Guidelines for Naturalized River Channel Design and Bank Stabilization

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Guidelines for Naturalized River Channel Design and Bank Stabilization

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Sincerely,

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CHAPTER 1.0: INTRODUCTION

1.1 Guidelines Overview

The practice of naturalized river channel design and bank stabilization has expanded over the past several decades, and a lot of work has been done to improve both theory and application. The practitioner can now draw from an expanded toolbox containing a broad range of well-established empirical, analog, and analytical design methods. The continually growing knowledge in applied local rehabilitation and enhancement, and full system restoration has led to an expanded set of available design procedures and tools. To address the challenge of selecting appropriate design methods for each unique project – the art associated with the science of naturalized river channel design and bank stabilization – a project classification system is presented that is based on the project goals, scope, physical site constraints, ecological risks, and likely level of societal acceptance. Classification of a project as routine, moderate, or comprehensive informs the planning process, guides selection of design methods, supports project implementation, and increases the chances for meeting goals and objectives.

Classification of routine, moderate, and comprehensive projects is described in Chapter 2.0, and examples of each are given. The project categories guide the selection of the appropriate design and monitoring. For topics that should primarily be considered according to whether a project is routine, moderate, or comprehensive, a flow chart is presented at the beginning of the chapter that directs the reader to the recommended design or monitoring methodology. The text within the chapters contains method details and reference to existing information.

Chapter 3.0 presents core data requirements that should be collected during the initial assessment of all naturalized river channel design and bank stabilization projects. This basic information can directly inform design on routine projects, and serve as the basis for additional data collections for moderate and comprehensive projects. In addition, findings of an initial assessment provide information to begin the typical project planning sequence – problem identification, determination of goals and objectives, design, project implementation, evaluation and management. There are situations, such as when an emergency repair is needed following a flood, when a complete initial assessment may not be possible, but as much of the recommended data should be collected as possible. For example, quick drainage area calculations from topographic maps can facilitate the use of regional curves that can guide emergency response to damaging flood events. It may be possible to collect some of the initial assessment data in advance of such events in anticipation that they will eventually occur and to be better prepared to respond.

All management activities can influence the biology and chemistry of rivers, and thus it is important to have some understanding of species or water quality parameters targeted for improvement before project implementation. Chapters 4.0 (biology) and 5.0 (chemistry) contain pre-project monitoring recommendations where biological and chemical recovery are included in project goals. The classification of the project as routine, moderate, or comprehensive, in addition to the specific project goals and objectives, guide the level of pre-project assessment. For example, pre-project biological and chemical monitoring is typically minimal for small routine projects where the main goal is infrastructure protection while comprehensive projects often include multiple rounds of data collections. Current monitoring protocols suggest that substantial time and funding is needed in order to confirm biological or chemical change following a river management activity; however, these resources are often not available. Scaled back monitoring recommendations are presented here that fit into the typical duration and funding of current projects. The monitoring recommendations will likely expand in the future as the desire to evaluate project effectiveness through pre- and post-project monitoring continues to grow.

Chapter 6.0 describes the primary types of river channel distress encountered in New Hampshire, and throughout the New England region of the United States. Accurate problem identification is the most important aspect of naturalized river channel design and bank stabilization project as self-sustaining solutions hinge on a good understanding of the sources of impairment. Field indicators of typical types of channel distress are presented to guide problem identification.

The fundamental parts of designing naturalized river channel or bank stabilization projects are hydrology (Chapter 7.0), geometric design considerations (Chapter 8.0), and computational tools (Chapter 9.0) – each used together to perform the alternatives analysis required for effective design. The combination of approaches and methods is a function of the type of project and whether a project is classified as routine, moderate, or comprehensive. In other words, the goals, scope, physical risks, ecological risks, and level of public acceptance determine the appropriate level of design.

Typical channel and bank practices (Chapter 10.0) used in river management projects are described in many existing manuals, and are referenced here for use in design. The application notes and specifications cited here can be obtained from the documents in the electronic library that accompanies these guidelines and is available on the Internet (http://www.des.state.nh.us/Rivers/). A discussion of selecting the appropriate practice and important application details for grade control, soft (bioengineering) bank stabilization, hard (traditional engineering) bank stabilization, habitat features, and riparian zone is presented.

After the design is complete, implementation (Chapter 11.0) takes place once the necessary permits are obtained and access to the project site is granted. Implementation should begin with a review of how actual construction will be done and a general plan to deal with unexpected challenges as they arise. Implementation is concluded with construction inspection.

