TECHNICAL NOTES

USDA NATURAL RESOURCES CONSERVATION SERVICE COLORADO

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GUIDANCE FOR STREAM RESTORATION

Illinois River, North Park, Colorado

Helping People Help the Land

Advisory Note:

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

ACKNOWLEDGEMENTS

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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 stream restoration. 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 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. The focus is restoration in Colorado in particular and the semi-arid Western United States in general. 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, on a computer connected to the web.

Many potentially useful references for stream restoration projects are cited. However, the quantity of the available literature can be intimidating, even when only summarized. Prudent use of the table of contents can help minimize the potential for being overwhelmed. Additionally, Table 1 provides a quick reference guide for common technical needs.

This document is organized in the typical sequence for assessing, analyzing, and designing stream restoration 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. However, it is important to not interpret this document structure as a philosophical framework for restoration design; that effort is left to other references. Instead, this Guidance for Stream Restoration technical note is a bibliographic repository of information available to assist professionals with the process of planning, analyzing, and designing a stream restoration project.

Table 1: Quick reference guide.

Technical Need	Page
Define goals and objectives for stream restoration projects	2
General methods for developing alternative restoration strategies	3
General references: stream system processes and restoration practices	8
Learn from past restoration projects, through case studies	9
What fish in Colorado are considered of concern, threatened or endangered?	9
Resources for collecting existing background data	10
What should be considered when evaluating condition? What preliminary assessment tools can be applied?	12
What is the Channel Evolution Model?	15
Methods for field data collection (surveying, discharge, water quality, sediment, vegetation, aquatic life)	16
How is bankfull elevation determined?	17
What analyses are performed for restoration designs?	22
How are flow-frequency estimates developed?	23
Computational modeling tools	28
Manning's *n* estimation	31
Role of vegetation for bank stabilization	33
Need and methods for livestock grazing management	35
Structures for bank stabilization (barbs, vanes, bendway weirs, spur dikes, toe wood, soil bioengineering, rip rap)	37
Bed stabilization and stream diversions	41
Role of instream wood (LWD)	42
Fish habitat enhancement	43
Designing for fish passage	45
What are the role of beavers?	47
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GOALS AND OBJECTIVES

One of the most important steps in a stream restoration project is the determination of project goals and objectives. The perceived success or failure of a project is dependent upon thoughtful and consensus-based development of objectives by the stakeholders and technical specialists. Objectives need to be specific, realistic, achievable and measurable (NRCS 2007, Ch. 2).

Project objectives often considered in stream corridor restoration projects include:

- Prevent streambank erosion, to protect residential properties and infrastructure.
- Habitat enhancement for native or sport fishes, to increase abundance and age class diversity.
- Slow the procession of headcutting in a watershed, to protect agricultural lands and infrastructure, and to reduce sediment delivery to downstream reaches.
- Reduce rates of lateral migration of channel meandering, to protect agricultural lands.
- Improve water quality, such as excessive nutrients and sediment, salts, and metals.
- Remove non-native riparian vegetation, such as tamarisk, replacing with more desirable species.
- Reestablish a sinuous channel, from a straight or braided form.
- Establish stream reaches capable of transporting sediment supply.
- Compliance with Endangered Species Act and Clean Water Act requirements.

Once established, general project objectives often need to be clarified through strategies that describe how the general objectives will be attained. For example, in a habitat enhancement for native cutthroat trout where excessive peak summertime temperatures is the primary impairment, an objective of increasing abundance needs to be clarified with such specific strategies 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.

During the planning and design processes, the attributes of the project must be assessed to assure that all the project objectives are being fully satisfied. Often, individual objectives are in conflict and need to be prioritized. After construction, project monitoring should be performed to assess if the project is fulfilling the project objectives. If they are 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 establish objectives for stream restoration 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 conservation planning process, the watershed approach to restoration, an overview of riparian management, adaptive management, extent of design and review.

Interdisciplinary Team

Stream corridor restoration projects are inherently complicated. In most restoration 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, 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 projects need a plan to develop a logical sequence of steps to satisfy the project objectives. The NRCS conservation planning process (Figure 1) 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 alternatives 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.

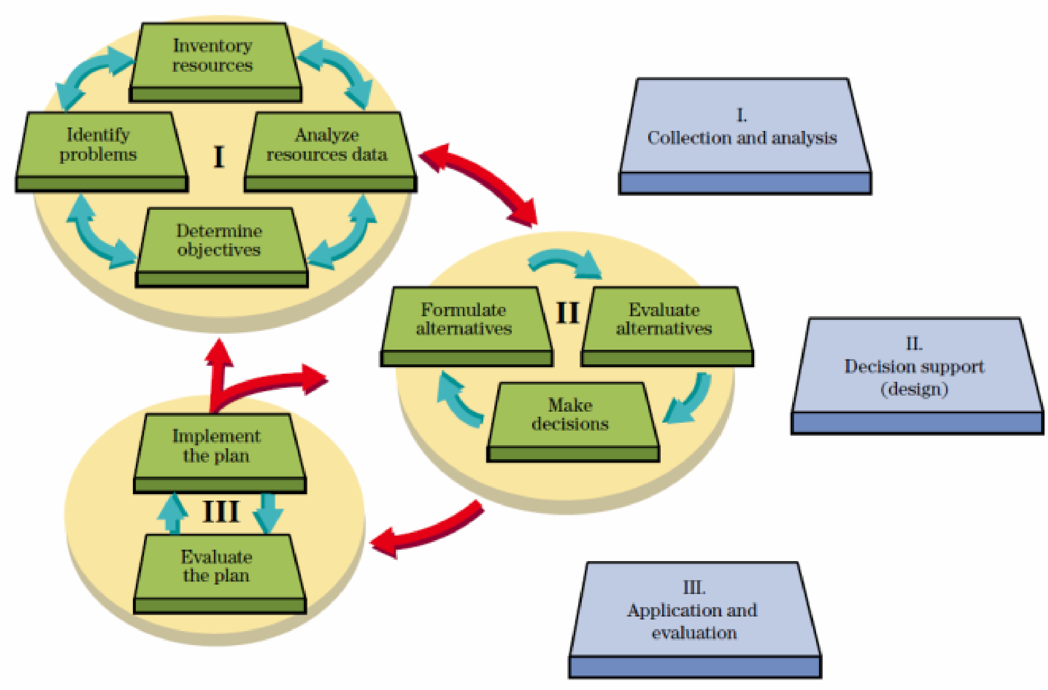


Figure 1: Planning process (NRCS 2007, Ch. 2).

The nine steps are as follows:

1. **Identify problems and opportunities:** What stream characteristics should be changed?
2. **Determine 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 changes. Include a no action option.
6. **Evaluate alternatives:** Which alternatives are sustainable and cost effective?
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; and,
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.

Ultimately, the project needs to balance the needs of the three primary constituents that NRCS represents: the client/producer, the natural resource, and the U.S. taxpayer (Figure 2).

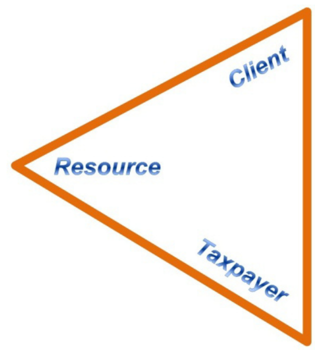


Figure 2: The three primary NRCS constituents, whose needs should be balanced.

Watershed Approach

While technical assistance is typically requested to address local concerns, a watershed approach is needed to address potential underlying mechanisms causing the impairments. An understanding of these mechanisms is necessary to develop an effective response. Relevant questions to address in a restoration 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 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?

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 NRCS synthesis on the conservation benefits of rangeland practices (Briske 2011). This summary report provides a helpful evaluation of 20 management tools (Table 2), evaluating their value through a review of the peer-reviewed literature.

Engineered restoration is often not needed to fulfill stakeholders objectives, with management being all that is required. In other situations, riparian management is used in combination with engineered restoration practices to satisfy project objectives in the desired timeframe. The NRCS describes numerous riparian management practice standards, including such tools as channel bank vegetation (322), fence (382), prescribed grazing (528), and streambank and shoreline protection (580). Such practices may be solely management or can include engineering components. 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.

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 restoration projects. With adaptive management, uncertainty in the effectiveness of restoration approaches, due to limited understanding of mechanisms, is mitigated by "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.

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		
Stream habitat improvement and management (acres)	395	X	X	X	X	
Stream bank and shoreline protection (feet)	580	X	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 3) 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 restoration project. These questions parallel the NRCS conservation planning process.

