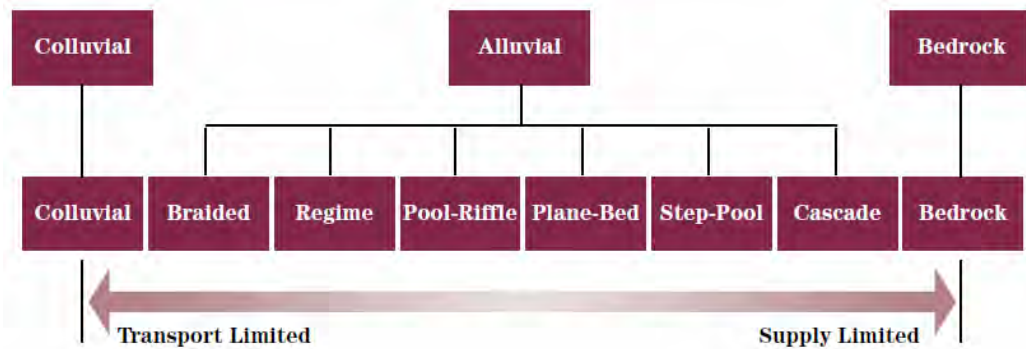
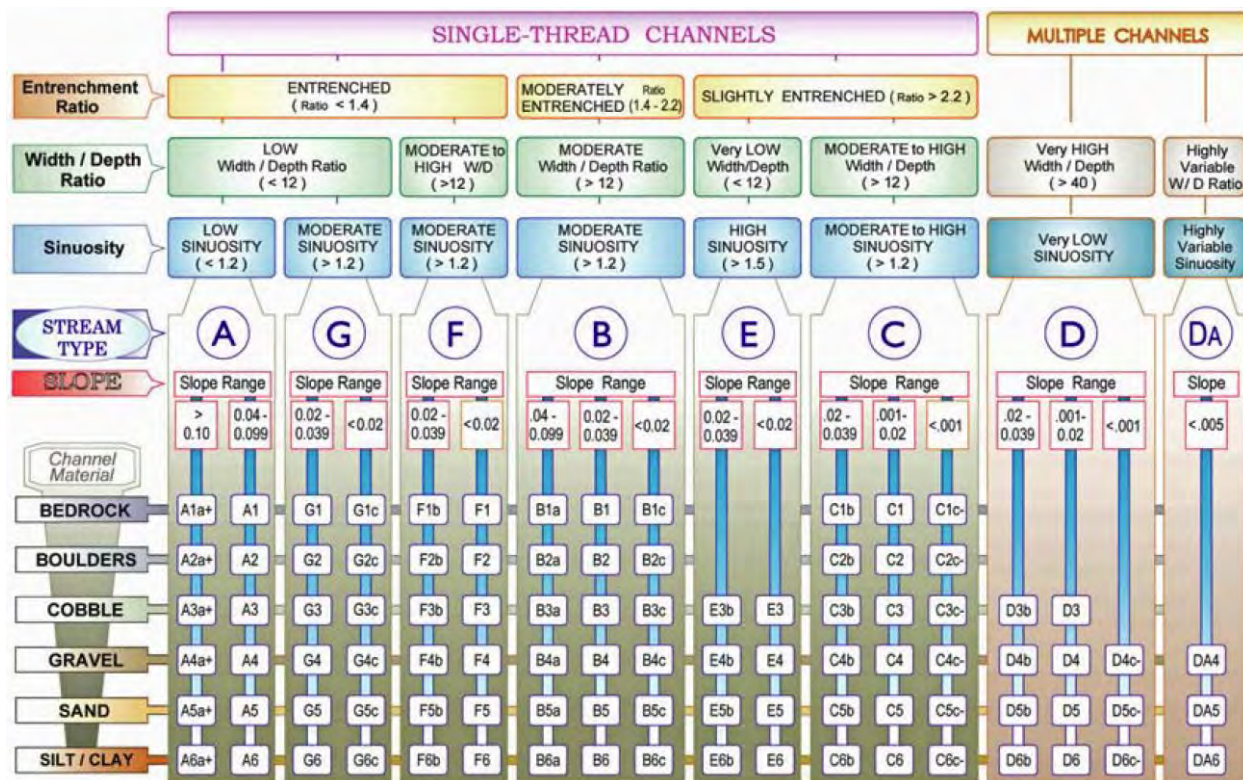


Figure 4: Montgomery and Buffington classification system (NRCS 2007, Ch3).



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

Figure 5: Rosgen classification system (NRCS 2007, Ch3).

Channel Evolution Model

The channel evolution model (CEM), originally developed by Schumm et al. (1981) and modified for channelized streams (Simon and Hupp 1987, Simon 1989), 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 6), providing an evaluation of longitudinal response and restoration potential. At a specific location the channel evolves from an initial stable state (stage I) through incision (stage II), widening (stage III), deposition and stabilization (stage IV), and once again stable (stage V). Stages II and III are the most problematic period of evolution, when the most sediment supply is available for transport and restoration options are limited. Simon and Hupp (1987) and Simon (1989) modified the method to include an additional stage for an anthropogenic-induced, un-incised channelized section while Watson et al. (2002) extended the CEM method by providing a quantitative method for developing channel-restoration strategies. Cluer and Thorne (2013) adapted the method to include anastomosing (multi-thread) stages and provide better integration of habitat and ecosystem benefits, in what they refer to as the Stream Evolution Model (SEM). Anastomosing wet complexes are biologically rich and can be an excellent alternative to other restoration strategies.

Additional information regarding this conceptual model is provided in NRCS (2007), chapter 3; and SVAP2 (NRCS 2009). The Rosgen geomorphic channel design method (NRCS 2007, Ch11) draws on lessons learned from the CEM, through its use of successional stages of channel evolution (Figure 7). Understanding the present and potential future successional stages and stream classifications of a stream can be very helpful for understanding channel stability and trends, and identifying realistic project goals.

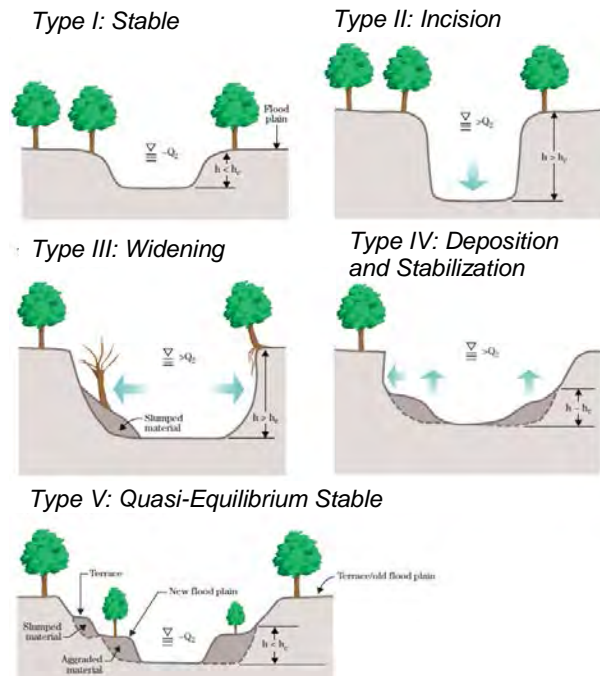


Figure 6: Channel cross sections illustrating the 5 CEM classes (NRCS 2007, Ch3).

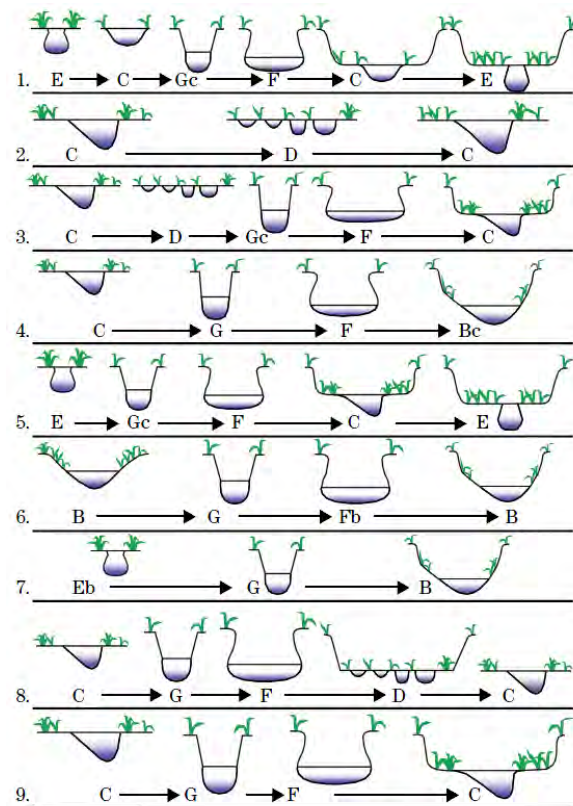


Figure 7: Various possible stream succession stages (NRCS 2007, Ch11).