Funding for design and implementation can take place in different stages for more involved moderate and comprehensive projects. If funding for implementation was not in place at the beginning of the project then additional resources will be needed once the design is complete. Common funding sources for New Hampshire river management projects, as well as typical municipal, state, and federal regulatory permitting requirements are presented.

The final aspect of the project is evaluation and management (Chapter 12.0). As with the pre-project monitoring and design, the appropriate level of project evaluation and available management options is a function of whether the project is classified as routine, moderate, or comprehensive. For example, routine projects with limited biological objectives would receive little post-project monitoring and management, while comprehensive projects with extensive biological goals should be monitored for longer periods of time and may require several phases of adaptive management.

Although introduced in separate chapters as individual aspects of naturalized river channel design and bank stabilization projects, the above components are best treated as an integrated set. To assist with application of the many design principals presented in this guidelines document, checklists of common steps to follow for typical naturalized channel design and bank stabilization projects are presented (Appendix A).

Improving river crossings, removing dams, and establishing natural instream flows are activities that can increase channel stability and the overall health of aquatic ecosystems. Although beyond the scope of this guidelines document, these topics are briefly covered (Chapter 13.0) to summarize existing guidelines used in the State of New Hampshire, in addition to common practices for the New England region.

1.2 Applicability and Accompanying Materials

This guidelines document is created with specific attention to river management in the State of New Hampshire, although applicability will extend beyond state limits and even beyond the region given the widespread use of many of the topics addressed here. Anticipated guidelines users include those participating in the planning, design, review, or construction of river management activities with some existing experience in the topic. A comprehensive glossary of technical terms is included in the back of this document to assist the reader. A white paper on fluvial geomorphology and river restoration (Schiff et al., 2006) was previously drafted to review existing manuals and offer guidelines users an overview of the science behind the applied methods used for naturalized river channel design and bank stabilization projects. The white paper is available on the Internet at the website of the New Hampshire Department of Environmental Services (DES), Watershed Management Bureau, River Management and Protection Program (RMPP) (http://www.des.state.nh.us/rivers/).

The application and theory typically used today for naturalized river channel design and bank stabilization projects is largely published in a variety of existing manuals (e.g., NRCS, 1996; FISRWG, 1998; Watson et al., 1999; MDE, 2000; Copeland et al., 2001; OMNR, 2001; Soar and Thorne, 2001; Flosi et al., 2002; KST, 2002; Cramer et al., 2003; Doll et al., 2003; Saldi-Caromile et al., 2004; NRCS, 2005). An accompanying electronic library of documents that are available for public use has been assembled to connect guidelines users to the appropriate design and background information. The electronic library is available on the Internet at the DES RMPP website (http://www.des.state.nh.us/rivers/).

1.3 A Comment on Standardization of Design Methods

The consensus on the standardization of monitoring and analyses associated with naturalized river channel design and bank stabilization methods is that a one-size-fits-all approach is not possible. The wide variety of problems and solutions, site and watershed conditions, climate, geography, and other aspects require such a broad range of design sequences that standardization is complex. Although standardization of detailed design aspects is not feasible, some generally applicable guidelines are presented here that will help inform routine, moderate, and comprehensive river management projects. The design recommendation made here may need fine-tuning based on the specific details of a given project.

1.4 River Management Axioms

Common themes identified during the review of the existing manuals and drafting of the white paper exposed several fundamental axioms that should be considered throughout naturalized river channel design and bank stabilization projects.

- Where unconstrained, the natural process design approach is less costly to design and implement, and more effectively balances the common goals of channel stability and aquatic habitat improvement.
- Project goals, scope, physical site constraints, ecological risks, and likely level of societal acceptance guide the type and amount of design, and thus accurately classifying project type can help with the appropriate selection of design methods.
- Monitoring (baseline, effectiveness, etc…) at some level (even at a very basic level for small routine projects) should be the first item in the planning process and the last activity of the project where possible. This will help with accurately identifying the problem, informing the design, identifying how the local site or reach change, and evaluating project effectiveness.
- Natural channel stability is not equal to channel immobility. “A stable channel is one that has neither a net deposition nor net erosion of channel substrate in the long term (TRANS, 2001).”
- “Work with, not against, a stream’s natural form and function (KST, 2002).”