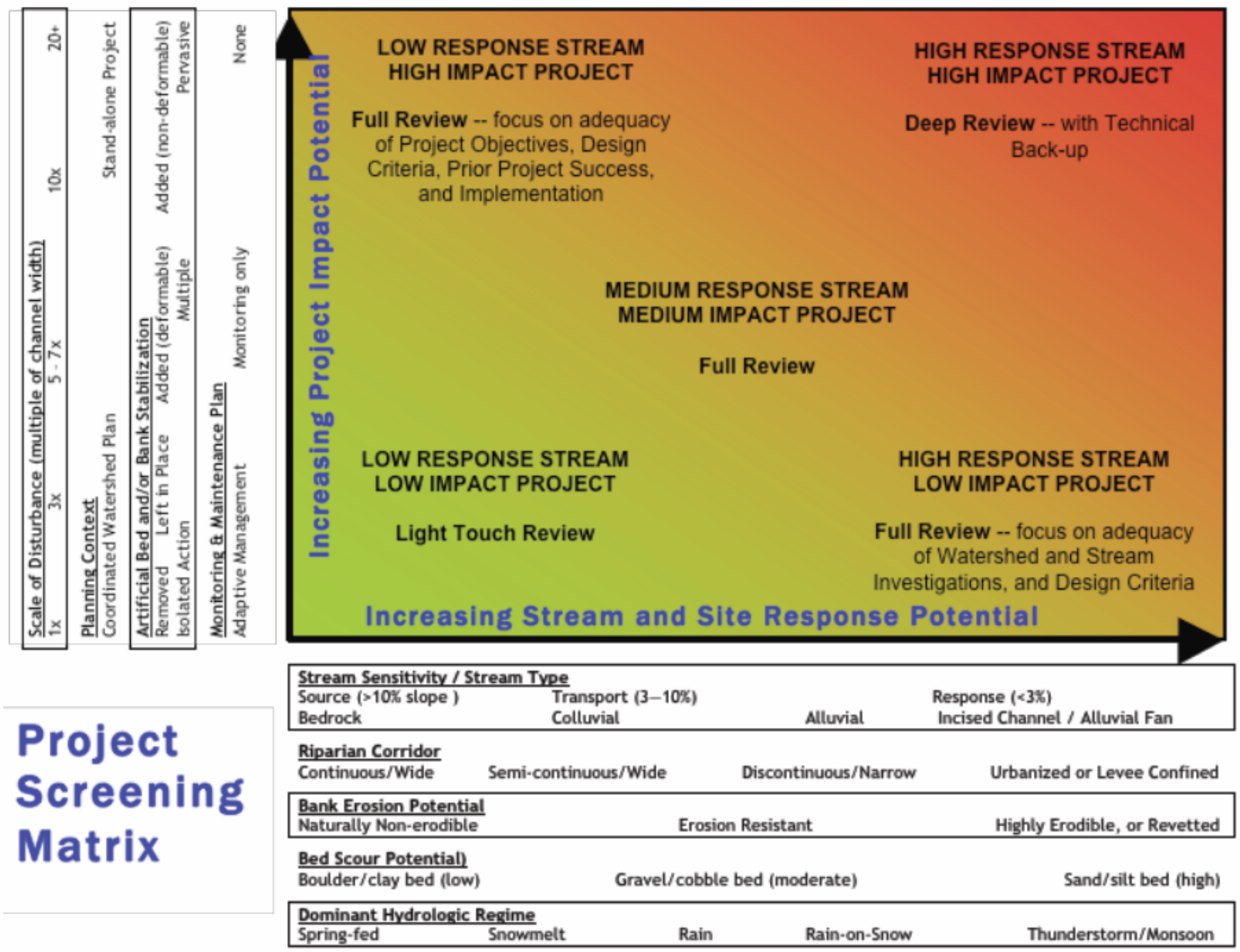


Figure 3: Project screening matrix (Skidmore et al. 2011)

OVERVIEW OF STREAM PROCESSES

Numerous references are available that provide summaries and details of stream processes and restoration practices. Examples include:

- 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.
- Wohl 2011: Mountain Rivers Revisited
- Burton et al. 2011: Multiple Indicator Monitoring of Stream Channels and Streamside Vegetation
- Helfman 2007: Fish Conservation
- NRCS 2007: Stream Restoration Design
- Conyngham et al. 2006: Engineering and Ecological Aspects of Dam Removal – An Overview.
- Kershner et al. 2004: Guide to Effective Monitoring of Aquatic and Riparian Resources
- 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.
- Leopold et al. 1964: Fluvial Processes in Geomorphology

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

- Runoff Generation in Forested Watersheds (Jeff McDonnell)
- Dividing the Waters – Rethinking Management in a Water-Short World (Sandra Postel)
- The Geomorphic Response of Rivers to Dam Removal (Gordon Grant)
- Undamming the Elwha: The Documentary (Katie Campbell and Michael Werner)

CASE STUDIES

NRCS (2007) provides a wide variety of case studies that can aid practitioners in planning and designing stream restorations. These case studies illustrate both perceived successes and partial failures, showing potential project approaches and pitfalls. Appendix A provides a list of the available case studies.

Additional case studies are provided in:

- Major et al. 2012: Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam.
- Sustain 24, Spring/Summer 2011: Stream Restoration
- USFS: Case Studies for Structure Placement in the Aquatic Environment
- 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.
- Alexander and Allen 2007: Ecological Success in Stream Restoration – Case Studies from the Midwestern United States.
- 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

FISH OF CONCERN IN COLORADO

According to Colorado Parks and Wildlife, there is concern that the following native fish species may not be sustainable in Colorado:

- Arkansas Darter, *Etheostoma cragini* (state threatened)
- Bonytail, *Gila elegans* (**federal & state endangered**)
- Brassy Minnow, *Hybognathus hankinsoni* (state threatened)
- Colorado Pikeminnow, *Ptychocheilus lucius* (**federal endangered**, state threatened)
- Colorado River Cutthroat Trout, *Oncorhynchus clarki pleuriticus* (state special concern)
- Colorado Roundtail Chub, *Gila robusta* (federal candidate, state special concern)
- Common Shiner, *Luxilus cornutus* (state threatened)
- Flathead Chub, *Platygobio gracilus* (state special concern)
- Greenback Cutthroat Trout, *Oncorhynchus clarki stomias* (federal & state threatened)
- Humpback Chub, *Gila cypha* (federal endangered, state threatened)
- Iowa Darter, *Etheostoma exile* (state special concern)
- Lake Chub, *Couesius plumbeus* (state endangered)
- Mountain Sucker, *Catostomus playtrhynchus* (state special concern)
- Northern Redbelly Dace, *Phoxinus eos* (**state endangered**)
- Plains Minnow, *Hybognathus placitus* (**state endangered**)
- Plains Orangethroat Darter, *Etheostoma spectabile* (state special concern)
- Razorback Sucker, *Xyrauchen texanus* (**federal & state endangered**)
- Rio Grande Chub, *Gila Pandora* (state special concern)
- Rio Grande Cutthroat Trout, *Oncorhynchus clarki virginalis* (state special concern)
- Rio Grande Sucker, *Catostomus plebeius* **(state endangered)**
- Southern Rebbelly Dace, *Phoxinus erythrogaster* **(state endangered)**
- Stonecat, *Noturux flavus* (state special concern)
- Suckermouth Minnow, Phenacobius mirabilis **(state endangered)**

DATA COMPILATION

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

Data Sources

Multiple federal and state agencies collect and distribute data that are relevant for stream restoration projects. Data sources that can be helpful for restorations include:

Water Quantity

- USGS water data: real-time and historical streamgage information, from the U.S. Geological Survey.
- Colorado DWR water data: real-time and historical streamgage information, from the Colorado Division of Water Resources.
- Colorado Decision Support Systems: water rights, diversion and streamflow data, GIS.
- 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.

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.
- 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.

GIS Data and Mapping

- NRCS Geospatial Data Gateway: GIS data, such as ortho imagery, topographic images and hydrologic unit boundaries.
- USGS Seamless GIS Data: elevation, orthoimagery, landcover, hydrography, etc.
- EarthExplorer: USGS historic aerial photography archive.
- EPA ECHO: Enforcement and Compliance History, from the Environmental Protection Agency.
- NRCS Web Soil Survey: soil data and information.
- National Wetland Inventory: Wetlands and deepwater habitats, from the U.S. Fish and Wildlife Service.
- SoilWeb: Smart phone app. providing GPS-based access to NRCS soil data.
- USFS Watershed Condition: watershed condition class and prioritization information of U.S. Forest Service managed lands.

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.
- FEMA floodplain mapping: 100-year flood inundation boundaries, from the Federal Emergency Management Agency.

Vegetative Information

- PLANTS Database: standardized information about vascular plants, mosses, liverworts, hornworts, and lichens of the U.S. and its territories, from the NRCS.
- Ecological Site Information System: Repository for ecological site descriptions and information associated with the collection of forestland and rangeland plot data, from the NRCS.
- Plant Materials Program: application-oriented plant material technology, from the NRCS.
- Tamarisk Coalition: education and technical assistance for the restoration of riparian lands.
- Colorado National Heritage Program: status and location of Colorado's rarest and most threatened species and plant communities.

Literature

- Google Scholar; USGS Publications Warehouse; Web of Knowledge: for discovering published texts and journal articles relevant to the stream being restored.
- DigiTop: USDA access to journal articles from principle publishers

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 restoration planning and design. Viewing data spatially helps understand context for particular stream reaches. Hence, GIS provides a powerful tool for analyzing stream systems and developing stream restoration designs. Fundamental data that are useful for all restoration 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 could be discarded.

Historical Information

Historical information (historic analogs) can be an important tool for understanding the anthropogenic impacts and the historical range of variability (Wohl 2011) of streams, to provide guidance for the potential condition. Such information can be invaluable for identifying reasonable goals and objectives for a restoration.

Methods for the use of historic information in restoration 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
- 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 an 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 decision points for the technical specialists and stakeholders on if it is desired to proceed with the project and if an active engineering approach or merely 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 restoration reach (Figure 4).

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 the 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 peirs
- 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
- presence of midchannel bars
- uniform sediment deposition across channel
- tributary outlets buried in sediment
- sediment deposition in floodplain
- buried vegetation
- channel bed above the floodplain elevation
- significant tributary backwater effects
- hydrophobic vegetation low on bank or dead in floodplain

evidence of stability
- vegetated bars and banks
- limited bank erosion
- older bridges and culverts with at-grade bottom elevations
- mouth of tributaries at or near mainstem stream grade
- no exposed pipline crossings or bridge footings

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.

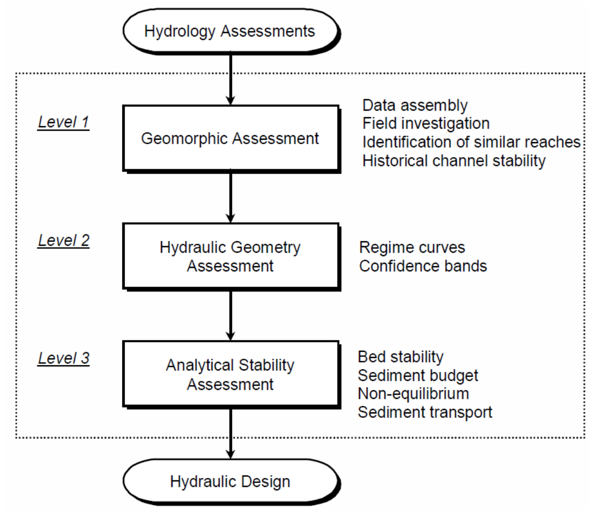


Figure 4: Levels of stability assessments (Copeland et al. 2001).