FIELD DATA COLLECTION

Field data collection can consist of many different activities. The specific data needing to be collected varies by the stream reach of concern and the specific project objectives. Examples briefly discussed in this guidance include topographic surveying, bankfull identification, discharge and water quality measurements, bed material composition and transport, riparian vegetation identification, and macroinvertebrate and fish sampling. While such data collection and analysis can be essential for assessing dominant mechanisms and impairments, these activities can take a substantial investment of time and money – only the data needed to satisfy the project objectives and minimize failure risk should be collected.

Topographic Survey Data

For stream projects, 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 8; Harrelson et al. 1994). This is an older but standard technique for stream projects, though survey grade GPS (Figure 9) 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. Airborne-collected LiDAR data are increasingly available at many locations, allowing for unparalleled 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.

Key advantages of survey-grade GPS is the enhanced capability of georeferencing the survey so that the data points can be easily overlaid 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. 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](#).

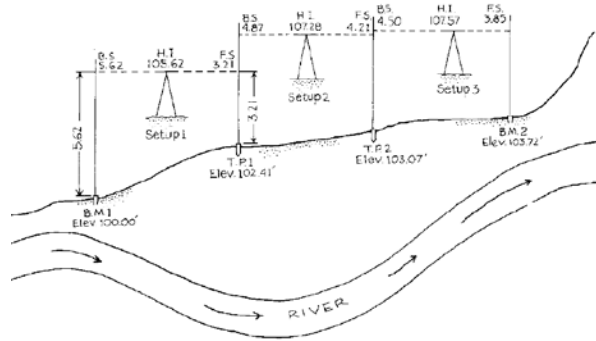


Figure 8: Differential surveying (Harrelson et al. 1994).



Figure 9: 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 restoration of a mile long reach by such features as grade and bank stabilization, pool excavation, and habitat enhancement structures, more survey data will likely be needed to analyze and design the project.

This latter complexity level of project may require a general land survey of the riparian zone, up the 50- or 100-year flood level, so that a hydraulic model with a detailed sequence of cross sections can be developed, as well as development of more complex hydraulic models if they are deemed necessary. This type of survey should not be simply a series of cross sections but rather a feature survey that combines the description of landform features with a varying density grid. The features are surveyed to measure the location of relevant landforms and the grid data is 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.

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 somewhat controversial issues tied to bankfull stage and discharge; discussions of these subjects are left 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 1994 A View of the River
- Dunne and Leopold 1978 Water in Environmental Planning

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

- [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)

Discharge Measurements

Discharge measurements are oftentimes collected for stream restoration and rehabilitation work. These data are collected to measure such things as bankfull and low flow discharge, for geomorphic design and 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
- [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

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, the lack of shading in or upstream of the 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 10). 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.

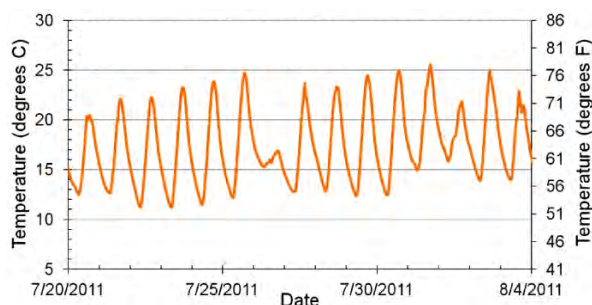


Figure 10: Diurnal temperature fluctuations.

Hach kits, for instantaneous measurements of dissolved oxygen, nitrogen and phosphorus, can provide data at fairly 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 is 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 2012](#) Water Quality Criteria for Aquatic Life and Human Health
- [EPA 2008](#) Aquatic Life Criteria for Contaminants of Emerging Concern
- 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:

- [USFS](#) (internal USFS only) Monitoring Water Quality: Collecting Stream Samples
- [USFS](#) (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

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 11) 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.

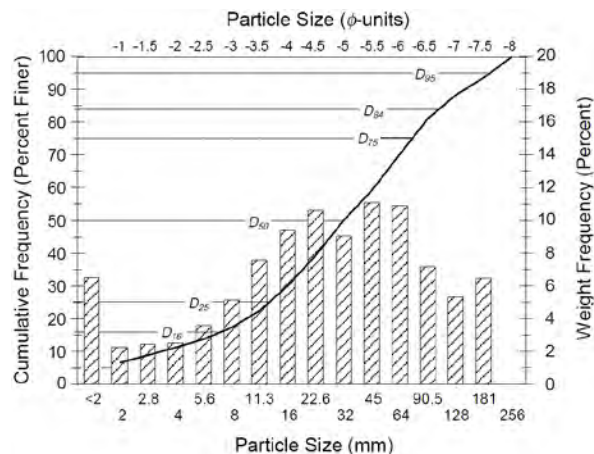


Figure 11: Example bed material particle size distribution (Bunte and Abt 2001).

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.

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). Suspended sediment is measured using such devices as a DH-81 handheld depth-integrated sampler, while bedload is measured using such equipment as the Helley-Smith sampler or bedload traps (Figure 12). 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). Bedload and suspended sediment sampling provide valuable data for developing and calibrating sediment rating curves.

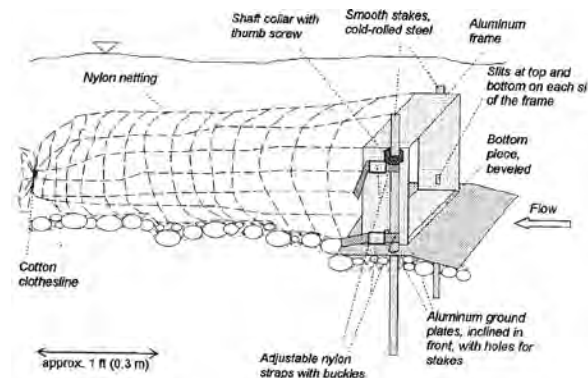


Figure 12: Bedload trap (Bunte et al. 2007).

References to assist with sediment transport data collection include:

- [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

Riparian Vegetation

Riparian vegetation (Figure 13) offers many benefits to streams, including reduced erosion rates and increased bank stability, increased flow resistance and reduced velocities, increased vadose zone recharge, and the provision of cover, shade, 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, establishing the status of riparian vegetation is an essential component of stream restoration planning and design.

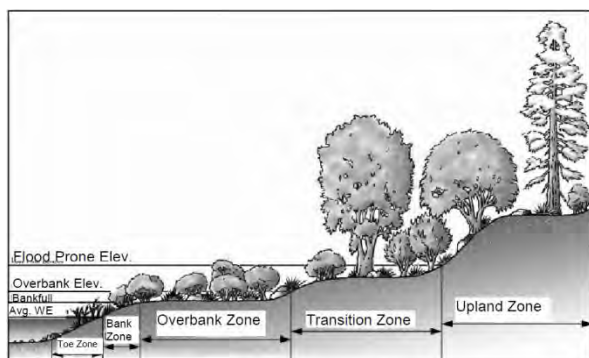


Figure 13: Vegetation zones within a riparian cross section (Hoag et al. 2008).

References available for quantifying the status of riparian vegetation include:

- [Burton et al. 2011](#) 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.
- [Kershner et al. 2004](#) Guide to Effective Monitoring of Aquatic and Riparian Resources
- [Winward 2000](#) Monitoring the Vegetation Resources in Riparian Areas

Aquatic Organisms

Habitat improvement for aquatic organisms is a common objective of stream restoration and rehabilitation projects. To have measureable objectives in such projects, quantifying aquatic organism populations (Figure 14, Figure 15) is necessary both in the planning phase as well as after construction. Both fish sampling and macroinvertebrate sampling are valuable tools for assessing status. Two common biotic indicators are the Index of Biotic Integrity (IBI), which uses fish surveys to assess human impacts, and the Ephemeroptera, Plecoptera, and Trichoptera (mayfly, stonefly, caddisfly; EPT) index, which uses macroinvertebrate abundance and diversity as indicators of water quality (NRCS 2007).