CHAPTER 2.0: UNDERSTANDING THE PROJECT VIA CLASSIFICATION

2.1 Introduction

At the beginning of the project, whether it be naturalized river channel design, bank stabilization, or other activities, a clear understanding of the goals, scope, physical site constraints, ecological risks, and societal acceptance is crucial. An initial identification of these five project characteristics supports the planning process (Chapter 3.0), guides pre-project monitoring (Chapters 4.0 and 5.0), assists with selection of appropriate design tools (Chapters 7.0 to 10.0), and increases the chances for successful project implementation (Chapter 11.0 and 12.0).

Five questions are presented in this chapter to guide project classification.

1. What are the over-arching goals?
2. What is the scope?
3. What are the physical site constraints?
4. What is the anticipated level of ecological risk?
5. What is the likely level of societal acceptance?

This chapter contains information to assist with answering these questions. Each question should be occasionally re-visited because an answer to one question will likely add information to another. Based on the responses to these questions, the project will be placed into one of three classification categories – routine, moderate, or comprehensive (Table 2-1 and Figure 2-1).

Table 2-1: Possible responses to project classification questions (A) and definition of classification categories (B).

(A)

Goals	Scope	Physical constraints	Ecological risk	Acceptance
Limited	Small	Low	Low	Low
Stability / Rehab / Enhance	Medium	Medium	Medium	Medium
Restoration	Large	High	High	High

(B)

Project Category	Goals	Scope	Physical constraints	Ecological risk	Acceptance
Routine	Limited to Stability / Rehab / Enhance	Small to Medium	Low to Medium	Low to Medium	Medium to High
Moderate	Limited to Stability / Rehab / Enhance	Medium	Medium to High	Medium to High	Low to Medium to High
Comprehensive	Stability / Rehab / Enhance to Restoration	Medium to Large	Medium to High	Medium to High	Low to Medium