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)
- Colorado SVAP 2: Colorado version of the national SVAP 2 method. Field Sheet.
- 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)

Stream Classification

Stream classification systems are essential 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 5) 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 6) 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.

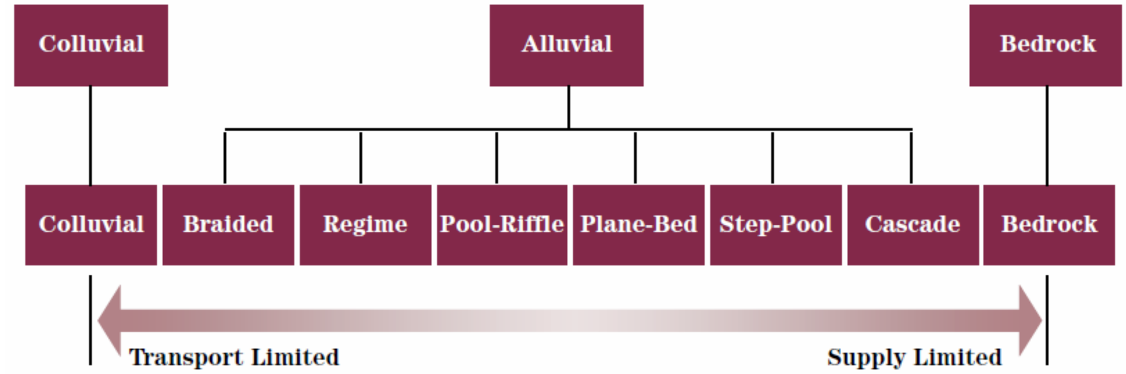


Figure 5: Montgomery and Buffington classification system (NRCS 2007, Ch3).

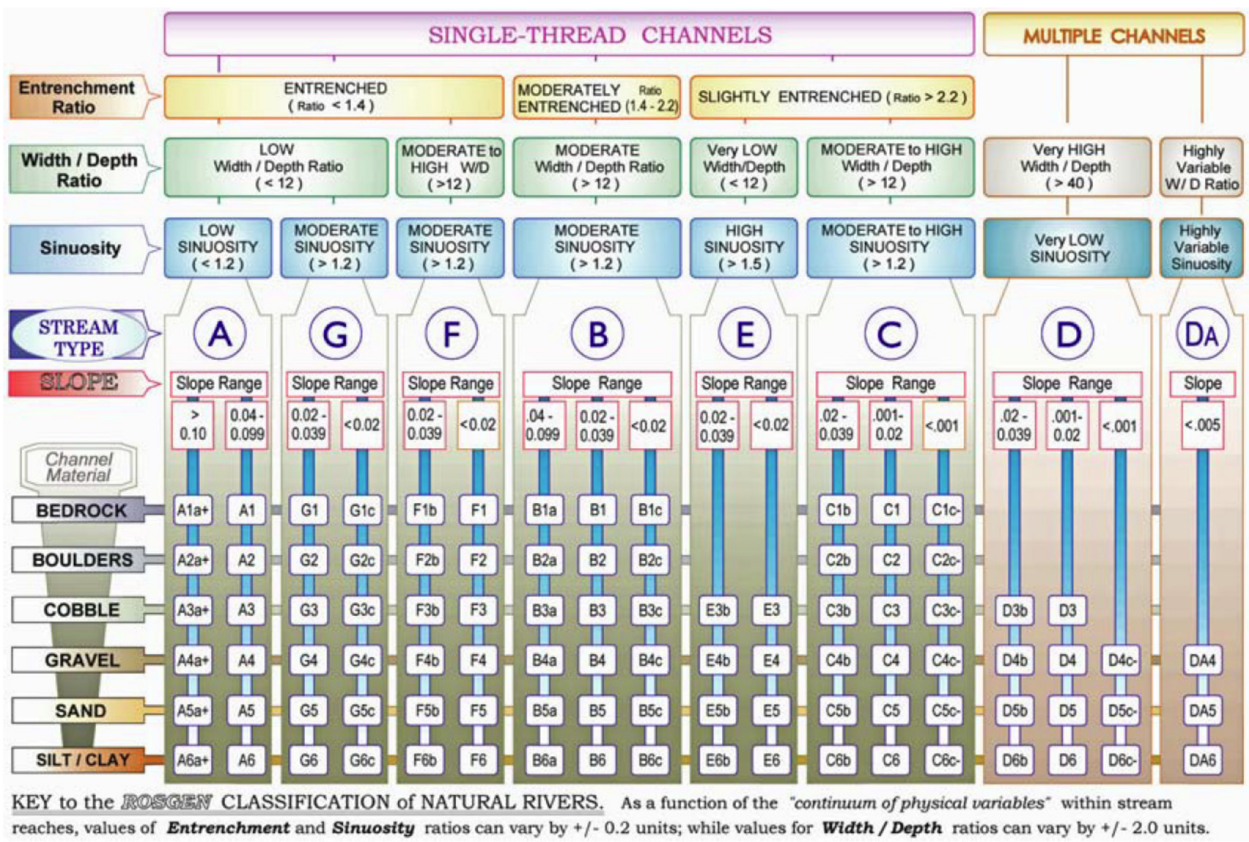


Figure 6: Rosgen classification system (NRCS 2007, Ch3)

Channel Evolution Model

The channel evolution model (CEM), originally developed by Schumm et al. (1981) and modified by Simon (1989) for channelized streams, 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 7), 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 (1989) modified the method to include an additional stage for an anthropogenically-induced, un-incised channelized section. Watson et al. (2002) extended the method by providing a quantitative method for developing channel-restoration strategies.

Additional information regarding this conceptual model is provided in NRCS (2007), chapter 3, as well as 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 8). 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 restoration goals.

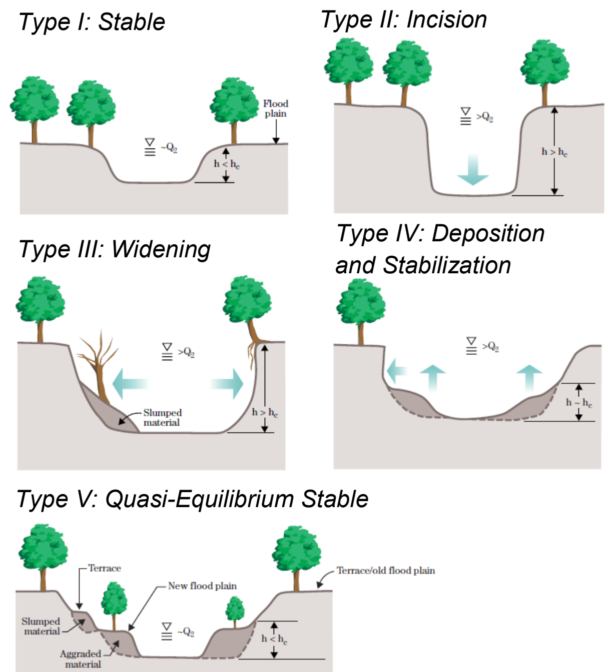


Figure 7: Channel cross sections illustrating the 5 CEM classes (NRCS 2007, Ch3).

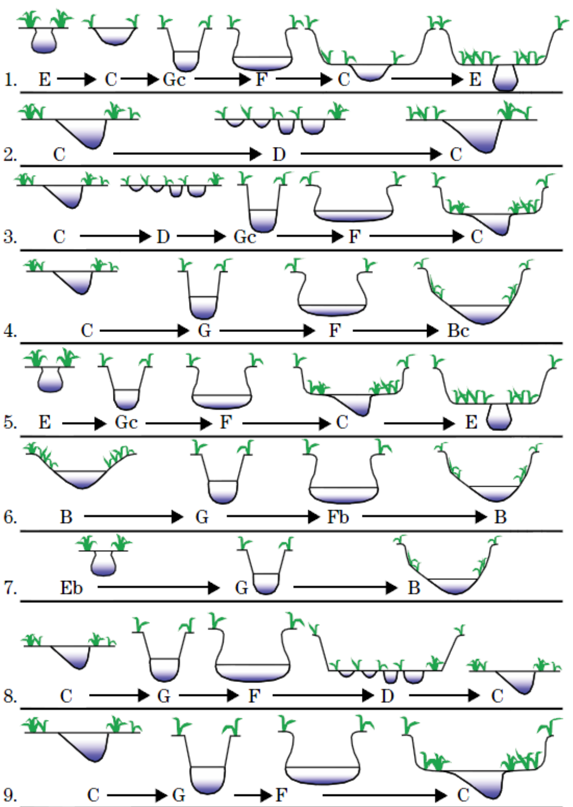


Figure 8: Various possible stream succession stages (NRCS 2007, Ch11).

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 using a tripod-mounted level (traditional or laser) and measuring tape (Figure 9; Harrelson et al. 1994) is a standard technique for stream projects, though survey grade GPS (Figure 10) allows single individuals to collect much more frequent and accurate data points, allowing for a general land survey. 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. Key advantages of survey-grade GPS is the enhanced capability of georeferencing the survey so that the data points can be easily overlayed with other data layers in GIS or Computer Aided Drafting and Design (CADD), and ease in construction layout. To properly georeference the data, an Online Positioning User Service (OPUS) solution is 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.

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 longitudinal profile 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.

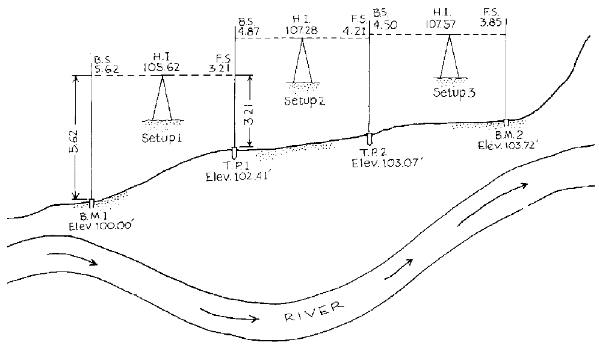


Figure 9: Differential surveying (Harrelson et al. 1994).

Figure 10: Survey-grade GPS.