Figure 14: Fish sampling (NRCS 2007).



Figure 15: Macroinvertebrate sampling equipment (Moulton et al. 2002).

References and websites for assessing aquatic organism populations include:

- [Becker and Russell 2014](#) (internal USFS 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

ANALYSES FOR STREAM RESTORATION and REHABILITATION

Stream restoration and rehabilitation analyses are performed to provide a channel (or channels) that will be in a physical form that is in dynamic equilibrium with its water and sediment load. Analyses also provide understanding of channel and floodplain characteristics that support ecologic function. The focus of analyses is typically determined by project objectives and extent, though hydraulic sufficiency and sediment transport continuity are important when altering stream channels. Both existing and proposed stream conditions are often assessed through analyses. Analysis extent is dependent upon the specific project needs.

Typically, projects are performed in alluvial channels, where sediment material exchange between the stream bed, banks, and floodplain creates channel dimensions that can effectively transport water and sediment through a stream channel. When considering a substantial range of flows, a degree of sediment discontinuity may be expected, further complicating the design process. Examples of this situation can include alluvial fans, canyon mouths, and stream confluences. Analysis and design approaches that are generally utilized for restoration and rehabilitation 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.

Guidance for these methodologies can be found in the following references:

- Cui et al. 2011 (in [Simon et al. 2011](#)) Practical Considerations for Modeling Sediment Transport Dynamics in Rivers
- [NRCS 2007, Ch6](#) Stream Hydraulics
- [NRCS 2007, Ch9](#) Alluvial Channel Design

- [NRCS 2007, Ch11](#) Rosgen Geomorphic Channel Design
- [NRCS 2007: Ch12](#) Channel Alignment and Variability Design
- [NRCS 2007: Ch13](#) Sediment Impact Assessments
- [Brierley and Fryirs 2005](#) Geomorphology and River Management: Applications of the River Styles Framework.
- [Soar and Thorne 2001](#) Channel Restoration Design for Meandering Rivers
- [Copeland et al. 2001](#) Hydraulic Design of Stream Restoration Projects

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.

This section provides summary guidance for a few key analysis and design techniques. Topics discussed include flow frequency estimates, bankfull characteristics, Rosgen geomorphic channel design, the River Styles fluvial geomorphic approach for assessing river form, condition, and recovery potential, Soar and Thorne restoration design, hydraulic modeling overview, hydrologic and ecologic modeling tools, and flow resistance estimation.

Bankfull Characteristics

Alluvial streams oftentimes develop a characteristic form, with a bankfull channel 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 (described in the next section), 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 can 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 bankfull. 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 ($A < 1.9 \text{ mi}^2$, $1.9 < A < 130 \text{ mi}^2$, $A > 130 \text{ mi}^2$).

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). 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).

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 16). 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.

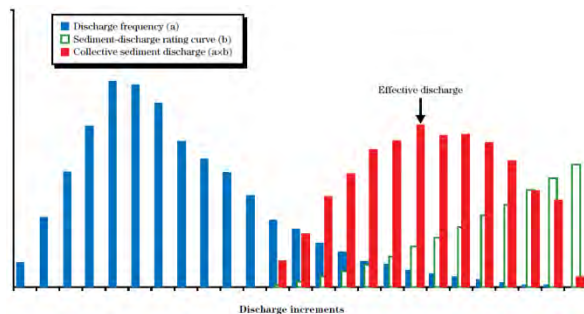


Figure 16: Effective discharge computation (NRCS 2007, Ch5).

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

Flow Frequency Estimates

Stream restorations and rehabilitations typically use bankfull discharge as a primary design discharge, in addition to low flow values for aquatic life. However, less frequent flood events (such as the 10-, 25- and 100-year 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 that instream structures are designed to resist. Hence, flow frequency estimates are typically needed for stream designs.

If the project is adjacent to a streamgage that has a sufficient record length, flow frequency estimates (Figure 17) can be obtained from the USGS or computed using the methods presented in Bulletin 17B (IACWD 1982) and outlined in NRCS (2007), Ch5. 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.

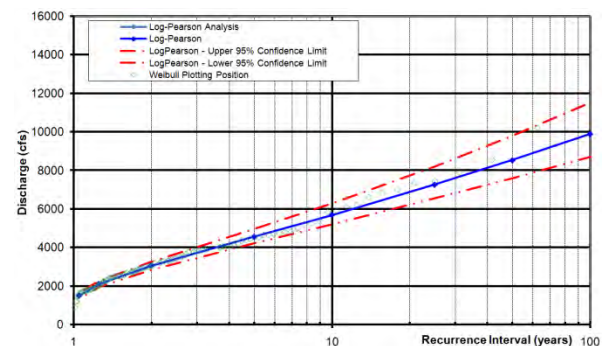


Figure 17: Flow frequency estimates for the Cache la Poudre River, CO (USGS 06752000).

However, many 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. To obtain results that can be used with greater confidence, results developed using a custom regional regression approach may be preferred. This methodology is discussed in NRCS (2007), Ch5. Alternatively, in rainfall dominated watersheds, rainfall-runoff models can also 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.

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, forest fires and conservation practices, as well as climate change and reservoir construction, has repercussions on the use of flow frequency relationships for stream restoration and rehabilitation design. For example, Haucke and Clancy (2011) found that conservation practices

can decrease frequent annual flood events, despite corresponding increases in precipitation. Trends in annual peak discharges in the Continental U.S. are illustrated in Figure 18.

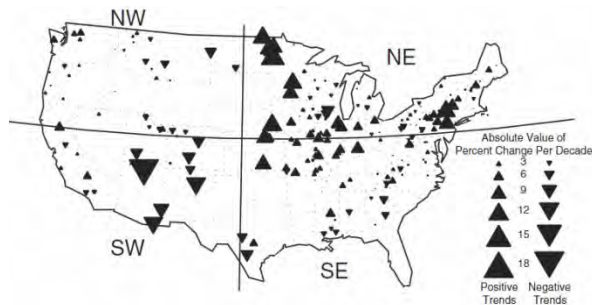


Figure 18: Annual peak discharge trends, with record lengths from 85 - 127 years (Hirsch 2011).

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

- [USGS](#): Questions and answers about floods.
- [NRCS 2007, Ch5](#) Stream Hydrology
- [IACWD 1982](#) Guidelines for Determining Flood Flow Frequency (Bulletin 17B)
- [log-Pearson Frequency Analysis Spreadsheet](#) USFS National Stream and Aquatic Ecology Center
- [PKFQWin](#) USGS Flood Frequency Analysis Software, based on methods provided in Bulletin 17B.
- [HEC-SSP](#) U.S. Army Corps of Engineers Hydrologic Engineering Center – Statistical Software Package
- [USGS Streamstats](#) watershed and stream statistics, including approximate flow frequency values, mean flows and minimum flows for ungaged streams.

Rosgen Geomorphic Channel Design

The Rosgen geomorphic channel design method 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 19 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).

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 anthropogenic disturbances in streams, such as livestock grazing in riparian zones and removal of instream wood, 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 inappropriate in regions where precipitation varies substantially (such as mountainous watersheds) and where there are substantial flow diversions. Additional predicting variables may need to be included in regional regressions, such as average annual precipitation.