This latter complexity level of project may require a general land survey of the riparian zone, up the 25-, 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.

Bankfull 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. Due to the fundamental nature of bankfull discharge, accurate identification of bankfull elevation is 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 show some of the best approaches for identifying bankfull elevation:

- A Guide for Field Identification of Bankfull Stage in the Western United States (by Leopold, Emmett, Silvey, Rosgen)
- Identifying Bankfull Stage in Forested Streams in the Eastern United States (by Wolman, Emmett, Verry, Marion, Swift, Kappesser)

Discharge Measurements

Discharge measurements are oftentimes collected for stream restoration work. These data are collected to measure such things as bankfull and low flow discharge, for geomorphic design and habitat assessment. 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
- 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 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. For example, stream temperatures typically have a daily (diurnal) cycle (Figure 11). 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 by channel narrowing, shading, and pool construction. Shading and narrowing can be accomplished by a combination of structures with vegetative planting and grazing management (for a rapid response) or only management (for a slower response). 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.

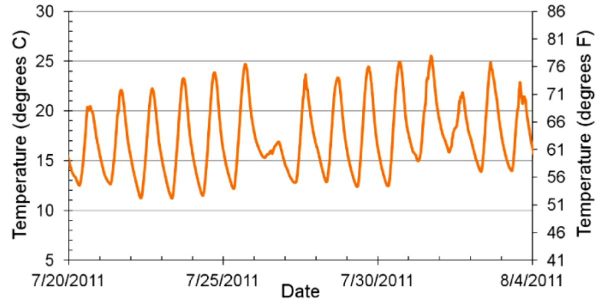


Figure 11: Diurnal temperature fluctuations.

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 is 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

Bed Material Sampling

A 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 excellent 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 12) 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.

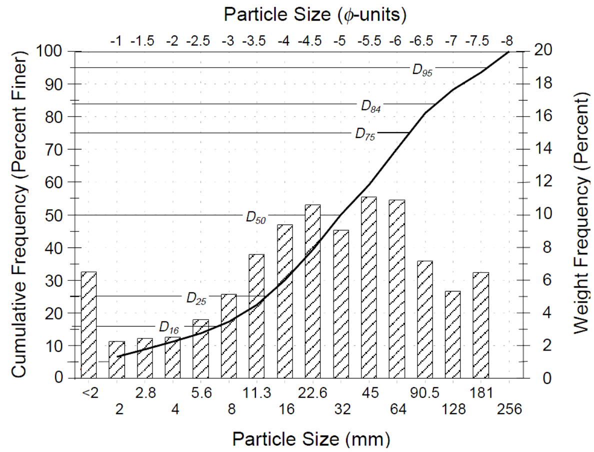


Figure 12: Bed material particle size distribution (Bunte and Abt 2001).

General references 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

Sediment Transport Measurements

Sediment transport continuity is fundamental for stream restorations, with restoration induced aggradation or degradation being common deficiencies in failed projects. 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 and bedload traps (Figure 13). 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.

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

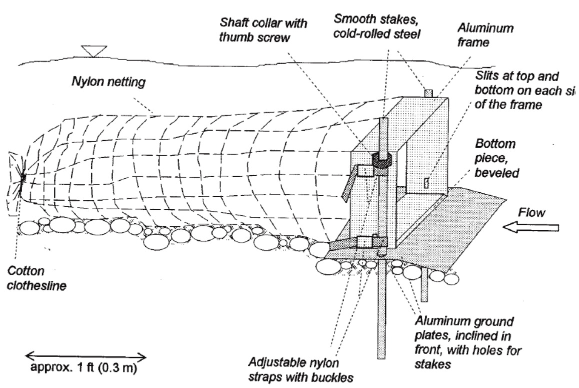


Figure 13: Bedload trap (Bunte et al. 2007).

Riparian Vegetation

Riparian vegetation (Figure 14) offers a number of 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.

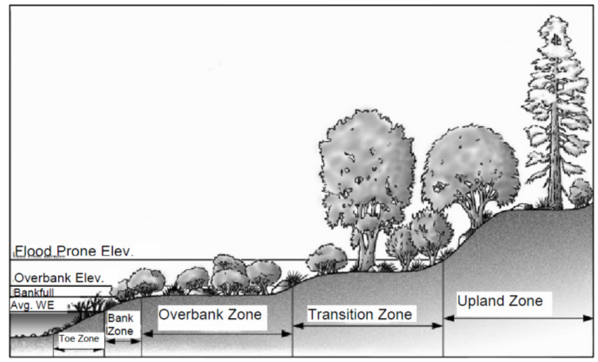


Figure 14: Vegetation zones within a riparian cross section (Hoag et al. 2008).

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 Booklet version. Non-booklet version
- Kershner et al. 2004: Guide to Effective Monitoring of Aquatic and Riparian Resources
- Winward 2000: Monitoring the Vegetation Resources in Riparian Areas

Aquatic Resources

Improvement of aquatic resources and habitat is a common objective of stream restoration projects. To have measureable objectives in such restorations, quantifying aquatic resources 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 15: Fish sampling (NRCS 2007).

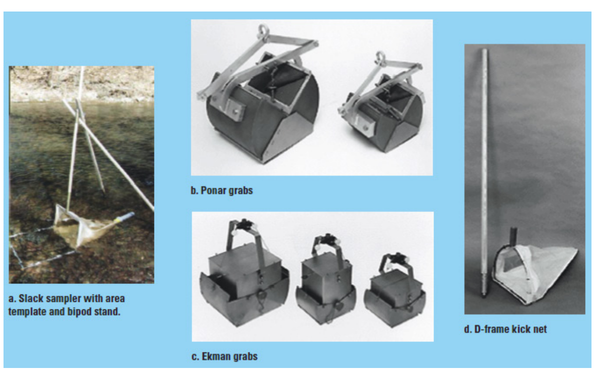


Figure 16: Macroinvertebrate sampling equipment (Moulton et al. 2002).

References and websites for assessing aquatic resources include:

- EPA Bioindicators: Invertebrates as indicators of watershed health
- Aquatic Insect Encyclopedia: Aquatic insects of trout streams.
- WQCD 2010: Benthic Macroinvertebrate Sampling Protocols (Appendix B of Policy Statement 10-1)
- 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
- Barbour 1999: Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish

ANALYSES FOR STREAM RESTORATION

Stream restoration analyses are performed to assure that the channel 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 always relevant 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, restorations 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. Analysis and design approaches that are generally appropriate for restoration projects are: the analogy method, which bases channel dimensions on a reference reach; the hydraulic geometry method, which relies upon hydraulic geometry relationships to select a dependent design variable (such as channel width and depth); and the analytical method, which uses computational modeling (NRCS 2007, Ch7). Designs should be 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
- 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 restoration 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? When is a sediment transport analysis needed? At what flows should sediment transport be computed, only at bankfull flow or for a range in discharges? When is sediment load low enough so that threshold analysis is adequate? These issues should be considered when performing an analysis.

This section provides summary guidance for a few key analysis and design techniques. Topics discussed include flow frequency estimates, bankfull and channel forming discharge, Rosgen geomorphic channel design, Soar and Thorne restoration design, hydraulic modeling overview, hydrologic and ecologic modeling tools, and flow resistance estimation.

Bankfull and Channel-Forming Discharge

Alluvial streams tend to 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). 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 (not low flow). However, the accurate identification of bankfull may be difficult or impossible in highly disturbed reaches.

Bankfull discharge 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 such as Colorado where precipitation varies substantially and irrigation diversions and reservoirs are common, resulting in drainage area alone being ineffective for prediction. Additionally, the variability in regional regressions often reduces their usefulness. This method 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 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 17). 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). This methodology 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

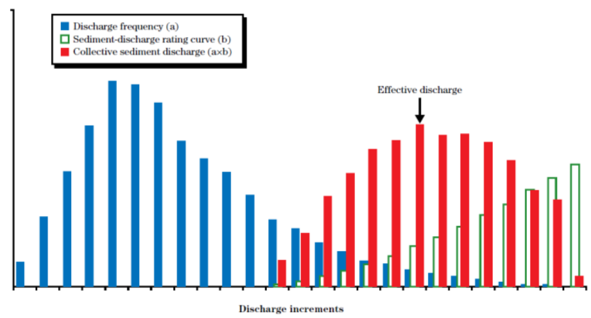


Figure 17: Effective discharge computation (NRCS 2007, Ch5).

Flow Frequency Estimates

Stream restorations typically use bankfull discharge as a primary design discharge, in addition to low flow values for aquatic life. Bankfull flow typically However, less frequent flood events (such as the 10-, 25- and 100-year floods) are also relevant for designs since these larger floods contribute the largest sediment loads to the channel as well as provide the high stresses that instream structures need to be designed to resist. Hence, flow frequency estimates are typically needed for stream restoration designs.

If the project is adjacent to a streamgage that has a sufficient record length, flow frequency estimates (Figure 18) 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.

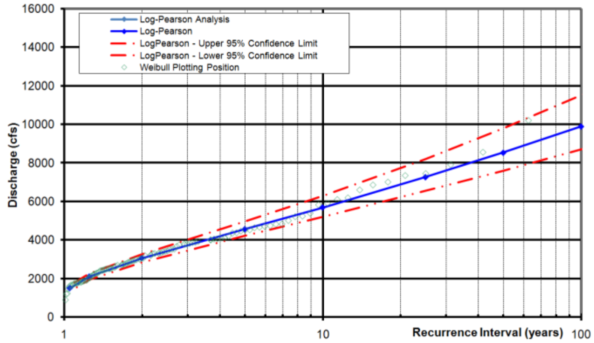


Figure 18: Flow frequency estimates for the Cache la Poudre River, CO (USGS 06752000).

However, most restorations 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. 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 methodology. Details of the prediction methods are discussed in Capesius and Stephens (2009). 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 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 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 19.

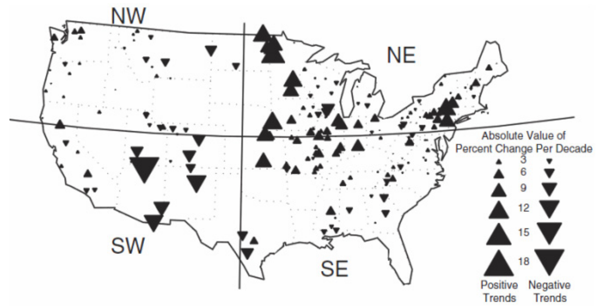


Figure 19: Annual peak discharge trends, with record lengths from 85 - 127 years (Hirsch 2011).

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)
- 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
- Yochum Log-Pearson Frequency Analysis Spreadsheet
- 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 restoration reach with appropriate channel dimension, planform pattern, and longitudinal profile. Figure 20 provides a conceptual outline of this design approach.

Various tools are available for the application of this design method. FLOWSED and POWERSED are 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 restoration 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 restoration reach (Rosgen 2011).

Regional curves, relationships between bankfull discharge and dimensions with drainage area, are simple linear regressions also used to develop the restoration 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 (e.g. PRISM), or irrigated acres diverted.

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

- Rosgen 2011: Natural Channel Design – Fundamental Concepts, Assumptions, and Methods
- Rosgen et al. 2008: River Stability Field Guide
- NRCS 2007, Ch11: Rosgen Geomorphic Channel Design
- NRCS 2007, TS3E: Rosgen Stream Classification Technique – Supplemental Materials
- Rosgen 1996: Applied River Morphology
- Harrelson et al. 1994: Stream Channel Reference Sites – An Illustrated Guide to Field Technique
- Regional Hydraulic Geometry Curves: Repository of regional curves relating bankfull dimensions with drainage area.
- Rivermorph: Stream restoration software developed for application of the Rosgen geomorphic channel design method.

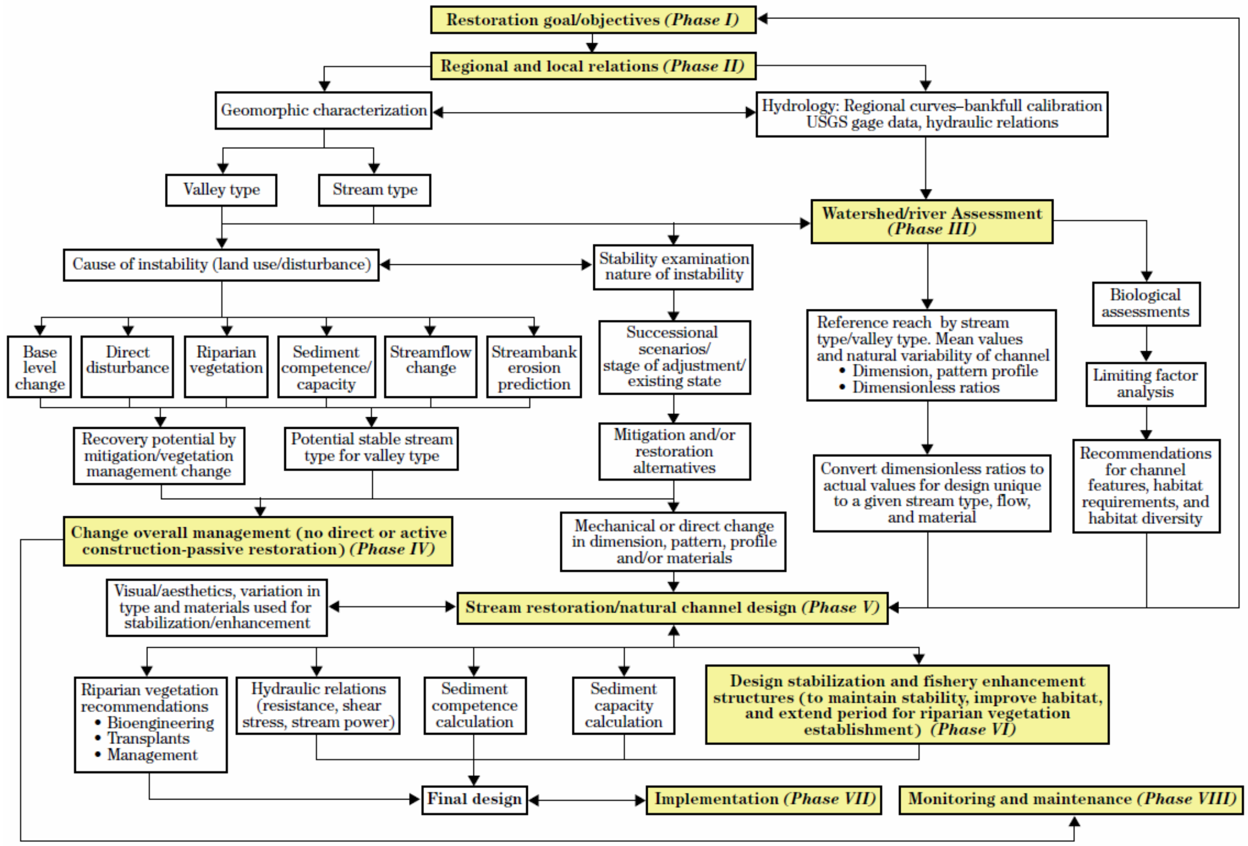


Figure 20: Schematic illustrating the Rosgen Geomorphic Channel Design method (NRCS 2007, Ch11).

Soar and Thorne Restoration Design

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

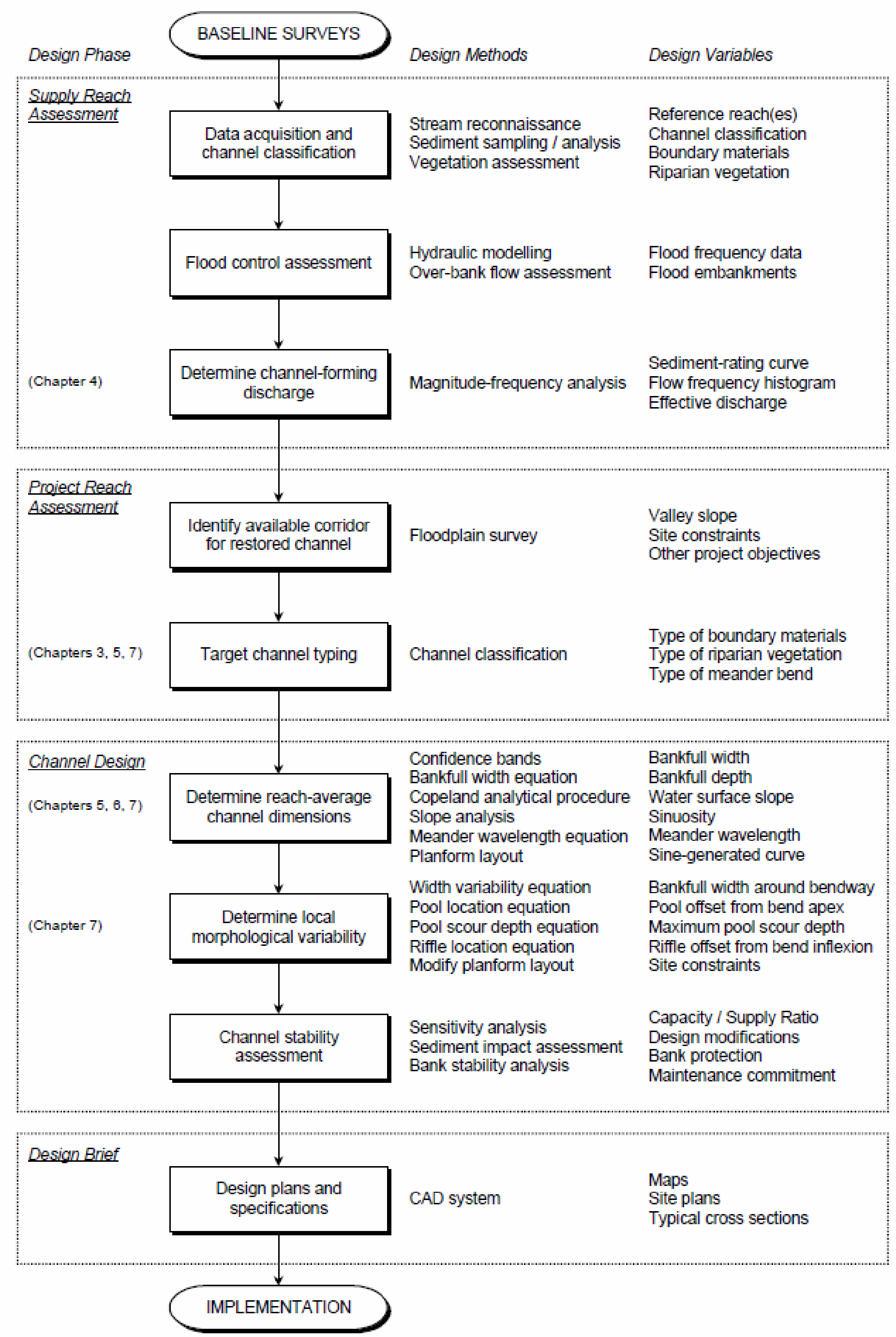


Figure 21: Soar and Thorne (2001) stream restoration design procedure.

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 design, to reduce the potential for restoration to cause undesirable outcomes.

Hydraulic computational modeling in support of stream restoration 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 likely require 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 restoration 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, which needs to be accounted for in the design or accounted for when revising project objectives or extent. 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 needed to assess unintended consequences of extrapolating reference geometry to the restoration reach.

While 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, it is better 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 to deal with ramifications associated with the reconstruction of a failed project that could have been prevented by the development of a HEC-RAS model to guide the original restoration design.

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.

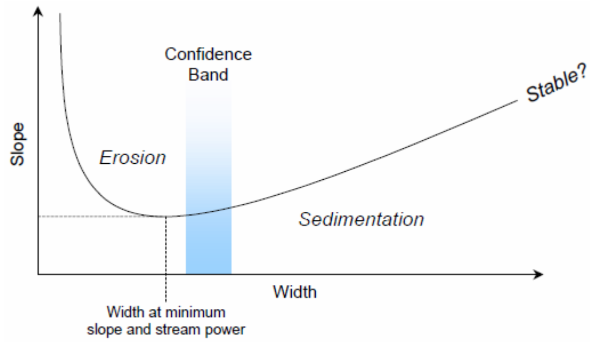


Figure 22: Analytical channel design using the Copeland method (Soar and Thorne 2001).