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

- [Rosgen 2013](#) Natural Channel Design – Fundamental Concepts, Assumptions, and Methods
- [Spreadsheet Tools for River Evaluation, Assessment, and Monitoring](#) Ohio Department of Natural Resources and Ohio State (Dan Mecklenburg and others)
- [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)

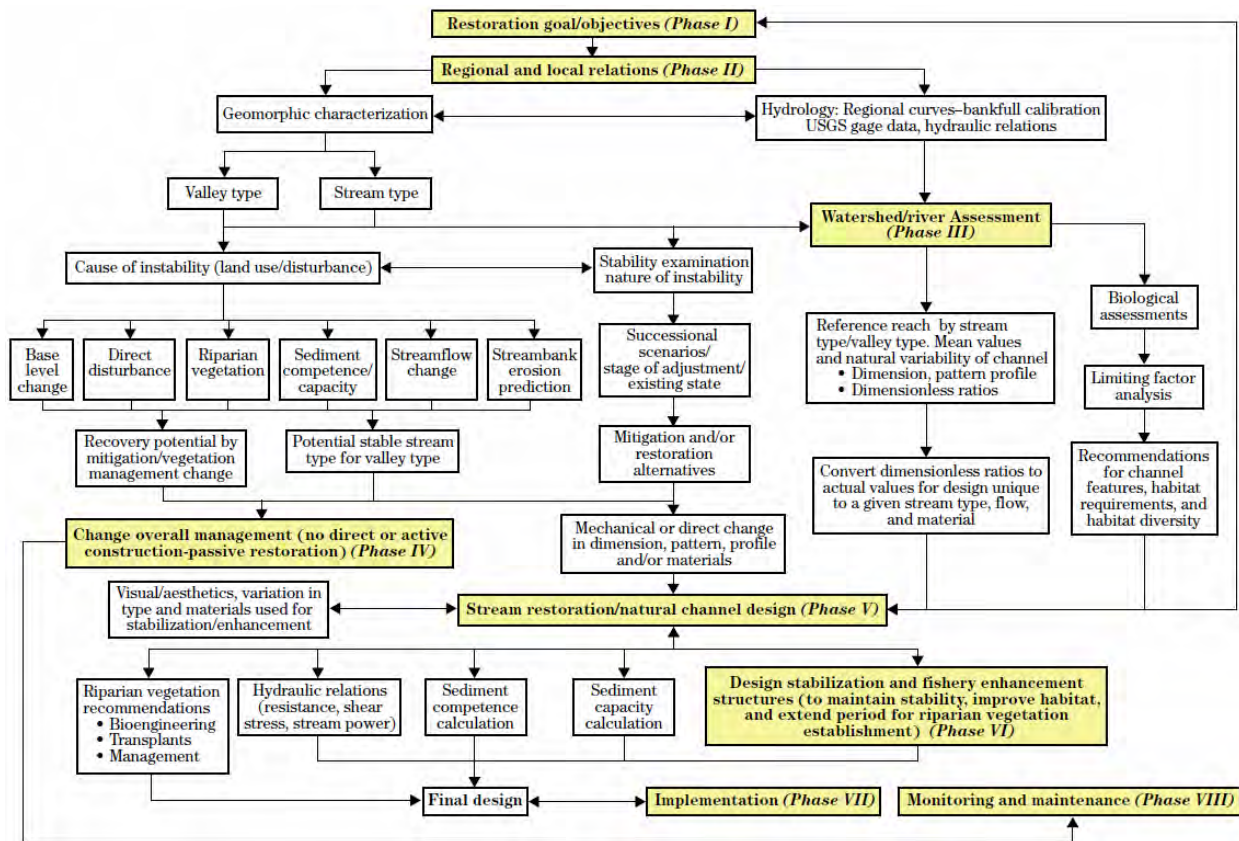


Figure 19: Schematic illustrating the Rosgen Geomorphic Channel Design method (NRCS 2007, Ch11).

River Styles

[River Styles](#)[®] (Figure 20) is a fluvial geomorphic approach for assessing river form, condition, and recovery potential. This method provides a physical template for stream management. As discussed in 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 20: River Styles framework (extracted from www.riverstyles.com).

Soar and Thorne Restoration Design

Soar and Thorne (2001) developed a stream restoration and rehabilitation design procedure that combines a range of techniques, including field reconnaissance, detailed site survey, discharge-frequency analysis, 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 21.

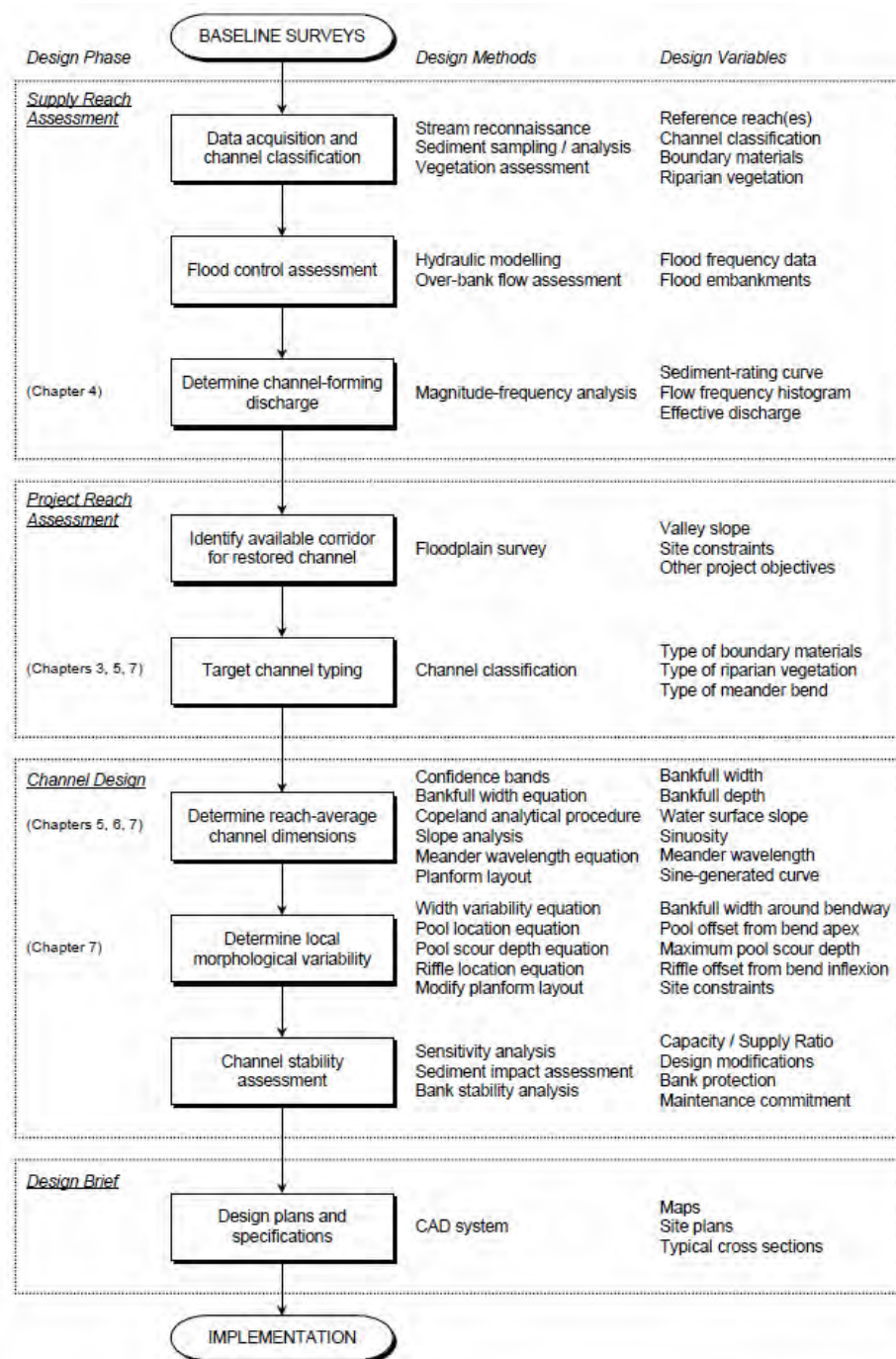


Figure 21: Soar and Thorne (2001) stream restoration design procedure.

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 or rehabilitation 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 and rehabilitation designs. They can be most useful in combination with other analysis techniques. Despite these limitations, it can 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. It can be quite awkward and expensive to deal with ramifications associated with the reconstruction of a failed project that could have been prevented by the development of hydraulic modeling.

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 22), 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.

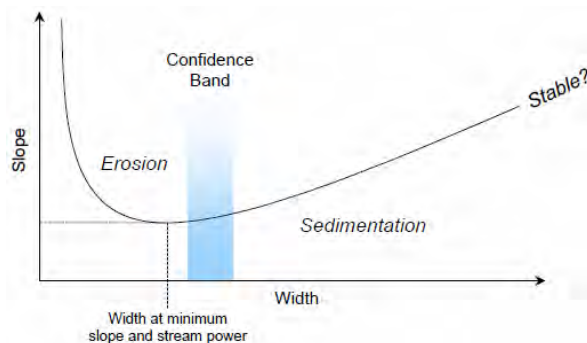


Figure 22: Analytical channel design using the Copeland method (Soar and Thorne 2001).

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 and rehabilitation projects is provided in:

- [Fischenich and McKay 2011](#) Hydrologic Analyses for Stream Restoration Design
- [Brunner 2010](#) 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

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.

Hydraulic Analysis and Aquatic Habitat

- [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.
- [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.
- [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.
- [REMM](#): Riparian Ecosystem Management Model. A model used to simulate hydrology, nutrient dynamics, and plant growth in riparian areas.
- [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.
 - Implements the Mesohabitat Simulation Model ([MesoHABSIM](#)).
 - [SRH-2D](#): 2-D hydraulic, sediment, temperature, and vegetation modeling.
 - [SSTEMP](#): Stream Segment Temperature Model. Used to assess the effects of riparian shade, stream diversions, and stream returns on instream temperature, as well as alternative reservoir release proposals.
 - [WinXSPro](#): Channel cross-section analysis.

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 (NRCS 2007, Ch11).

- [POWERSED](#): modeling tool to estimate sediment transport capacity (NRCS 2007, Ch11).
- [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).

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). Colorado pilot study 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.

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.
- [SWAT](#): Soil and Water Assessment Tool. River basin scale model for assessing the impact of land management practices in large, complex watersheds.
- [SWMM](#): Storm Water Management Model. Software for rainfall-runoff simulation in primarily urban watersheds.
- [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](#) web-based interfaces are available, providing such tools as peak flow estimates for burned areas and erosion prediction from forest roads.
- [WinTR20](#): NRCS software for single event, watershed scale, rainfall-runoff modeling.

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), plan form, vegetation, instream wood, and other obstructions. 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 (m²), P_w is the wetted perimeter (m), S_f is the friction slope, g is acceleration due to gravity (m/s²), 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. Following the three steps below is recommended when predicting flow resistance for 1-dimensional modeling:

1. **Consult a general 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 below).
 - b. Alternatively, implement a quasi-quantitative approach (Cowan 1956; Arcement and Schneider 1989)

Various tools are available for estimating flow resistance, with methods varying by channel type. The most relevant prediction methodologies are provided below:

General Guidance

- [USGS](#): Verified Roughness Characteristics of Natural Channels (online photo guide)
- [Brunner 2010](#) 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

Low-Gradient Channels

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

In sand-bed channels, bedforms need to be predicted, using such guidance as Brownlie (1983) and van Rijn (1984). Flow resistance varies by bedform type, as indicated in Table 4.

Table 4: Manning's n in sand-bed channels.

	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

- [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
- [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

Mid-Gradient Channels

(~0.2% < slopes < ~2%, gravel- and cobble-bed, riffle-pool and plane bed channels)

- 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
- [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

High-Gradient Channels

(slopes > ~2%, 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
- [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 23).

Floodplains

- [Arcement and Schneider 1989](#) Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains.

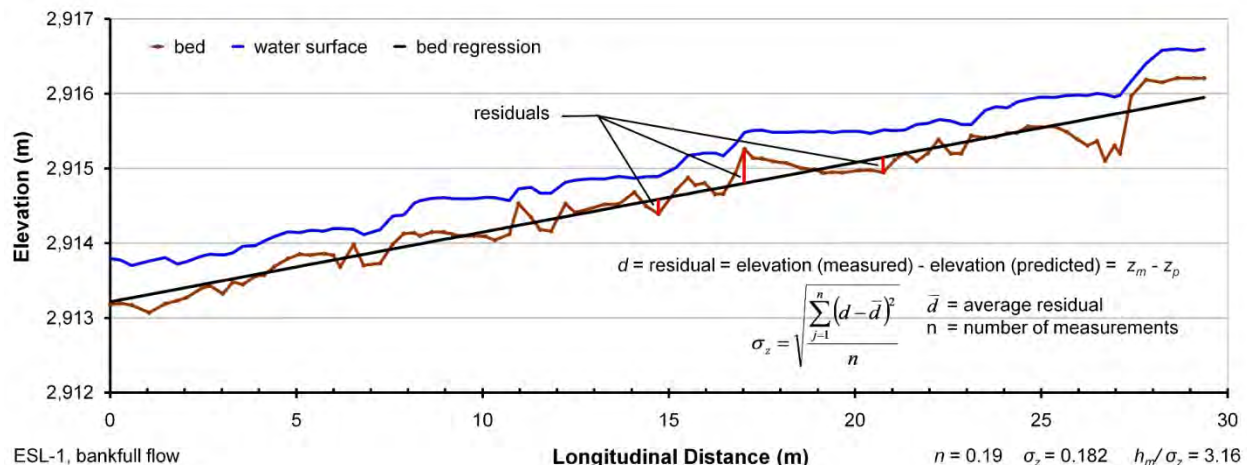


Figure 23: Computation methodology for σ_z (Yochum et al. 2014).

RESTORATION and REHABILITATION DESIGN FEATURES

This section provides guidance for specific planning and design features that are relevant when developing stream restoration and rehabilitation 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.

General references for the design of stream restoration and rehabilitation features are provided in the following publications, as well as in the publications presented in the Overview of Stream Processes and Restoration section.

- [Fischenich 2001a](#) Impacts of Stabilization Measures
- [Fischenich 2001b](#) Stability Thresholds for Stream Restoration Materials
- [Fischenich & Marrow 2000](#) Reconnection of Floodplains with Incised Channels

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

- [NRCS 2007, Ch17](#) Permitting Overview

Vegetation

Riparian vegetation offers a great variety of benefits to stream channels, 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 downstream while increasing flood duration.

In most streams, both woody and herbaceous wetland species are important for bank stabilization (Figure 24), 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).

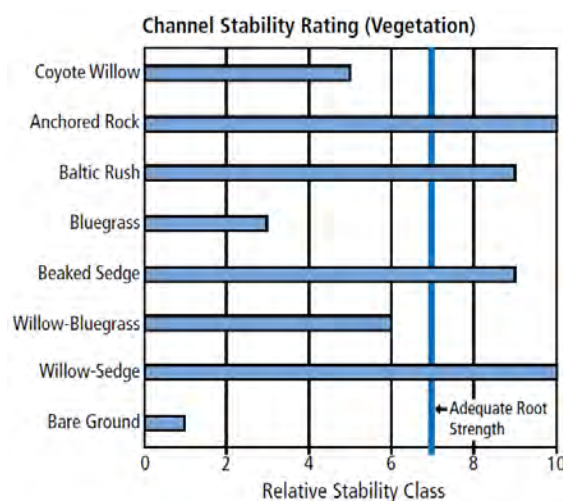


Figure 24: Channel stability ratings for various vegetative compositions (Wyman et al. 2006).

Since vegetation is an integral part of stream corridors, a revegetation component should be included in all stream restoration and rehabilitation projects. Where grazing exists, livestock management should also be included; otherwise, the wisdom of investment into a project can often be questionable. Additionally, previous channelization projects or induced 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 and reduce costs. The use of such tools as a stinger (Figure 25) or an electric hammer drill 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, it is equally important to establish herbaceous plants, including forbs, 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 25: The use of a stinger for vegetative plantings (courtesy nativerevegetation.org).

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

- [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 25)
- [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.
- [Dreessen 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.

- [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 & 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.
- [Shafer and Lee 2003](#) Willow Stake Installation – Example Contract Specifications
- [Hoag & Fripp 2002](#) Streambank Soil Bioengineering Field Guide for Low Precipitation Areas
- [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

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 peak summer 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 can deserve special attention in livestock grazing mitigation efforts. Consequently, exclusion, rest and deferment (Table 6), are typically critical components of stream restoration and rehabilitation projects in grazed areas.

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

A grazing management planning process is presented (Figure 26). 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 5).

Available information and guidance for riparian grazing management includes:

- [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

Table 5: 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

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 is the elimination of large predators, such as cougars and wolves. In areas that have had top predator extirpations, subsequent additional browsing by native ungulates have 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 (Beschta and Ripple 2012).