3. 1-D finite difference unsteady flow modeling, to assess the impacts of a complete 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 the complete 3-dimensional flow characteristics.

Example models used in hydraulic analyses are provided in the Hydrologic and Ecologic Modeling Tools section. Additional general information regarding hydraulic modeling for stream restoration 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 include:

Hydraulic Analysis and Aquatic Habitat

- 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.
- 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 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).
- 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.
- Sim-Stream: Physical habitat simulation model that describes the utility of instream habitat conditions for aquatic fauna, to simulate changes in habitat quality and quantity in response to flow alterations or changes in stream morphology.
    - Impliments the Mesohabitat Simulation Model (MesoHABSIM).

- SRH-2D: 2-D hydraulic, sediment, temperature and vegetation modeling.
- 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).
- 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

- 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 the prediction of flow resistance. 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. In-channel resistance typically decreases as stage and discharge increase; resistance coefficients need to 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 two resistance coefficients can be converted from one form to the other using

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

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

Flow resistance prediction is inexact, with varying results often obtained by different methodologies and practitioners. Experience is fundamental for the selection of the most appropriate resistance coefficient. To address this potential variability, at least two methods should be used and the results compared for consistency. Similarly, reasonable ranges of hydraulic resistance can be described and analyzed at each flow of interest.

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

General Guidance

- 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: Roughnesas Characteristics of Natural Channels

High-Gradient Channels

(slopes > ~2%, cobble- and boulder-bed, step pool and cascade channels)

- Yochum et al. 2012: Velocity Prediction in High-Gradient Channels
- Yochum and Bledsoe 2010: Flow Resistance Estimation in High-Gradient Channels
- Jarrett 1984: Hydraulics of High-Gradient Streams
- Barnes 1967: Roughness Characteristics of Natural Channels

Floodplains

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

RESTORATION DESIGN FEATURES

This section provides guidance for specific design features that are relevant when developing stream restoration projects. These include both traditional engineered structures as well as management, since both are relevant in designs. Guidance is provided for vegetation, livestock grazing, bank stabilization, bed stabilization and stream diversions, planform design, instream wood, fish habitat and environmental flows, fish passage, fish screening, and beavers.

General references for the design of stream restoration features are provided in:

- Fischenich 2001: Impacts of Stabilization Measures
- Fischenich 2001: 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. In most streams, both woody and herbaceous wetland species are important for bank stabilization (Figure 23), with the combination being substantially more effective at bank stabilization than woody species alone (Hoag et al. 2011). 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 inchannel 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.

Since vegetation is an integral part of stream corridors; a revegetation component should be included in all NRCS stream restoration projects. The vegetation used in stream corridor projects should be native, with the source material collected as close to the project site as possible, to assure inclusion of locally adapted plants. The use of such tools as a stinger (Figure 24) or a electric hammer drill can be valuable for willow pole and bundle plantings 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. Ecological site descriptions and historic photographs are valuable for assessing what vegetative communities to restore.

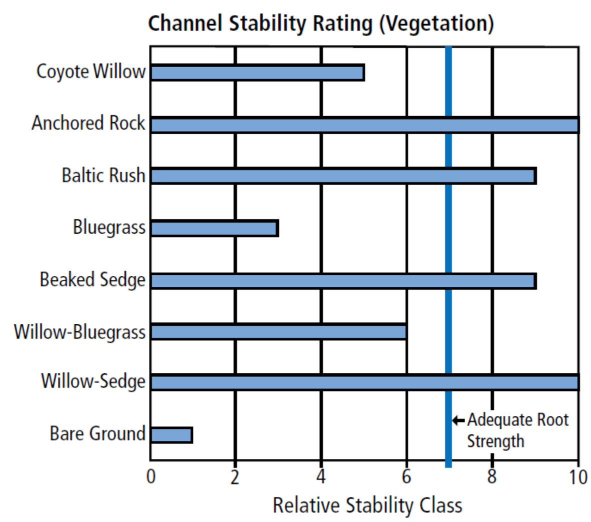


Figure 23: Channel stability ratings for various vegetative compositions (Wyman et al. 2006).

Figure 24: The use of a stinger for vegetative plantings (courtesy nativerevegetation.org).

References helpful for planning and designing vegetation aspects of projects include:

- Cramer 2012: Washington State Stream Habitat Restoration Guidelines
- 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
- Dreenen and Fenchel 2010: Deep-Planting Techniques to Establish Riparian Vegetation in Arid and Semiarid Regions
- Hoag & Ogle 2010: Willow Clump Plantings
- Stromberg et al. 2009: Influence of Hydrologic Connectivity on Plant Species Diversity Along Southwestern Rivers – Implications for Restoration.
- Dreesen and Fenchel 2009: Revegetating Riparian Areas in the Southwest "Lessons Learned"
- Hoag 2009: Vertical Bundles: A Streambank Bioengineering Treatment to establish willows and dogwoods on streambanks
- Hoag et al. 2008: Field guide for Identification and Use of Common Riparian Woody Plants of the Intermountain West and Pacific Northwest Regions. Booklet version. Non-booklet version.
- 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, C. 2001: 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

In riparian zones livestock grazing 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, especially native species such as cutthroat trout. As a result, exclusion as well as rest and deferment, inherent in the various methods of rotational grazing (Table 6), are typically critical components of stream restoration 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; and,
6) controlling season of use.

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:

- Jellison et al. 2007: Response of Prairie Stream Riparian Buffers to Livestock Exclusion and Short-Duration Grazing in Northeast Wyoming – A Pre- and Post-Photographic Comparison
- 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

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 rehabitative potential	Rating
Continuous season-long (cattle)	Heavy	Poor	Poor	Poor	Poor	Poor	1[1]
Holding (sheep or cattle)	Heavy	Excellent	Poor	Poor	Fair	Poor	1
Short duration–high intensity (cattle)	Heavy	Excellent	Poor	Poor	Poor	Poor	1
Three herd–four pasture (cattle)	Heavy to moderate	Good	Poor	Poor	Poor	Poor	2
Holistic (cattle or sheep)	Heavy to light	Good	Poor to good	Poor	Good	Poor to excellent	2–9
Deferred (cattle)	Moderate to heavy	Fair	Poor	Poor	Fair	Fair	3
Seasonal suitability (cattle)	Heavy	Good	Poor	Poor	Fair	Fair	3
Deferred rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Stuttered deferred rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Winter (sheep or cattle)	Moderate to heavy	Fair	Good	Fair	Fair to good	Good	5
Rest–rotation (cattle)	Heavy to moderate	Good	Fair to good	Fair	Fair to good	Fair	5
Double rest–rotation (cattle)	Moderate	Good	Good	Fair	Good	Good	6
Seasonal riparian preference (cattle or sheep)	Moderate to light	Good	Good	Good	Fair	Fair	6
Riparian pasture (cattle or sheep)	As prescribed	Good	Good	Good	Good	Good	8
Corridor fencing (cattle or sheep)	None	Excellent	Good to excellent	Excellent	Good to excellent	Excellent	9
Rest–rotation with seasonal preference (sheep)	Light	Good	Good to excellent	Good to excellent	Good	Excellent	9
Rest or closure (cattle or sheep)	None	Excellent	Excellent	Excellent	Excellent	Excellent	10

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

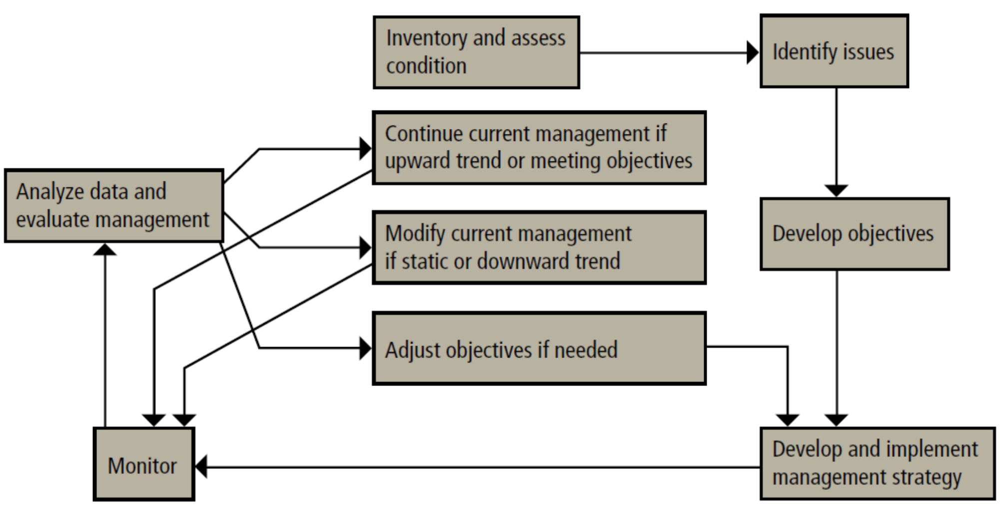


Figure 25: A grazing management planning process (Wyman et al. 2006).

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. The rate of bank erosion is an important consideration when setting objectives and performing a restoration design.

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.

Fundamental in all bank stabilization techniques is the use of vegetation, as discussed above. Channel bank cohesion can vary substantially, with resulting variability in bank erosion rates. Root systems can reinforce bank material up to 20,000 times more than equivalent sediment without vegetation (Knighton 1998). Vegetation provides a fundamental level of bank stabilization, hence the importance of the revegetation component of stream restorations. All NRCS stream restoration projects should include a revegetation component.

There are numerous types of protruding streambank stabilization structures, including stream barbs, vanes, bendway weirs, and spur dikes. 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. Stream barbs, vanes and bendway weirs tend to shift the secondary currents in channel bends (helicoidal flow patterns) away from the banks by forcing overtopping flow perpendicular to the structure alignment, decreasing near-bank flow velocity. These reduced velocities allow planting and recruitment of bank vegetation, enhancing bank stability.