Table 6: 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
Shuttered 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

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

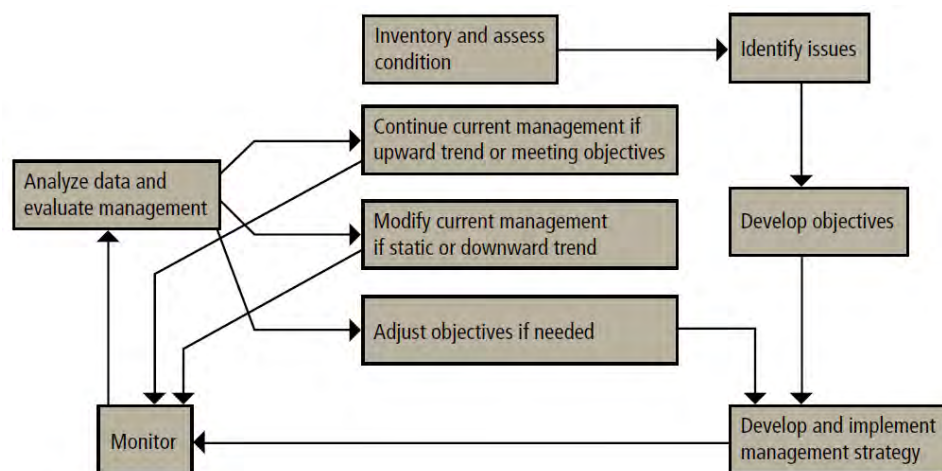


Figure 26: A grazing management planning process (Wyman et al. 2006).

Instream Wood

Most streams naturally have instream wood (large woody debris, LWD; Figure 27) to some extent but such wood has been frequently removed with the objectives of 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 et al. 1991). Removal of instream wood has been found to reduce 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. Increased riparian flow roughness, from instream wood as well as streambank and floodplain vegetation, substantially impacts flood wave celerity, and hydrograph dispersion and skew, with increased vegetation resulting 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.

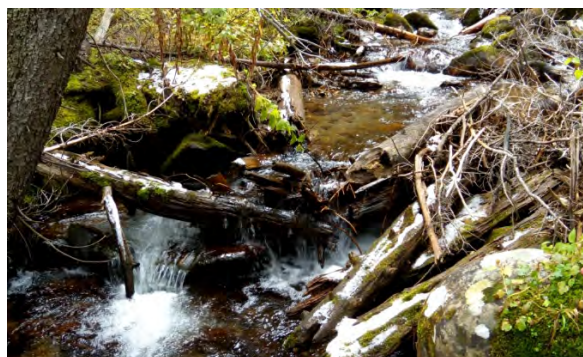


Figure 27: Substantial instream wood loading in a high-gradient stream channel (Fraser Experimental Forest, Colorado).

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). Instream wood has likely been historically prevalent in perennial stream channels, typically

providing 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, instream wood removal was a consequence of such extensive anthropogenic disturbances in Rocky Mountain streams as railroad tie drives (Figure 28) and placer mining. With tie drives, cut ties were driven downstream during peak snowmelt to railroad construction sites, requiring the removal of all instream wood to allow passage of the ties and severely altering the natural geomorphic channel features (Ruffing et al. 2015). A similar practice, splash damming, was utilized to transport logs to downstream mills along the West Coast of the United States, as well as other areas of North America.



Figure 28: Railroad tie drives in the Rocky Mountains resulted in instream wood removal and reduction in longitudinal variability (courtesy of the American Heritage Center).

The inclusion of instream wood into stream designs can be fundamental for satisfying project objectives focused on habitat restoration, since the increase in geomorphic and hydraulic variability benefits ecological diversity. Wood structures, such as toe wood (Figure 45), log vanes (Figure 39) and log jams (Figure 47), can provide these benefits in the short term. In the

long term, proper management of riparian zones for wood production is needed for providing sustainable wood recruitment to stream channels. However, instream wood can be a source of risk to bridge and culvert infrastructure and can also be a recreational hazard.

A summary of the ecological benefits of instream wood is provided at the following sites:

- [BBC Radio4](#): Nature – Wood and Water
- [Maser and Sedell 1994](#) From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans

References and tools helpful for the incorporation of instream wood into stream restoration and rehabilitation projects include:

- [Use of Wood in Stream Restoration](#) NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- [Large Wood Structure Stability Analysis Tool](#) (Michael Rafferty, 2013)
- [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.
- [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 et al. 1991 Rehabilitating and Modifying Stream Habitats (in [Influences of Forest Rangeland Management on Salmonid Fishes and Their Habitats](#))

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.

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 et 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 29).



Figure 29: Meadow restoration of Whychus Creek, Oregon (photo credit: Russ McMillian).

- 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.
- 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 45).
- Beaver reintroduction: Use of reintroduced beaver colonies to recover degraded stream corridors (Figure 30; discussed in a following section).



Figure 30: 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 47).
- Cross vane and W-weirs: Rock weirs installed to maintain pool habitat and channel grade control (Figure 49).
- Log or rock bank vane: Bank vane installed to narrow channels, provide bank stabilization, and to maintain pool habitat (Figure 38, Figure 39, Figure 40).
- 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 et 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 (Newberry et al. 2011).
- LUNKERS (Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids): Provide cover, refuge from high velocities, and bank stabilization; [NRCS 2007, TS140](#)).
- 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.

Design guidance for some of these habitat-enhancing features is provided in the following sections. Additional guidance and background material with respect to aquatic habitat enhancement and environmental flows is provided in:

- [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
- [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 et al. 1991 Rehabilitating and Modifying Stream Habitats (in [Influences of Forest Rangeland Management on Salmonid Fishes and Their Habitats](#))

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 (Poff et al. 1997). To improve riparian ecologic function in areas of altered streamflow, methods are being developed for defining natural flow regimes and applying them to 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). However, competing uses for limited water resources will be an ongoing problem for stream restoration projects.

Aquatic Organism Passage

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.

Road crossings provide substantial and numerous barriers to fish 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.

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.

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 culverts with open 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 31), 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 31: 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 32; Schmetterling et al. 2002).



Figure 32: Pool and weir fishway.

Helpful references discussing barriers and methods for fish passage include:

- [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.
- [USFS 2008](#) Stream Simulation: 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
- [Rosgen 2006](#) Cross-Vane, W-Weir, and J-Hook Vane structures: Description, Design, and Application for Stream Stabilization and River Restoration
- [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

USFS & NRCS tutorials and webinars discussing road crossing barriers and mitigation:

- [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 (gabions). A key component of an effective barrier includes a splash pad, to minimize fish acceleration.

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 33) allow the diversion of water without the accompanying fish and allow the safe return of the fish to their stream of origin.

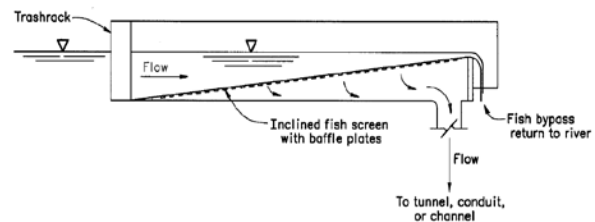


Figure 33: Fixed, inclined fish screen (courtesy Burgi et al. 2006).

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:

- Befford 2014 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)

Beavers

Through their dam-building activities, North American beavers (*Castor canadensis*) can cause a great deal of morphological and ecological changes in riparian corridors (Figure 34). 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.

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, increase mean temperature (potentially increasing temperature to more optimal levels in high-elevation streams), increase spawning sites (by reducing fine material deposition downstream of ponds and inducing gravel deposition upstream of ponds) and can be important refugia for fish from winter ice (Collen and Gibson 2001). 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).

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). The specific site and extent of the beaver population will dictate if beavers will provide net benefits.

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

- [Pollock et al. 2015](#) The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains
- [Beaver Wiki](#) Shared information on the impacts and benefits of beavers in streams
- [Cheap & Cheerful Stream Restoration – With Beaver](#): webinar on techniques and research surrounding partnering with beaver in restoration design, from Utah State University (Joe Wheaton and Jeremy Christensen)
- [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)

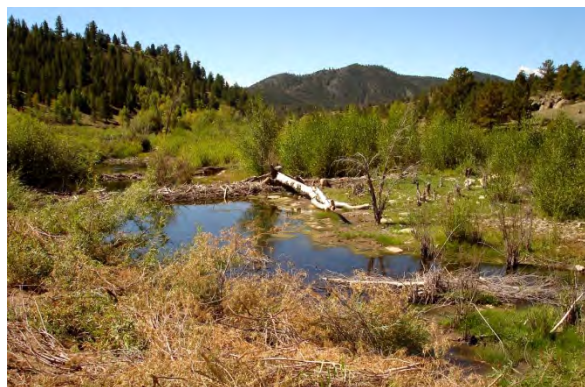


Figure 34: Beaver-dominated stream corridor (photo credit: Barry Southerland).

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 35), and beaver bafflers, a cylindrical wire mesh or perforated pipe device that provides stage control (Figure 36) 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. 2015](#) 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 35: Beaver deceiver (Brown et al. 2001).

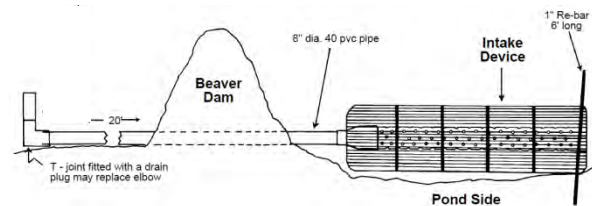


Figure 36: Beaver baffle (Clemson University 1994).

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 bank 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 action 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 (helical 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 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](#) Integrating Recreational Boating Considerations Into Stream Channel Modification & Design Projects

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 at times. However, there are legacy issues that can arise when introducing synthetic geotextiles, cable, and rebar into a fluvial setting that should be considered. The long-term fate of such materials should be a consideration.

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.

When planning the use of any structural measures in stream restoration and rehabilitation 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 and rehabilitation 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 environmentally sensitive bank protection measures are provided below:

- [NCHRP 2004](#): Environmentally Sensitive Channel- and Bank-Protection Measures.

Stream Barbs

Stream barbs are low dike structures (Figure 37), 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:

- [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 37: Stream barb (courtesy Jon Fripp).

Vanes

Vanes are a subcategory of barbs. Vanes (Figure 38, Figure 39, Figure 40) 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:

- [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

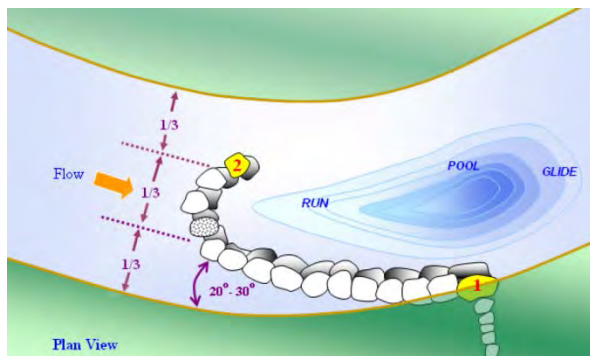


Figure 38: J-hook vane (NRCS 2007).



Figure 39: Log vanes providing bank stabilization and channel narrowing 2 years after construction (Milk Creek, Colorado).



Figure 40: Log J-hook vane providing bank stabilization and pool scour 4 years after construction (Pisgah National Forest, North Carolina; photo credit: Brady Dodd).

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 41; 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:

- [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 41: Bendway weir (Lagasse et al. 2009)

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 42). Flow patterns and scour pool development in the vicinity of spur dikes, as well as other information relevant for design, are provided in:

- [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

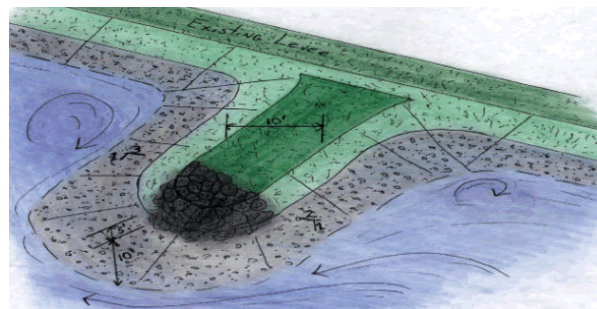


Figure 42: Spur dike (Walla Walla District USACE via Google Images).

Soil Bioengineering

Streambank soil bioengineering (Figure 43, Figure 44) is a technology that uses engineering practices combined with ecological principles to assess, design, construct, and maintain living vegetative systems (NRCS 2007, TS14I). 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 and rehabilitation projects include:

- [Soil Bioengineering](#) Washington State Department of Transportation
- [Zeedyk 2009](#) An Introduction to Induced Meandering – A Method for Restoring Stability to Incised Stream Channels.
- [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 43: Installation of coir fascines (NRCS 2007, TS14I).

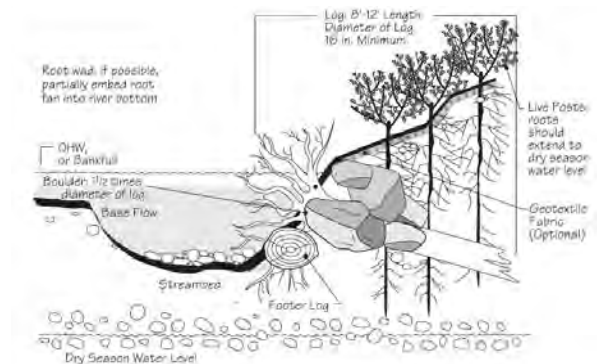


Figure 44: Rootwad with footer section (Eubanks and Meadows 2002)

Toe Wood

Toe wood is a method for constructing a bankfull bench or floodplain surface using primarily unmilled wood as the structural component, soil lifts to create the bankfull surface, and vegetation (Figure 45, Figure 46). 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:

- [Use of Wood in Stream Restoration](#) NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- [Large Wood Structure Stability Analysis Tool](#) (Michael Rafferty, 2013)
- [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

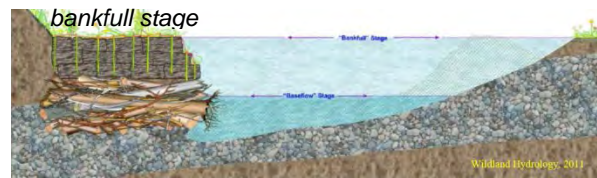


Figure 45: Toe wood cross section (Wildland Hydrology)

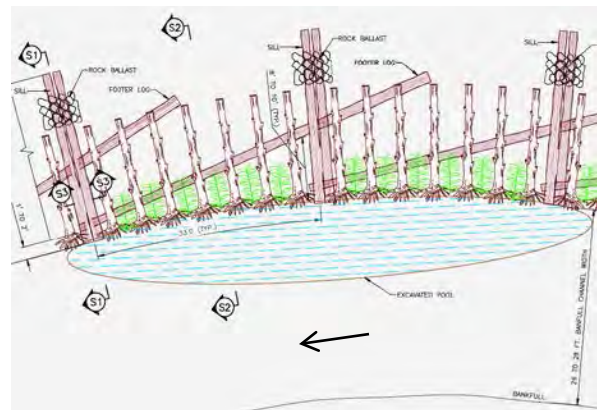


Figure 46: Two cells of a toe wood plan view. This configuration is intended for high-bank locations, with rock-ballasted sills embedded in the bank.