However, a common unintended consequence of protruding streambank stabilization structures is shifts in the channel thalweg causing downstream meander translation. Hence, the use of such streambank stabilization structures may force the need for additional structural streambank stabilization downstream. Additionally, 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

All rock and log bank protection measures typically require the use of filters, such as geotextile filter fabric, to reduce structural porosity and material piping through the structure.

When planning the use of any structural measures in stream restoration projects, it is essential that geomorphic processes and project objectives are first considered before specific structural measures are planned. Oftentimes, restoration professionals have a tendency to default to specific structure types, such as rip rap, J-hooks, bendway weirs, and gabions, without full consideration of the geomorphic context and suitability for a specific project. Additionally, this tendency can lead to bias for or against specific restoration features, potentially excluding the best remediation practice for a specific circumstance. This practice has led to many inappropriate or less effective restoration 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 restorations, including woody armoring revetments, such as root wads, toe wood, and logs; soil bioengineering; rock walls; and rip rap. Descriptions and references for the various types of bank stabilization methods are discussed below.

Stream Barbs

Stream barbs are low dike structures (Figure 26), 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 26: Stream barb (courtesy Jon Fripp).

Vanes

Vanes are a subcategory of barbs. Vanes (Figures 27 and 28) are implemented with an upstream orientation of 20 to 30 degrees from the tangent to the bank line, have a crest elevation at the bankfull level of the bank, and slope 2 to 7 degrees towards the tip. They 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
- Rosgen 2006: Cross-Vane, W-Weir and J-Hook Vane Structures
- Johnson et al. 2001: Use of Vanes for Control of Scour at Vertical Wall Abutments

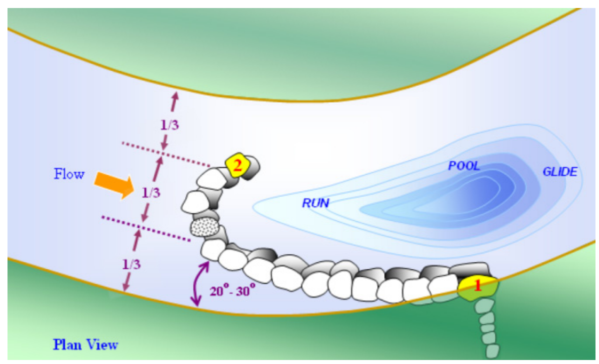


Figure 27: J-hook vane (NRCS 2007).

Figure 28: Log vanes, providing bank stabilization shortly after construction.

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 29; 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

Figure 29: 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 30). 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
- Rahman and Muramoto 1999: Prediction of Maximum Scour Depth Around Spur-Dike-Like Structures
- Kuhnle et al. 1999: Geometry of Scour Holes Associated with 90° Spur Dikes
- Copeland 1983: Bank Protection Techniques Using Spur Dikes

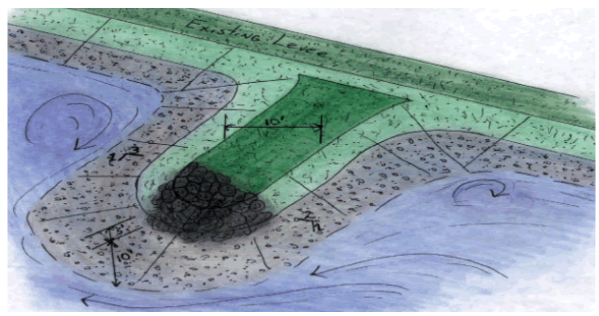


Figure 30: Spur dike (Walla Walla District USACE via Google Images).

Toe Wood

Toe wood is a method for constructing a bankfull bench or floodplain surface using primarily un-milled wood as the structural component, soil lifts to create the bankfull surface, and vegetation (Figure 31). 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. Guidance for the construction of toe wood is currently being developed. However, the following reference is helpful for toewood design:

- Sotir and Fischenich 2003: Vegetated Reinforced Soil Slope Streambank Erosion Control

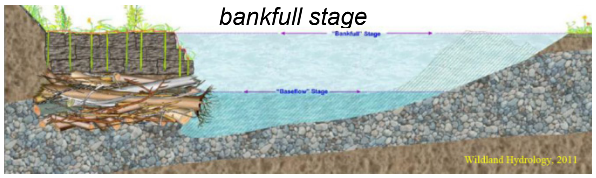


Figure 31: Toe wood (Wildland Hydrology)

Soil Bioengineering

Streambank soil bioengineering (Figure 32) is a technology that uses engineering practices combined with ecological principles to assess, design, construct, and maintain living vegetative systems (NRCS 2007, TS14I). In addition to the previous references provided for vegetation, references for the use of soil bioengineering in stream restorations include:

- 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 32: Installation of coir fascines (NRCS 2007, TS14I).

Rock Walls

Rock walls can be a valuable tool 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

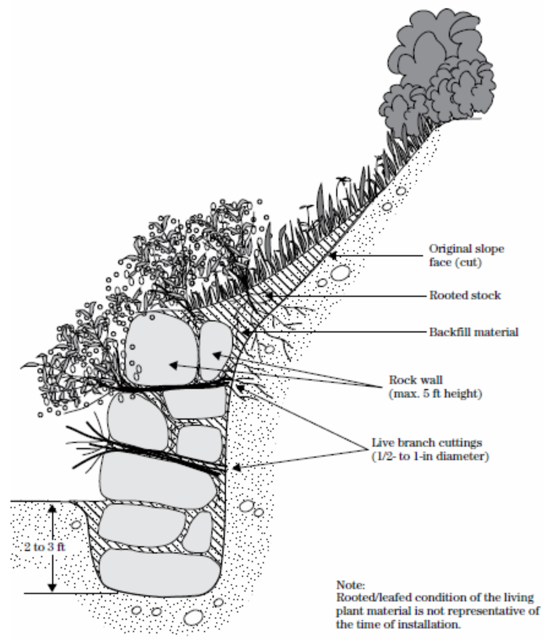


Figure 33: Vegetated rock wall (NRCS 2007, TS-14M)

Rip rap

Rip rap is a basic bank protection tool that can be used alone or in combination with other structural methods. The use of rip rap should be minimized, since rip rap can impair vegetative growth and ecologic function for many decades (Thompson 2002). However, it is a needed bank stabilization tool in some situations where infrastructure protection is required. 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 CEM, as described in the Preliminary Assessment section. Grade control is a common component of stream restoration projects, to provide for bed stabilization.

Channel spanning vanes and weirs are common grade control structures. A cross vane type is shown in Figure 34. 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 aquatic life passage; this should be accounted for in their application.

Figure 34: Cross vane on the Rio Blanco, CO (NRCS 2007, Ch11).

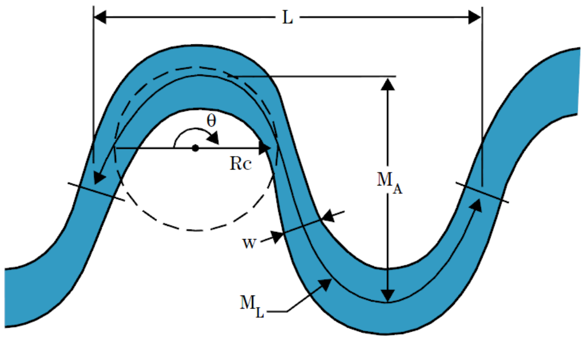
References helpful for bed stabilization and stream diversion structures include:

- Colburn 2012: Integrating Recreational Boating Considerations Into Stream Channel Modification & Design Projects
- Scurlock et al. 2012: Equilibrium Scour Downstream of Three-Dimensional Grade-Control Structures
- Thomas et al. 2011: Effects of Grade Control Structures on Fish Passage, Biological Assemblages and Hydraulic Environments in Western Iowa Streams – A Multidisciplinary Review
- Thornton et al. 2011: Stage-Discharge Relationships for U-, A-, and W-Weirs in Un-Submerged Flow Conditions
- 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
- Rosgen 2006: Cross-Vane, W-Weir and J-Hook Vane Structures
- 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

Planform Design

Natural channels are inherently sinuous to some extent. Hence, channel relocations require the design of planform characteristics (Figure 35). 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



L Meander wavelength
M_L Meander arc length
w Average width at bankfull discharge
M_A Meander amplitude
Rc Radius of curvature
θ Arc angle

Figure 35: Schematic illustrating variables describing channel planform characteristics (NRCS 2007, Ch12).

Instream Wood

Most streams naturally have instream wood (large woody debris, LWD; Figure 36) to some extent but such wood has been frequently removed to increase flow conveyance (clearing and snagging). 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. 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 historically been prevalent in Rocky Mountain 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.

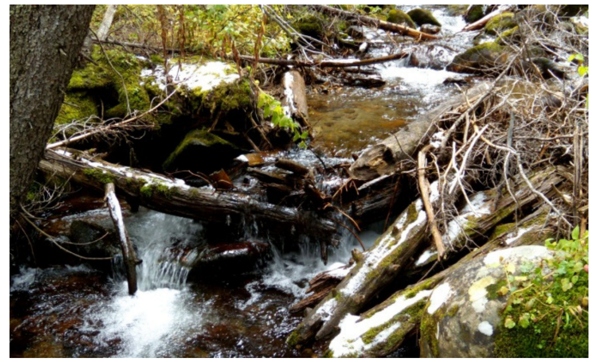


Figure 36: Substantial instream wood loading in a high-gradient stream channel.

For example, instream wood removal was a consequence such extensive anthropogenic disturbances as railroad tie drives (Figure 37) and placer mining. With tie drives, for example, 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.

Figure 37: 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 restoration 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 31), log vanes (Figure 28) and engineered log jams, can provide these benefits in the short term. In the long term, 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 infrastructure and can also be a recreational hazard.

A summary of the ecological benefits of using instream wood in stream restoration projects is provided in the following BBC radio program:

- BBC Radio4: Nature – Wood and Water

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

- 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.
- 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
- 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
- Gippel et al. 1996: Hydraulic Guidelines for the Re-Introduction and Management of Large Woody Debris in Lowland Rivers

Fish Habitat and Environmental Flows

In general, fish need appropriate physical habitat, water quality, and flow to thrive. The lack of longitudinal complexity (riffles, runs, pools and glides) 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 West, sufficient discharge to maintain habitat extent and quality is an ongoing challenge.