Log Jams

Log jams (Figure 47; 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 37), 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 47: Log jam (photo credit: Paul Powers)

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

- [Use of Wood in Stream Restoration](#) NRCS webinar, 2015 (Jon Fripp, Rob Sampson)
- [Engineered Log Jam Calculations](#): Spreadsheet tool for the design of engineered log jams (Scott Wright).
- [Large Wood Structure Stability Analysis Tool](#) (Michael Rafferty, 2013)
- [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

Rock Walls

Rock walls (Figure 48) 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

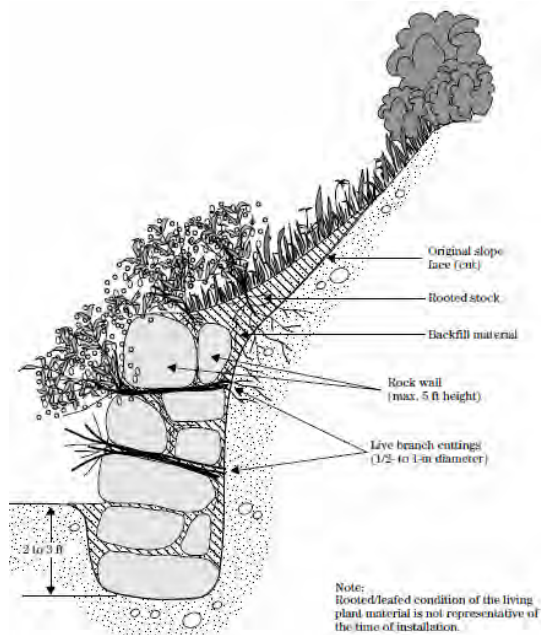


Figure 48: Vegetated rock wall (NRCS 2007, TS-14M)

Rip rap

Rip rap is a basic bank protection tool that can be used alone or in combination with other structural methods. Rip rap is a needed bank stabilization tool in some situations, such as where infrastructure protection is required. The use of rip rap should be minimized, since rip rap can impair vegetative growth and eliminate ecologically-important undercut banks for many decades (Thompson 2002). Generally, rip rap 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, rip rap has been noted to be beneficial to some species in degraded systems or where little bank complexity already exists. Additionally, the negative impacts of rip rap 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 sizing rip rap include:

- [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

Bed Stabilization and Stream Diversions

Incising streams can 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. Grade control is a frequently-used component of stream restoration and rehabilitation projects, to provide for bed stabilization.

Channel spanning vanes and weirs are common grade control structures. A cross vane type is shown (Figure 49). Such structures are also useful component for gravity-fed stream diversions. 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. Bed stabilization structures can act as substantial barriers to some types of aquatic life passage; this should be accounted for in their application.



Figure 49: Cross vane on the Rio Blanco, CO (NRCS 2007, Ch11).

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.

For a U-type structure (cross vane), 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 50). 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:

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

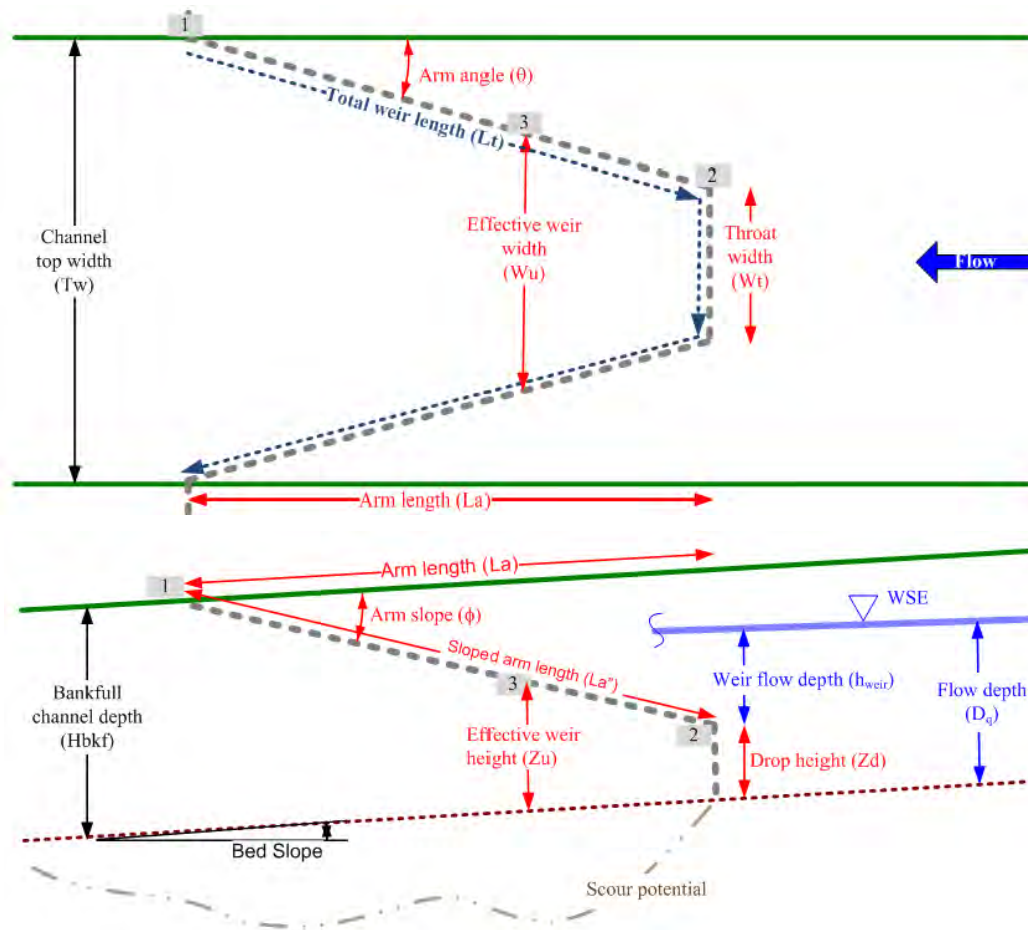


Figure 50: Variable descriptions for U-vane stage-discharge rating (from Holmquist-Johnson 2011).

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

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

- [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
- Holmquist-Johnson 2011 Numerical Analysis of River Spanning Rock U-Weirs – Evaluating Effects of Structure Geometry on Local Hydraulics
- [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
- [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
- [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](#)

Planform Design

Natural channels are inherently sinuous. Hence, channel relocations require the design of planform characteristics (Figure 51).

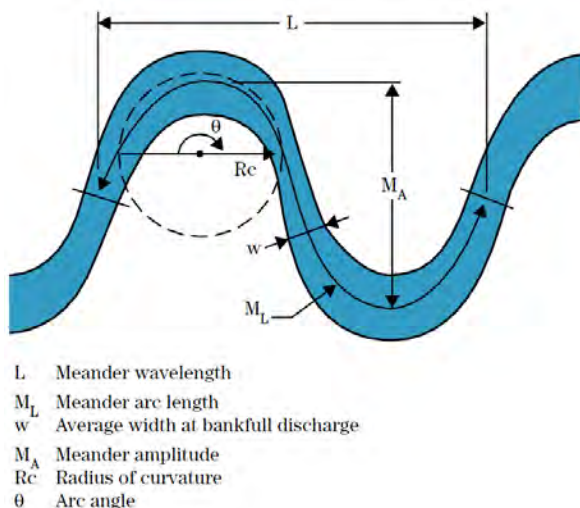


Figure 51: Schematic illustrating variables describing channel planform characteristics (NRCS 2007, Ch12).

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

Dam Removal

Dam removal is increasingly being implemented as a primary approach for addressing such impairments as the lack of longitudinal connectivity for aquatic organisms. This is oftentimes in response to concerns (and Endangered Species Act listings) for anadromous fish, such as in the Pacific Northwest. The following links provide information on dam removals for stream restoration:

- [Clearinghouse for Dam Removal Information](#): Online repository for documents about proposed and completed dam removal projects.
- [The Geomorphic Response of Rivers to Dam Removal](#) (Gordon Grant)
- [Undamming the Elwha](#) The Documentary, 2012 (Katie Campbell and Michael Werner)
- [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.
- [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.

Assess the Success of Riparian Restoration Efforts in Arid and Semi-Arid Landscapes.

- [Thom and Wellman 1996](#) Planning Aquatic Ecosystem Restoration Monitoring Programs.

Monitoring and Reporting

Nationally, more than \$1 billion is spent each year on stream restoration and rehabilitation projects though only 10% of projects report post-project monitoring and assessment (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 and reporting of post-project monitoring data should be priority. Monitoring should be performed to assess fulfillment of project objectives. One of the most important aspects of monitoring streams is to help understand the importance of feedback mechanisms, drawing inferences regarding the impacts of restoration practices. The results should be documented in project reports, at a minimum, and, for more interesting projects, in conference proceedings and case study journal articles.

Guidance for post-project monitoring is provided in:

- [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

SUMMARY

Guidance for stream restoration and rehabilitation 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 and rehabilitation projects.

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

NRCS 2007

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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.

D₅₀, D₈₄, D₁₀₀: The particle size for which 50, 84 and 100 percent, respectively, of the sample is finer. D₅₀ is thus the median size, while D₁₀₀ is the maximum size. D₈₄ 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 stream 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)	(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.