There is interest in Colorado for restoration projects that expand habitat for native subspecies of cutthroat trout (*Oncorhynchus clarkia*). To establish or increase cutthroat trout abundance and age class diversity, habitat enhancement structures and management must be developed to provide basic characteristics, specifically:

1. Isolation from non-native fish, by an effective barrier.
    a. Mechanisms for displacement of native fishes by introduced species (rainbow, brown, brook trout) include hybridization, disease transfer, competition, and predation, with the most common failure mechanism for native trout projects being reinvasions by non-native salmonids (Harig et al. 2000).
2. Appropriate temperatures.
    a. Summer temperature extremes below the thermal limit. Using cyclical temperature testing, cutthroat trout respond to peak temperatures of 25 C (77 F) without mortality, 28 C (82 F) with 22 percent mortality, and 29 C (84 F) with 100 % mortality (Johnstone and Rahel 2003).
    b. Summer temperatures high enough to provide for sufficient productivity, with mean July temperatures < 7.8 C (46 F) resulting in delayed spawning and emergence and mean temperatures >10 C (50F) having the greatest abundance (Harig and Fausch 2002).
3. Sufficient habitat for multiple age classes of fish, specifically:
    a. Larger juvenile and adult cutthroat trout require pools, to maintain positive energy balances (Rosenfeld 2003) and provide refuge from peak summertime temperatures. Pools associated with instream wood can be preferred to pools

formed through meander hydraulics (Young 1996). Lakes and beaver ponds can be important as winter habitat, especially in streams lacking large, deep pools (Collen and Gibson 2001; Harig and Fausch 2002).
   b. Young cutthroat trout require stream channels that provide refuge from high velocities and predation by adult fish. Appropriate habitat includes such refugia as bank complexity, instream wood and boulders that are not within pools preferred by larger fish (Bozek and Rahel 1991; Horan et al. 2000; Rosenfeld and Boss 2001).
   c. Instream wood is important to both younger and mature cutthroat trout.
   d. Spawning gravel 10 to 25 cm (4 to 10 inches) deep, with gravel size of 1 to 100 mm and with a median size of 10 to 30 mm (Young 2008).
4. Vegetative canopy, to provide cover and reduce solar radiation, minimizing peak summer temperatures.
5. Diversity in longitudinal and lateral habitat, with connections between patches.
6. Habitat extent of sufficient size to provide required diversity, with length greater than about 6 km (3 mi), stream area greater than about 2 ha (5 acres), and watershed area greater than about 15 km^2 (6 mi^2) (Horan et al. 2000; Harig et al. 2000).

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. 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 management used to provide favorable habitat for the longer term.

For cutthroat trout and other salmonids, the following structures have been used to enhance habitat:

- Cross vane weirs (Figure 34), to maintain pool habitat and channel grade control.
- W-weir, to maintain pool habitat and channel grade control in wider streams.
- Log or rock vane (Figures 27 & 28), to maintain pool habitat and provide bank stabilization.
- Excavated pools, located immediately downstream of structures to provide maintenance of pool depth. Pools provide refuge and can reduce temperature extremes by enhancing hyporheic exchange.
- Excavated pools in meander bends, constructed in ae manner that takes advantage of helical flow for maintenance of pool depth.
- Toe wood, to provide cover, refuge from high velocities, and bank stabilization (Figure 31).
- Side channel and off-channel habitat
- LUNKERS (Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids), to provide cover, refuge from high velocities, and bank stabilization (Figure 38; NRCS 2007, TS14O).

Figure 38: LUNKERS installation (NRCS 2007).

- Bank-attached and mid-channel boulders, to provide refuge from high velocities for juvenile fish (Shen and Diplas 2010). Mid-channel boulders are only appropriate in riffles and should be avoided in narrow streams, since their use can result in increased bank shear stress and instability.
- Constructed riffles, to increase hydraulic complexity and habitat, restore fish passage, and stabilize mobile bed streams (Newbery et al. 2011).
- Drop 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 longevity.

Design guidance for enhancing habitat features is provided in the above Structural Bank Stabilization and Bed Stabilization sections. Additional guidance is provided in:

- 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
- 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

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 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. 2011). However, competing uses for limited water resources will be an ongoing problem for stream restoration projects.

The Colorado Instream Flow Program provides a mechanism for providing environmental flows through appropriation, acquisition, protection and monitoring of minimum instream flow. This program provides a mechanism for water rights to be donated, sold, leased, or loaned to the Colorado Water Conservation Board on a permanent or temporary basis. If an interested water right holder is available, this tool can be valuable for providing minimum flows through a restoration reach.

Fish Passage

Fish passage is often included as an objective for stream restoration work, with irrigation diversion weirs and road crossings being common barriers. Passage is important, since fish populations need habitat diversity to flourish and isolated populations are 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 up to up to 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 high 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 is high velocity, though shallow depth is also relevant (Warren and Pardew 1998).

Crossings that most substantially alter flow from natural conditions may provide the most substantial barriers, which provides a conceptual model for passage design. To reduce these 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 39), 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.

Figure 39: Culvert outlet drop, with Coho.

Fish passage barriers from irrigation diversions are often 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. To reduce the impact of barriers, several options are available including the consolidation of the ditch companies to reduce the number of stream diversions; 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 40; Schmetterling et al. 2002).

Figure 40: Pool and weir fishway.

Helpful references discussing barriers and methods for fish passage include:

- 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
- 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
- Bates et al. 2003: Design of Road Culverts for Fish Passage
- Clay 1995: Design of Fishways and Other Fish Facilities
- Clancy and Reichmuth (1990): A detachable fishway for steep culverts

Examples of diversion-oriented fish passage projects in the Rocky Mountains include:

- USBR 2006: Price-Stubb Fish Passage on the Colorado River – Environmental Assessment
- USBR 2005: Appraisal Study, Fish Passage improvements, Bohannon Creek Diversions 3, 4 and 6, Lemhi River Basin, Idaho
- USBR 2001: Endangered Fish Passage at the PNP Diversion Dam on the San Juan River

USFS tutorials discussing road crossing barriers:

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

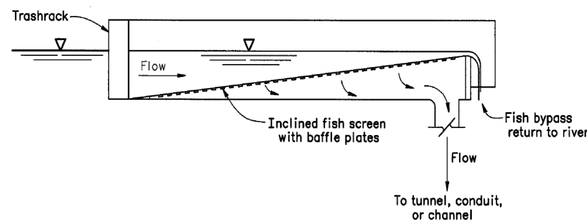


Figure 41: Fixed, inclined fish screen (courtesy Burgi et al. 2006)

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:

- 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

Beavers

Through their dam-building activities, beavers (*Castor canadensis*) can cause a great deal of morphological and ecological changes in riparian corridors. 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). However, the 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 causing barriers to fish passage during low flow (Collen and Gibson 2001). The specific site and extent of the beaver population will dictate if beavers will provide net benefits to a stream restoration.

Background information and guidance for the incorporation of beavers into stream restoration projects include:

- Cramer 2012: Washington State Stream Habitat Restoration Guidelines
- Burchsted et al. 1010: The River Discontinuum – Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters

Figure 42: Beaver-dominated stream corridor (courtesy 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 subirrigation 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 43), and beaver bafflers, a cylindrical wire mesh or perforated pipe device that provides stage control (Figure ??) are 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. References helpful for designing such structures include:

- 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

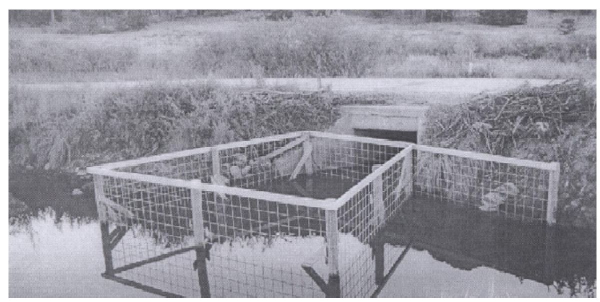


Figure 43: Beaver deceiver (Brown et al. 2001)

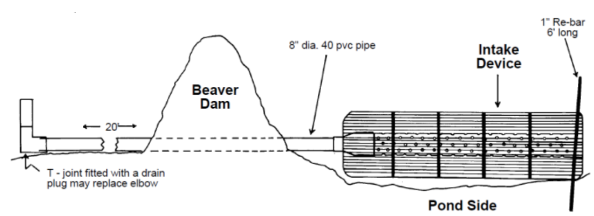


Figure 44: Beaver baffler (Clemson University 1994).

MONITORING AND REPORTING

Nationally, more than $1 billion is spent each year on stream restorations 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 is a high 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.
- NRCS 2007, Ch11: Rosgen Geomorphic Channel Design
- NRCS 2007, Ch16: Maintenance and Monitoring
- Guilfoyle and Fischer 2006: Guidelines for Establishing Monitoring Programs to Assess the Success of Riparian Restoration Efforts in Arid and Semi-Arid Landscapes.
- Thom and Wellman 1996: Planning Aquatic Ecosystem Restoration Monitoring Programs.

SUMMARY

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

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

NRCS 2007

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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.

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

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

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

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

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

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

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

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

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

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

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

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

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

Fine Sediment: Clay, silt and sand sized particles.

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

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

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

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

Fluvial: Pertaining to streams or produced by stream action.

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

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

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

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

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

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

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

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

Hydrograph: A curve showing discharge over time.

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

Ice Types

> **Anchor Ice** – Ice formed on the stream bed materials when, due to outward radiation in evening, they become colder than the water flowing over them.
>
> **Frazil Ice** – Needle-like crystals of ice that are slightly lighter than water, but carried below the surface due to turbulence. This causes a milky mixture of ice and water. When these crystals touch a surface that is even a fraction of a degree below freezing, they instantly adhere and form a spongy, often rapidly growing, mass.

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

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

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

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

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

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

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

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

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

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

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

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

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

Nick Point: See "headcut."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Name	Size (mm)	(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.