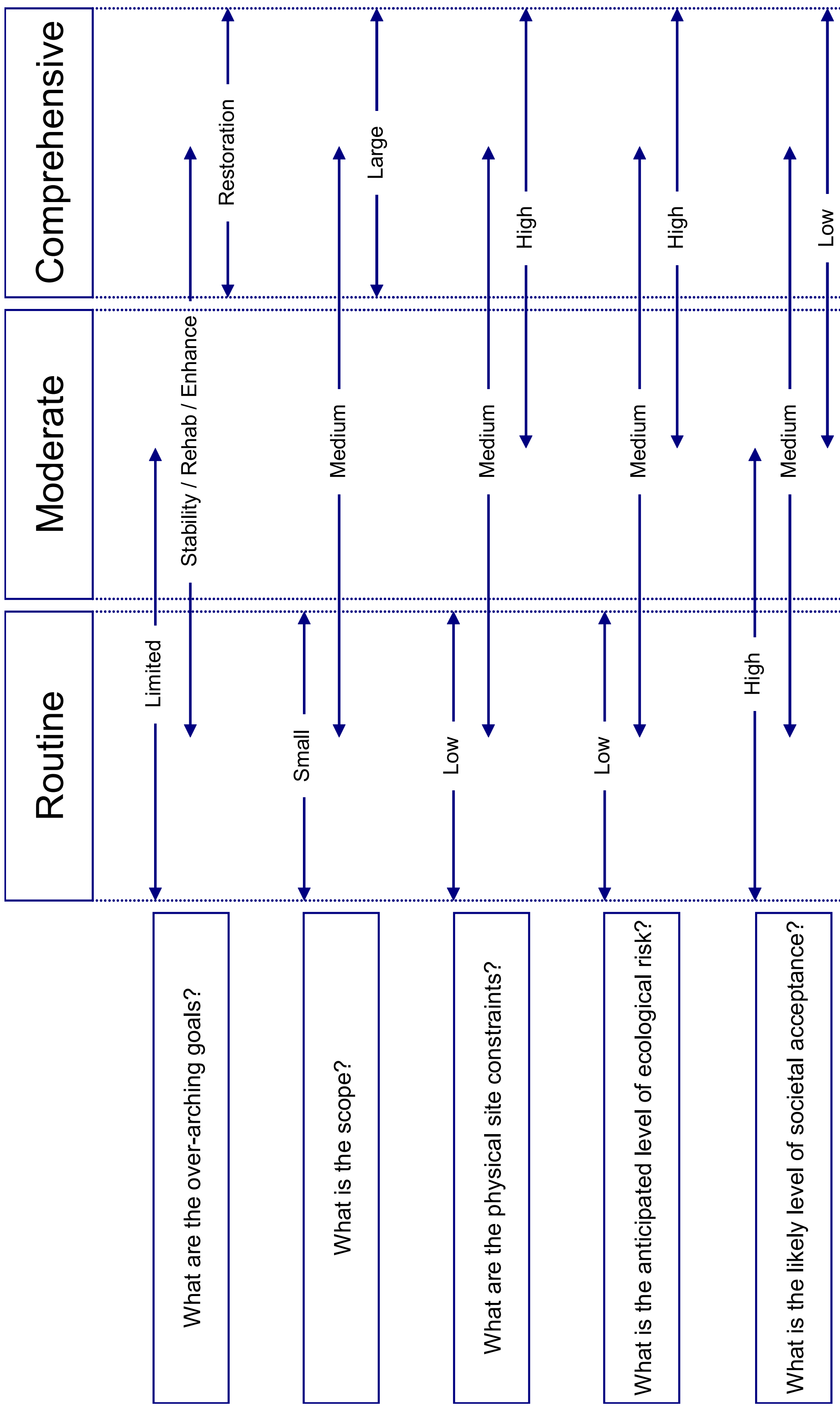


Figure 2-1: Project classification as routine, moderate, or comprehensive based on goals, scope, site constraints, ecological risk, and societal acceptance.

2.2 Goals

What are the over-arching goals of the project?

- Limited: Rapid patches, infrastructure protection, or improve small habitat feature
- Stability, rehabilitation, and enhancement: Natural form-based design with infrastructure protection and habitat improvement components. Often includes combination of hard and soft approaches to stabilize banks.
- Restoration: Full restoration of natural form and process

Goal identification requires thinking about planned goals, in addition to those that are achievable with no or little additional work. There are often biological goals that can readily be included in projects that primarily address other issues such as channel and bank stability, infrastructure protection, erosion hazards, and water quality without substantial change in level of work. Establishment of over-arching project goals often includes the initial phase of creating specific objectives that define narrower project milestones. Differentiating between goals and objectives is important as goals are often too broad to measure, and thus specific objectives are essential for identifying project success.

2.2.1 Created Channel Types

An accurate classification of created channel types based on geomorphic characteristics helps determine the important design principals, biological potential, and the likely social components of a project (Table 2-2). Many of these aspects of channel design are typically addressed superficially during the planning process; however, a clear understanding of created channel types and associated practices such as bank stabilization helps set realistic project goals and objectives.

Table 2-2: Classification of different types of created river channels, including the fluvial geomorphology, habitat, design, and social aspects of each.

		Unnatural Rigid Design	Semi-Natural Form Design	Natural Process Design
Fluvial Geomorphology	Form vs. process	N/A	Form	Form and process
	Planform	Constrained	Partially constrained	Unconstrained
	Profile	Uniform	Non-uniform	Non-uniform
	Cross-section	Uniform, prismatic	Non-uniform, variable	Non-uniform, variable
	Floodplain connectivity	Absent	Variable	Present
	Channel stability	Rigid	Threshold	Equilibrium
	Channel evolution	Static	Static	Dynamic
Habitat	Biological potential	Limited	Rehabilitation/enhancement	Restoration
	Eco-hydraulics	Homogenous	Variable	Heterogeneous
	Substrate	Homogenous	Variable	Heterogeneous
	Streambanks	Hard	Combination	Soft
	Near riparian	Unvegetated	Partly vegetated	Vegetated
	Connectivity	Limited	Typically limited	Lateral and longitudinal
Design	Flood magnitude	Large flood	Bankfull discharge	Low to high
	Sediment regime	Limited information	Limited information	Known
	Method	Empirical & analytical	Analog and analytical	All
	Experience	High	Medium	Limited
	Primary goal	Flood conveyance	Improve structural form	Restore process and form
	Resiliency	High	Variable	Self-sustaining
	Long-term cost	Medium	Medium to high	Low to medium
Social	Aesthetics	Low	Medium to high	High
	Infrastructure	Present	Moderate	Minimal
	Community risk	Low to Medium	Medium to high	Low to medium to high
	Stakeholder involvement	Low	Medium to high	Medium to high
	Public access	Low	Variable	Variable
	Public experience	Moderate	Moderate	Low
	Funding	High	Medium	Low

2.2.1.1 Unnatural Rigid Design

Unnatural rigid channel design uses hard materials to fix channels in place in all dimensions (Figure 2-2), and eliminate natural processes and evolution. This river management method is common for routine projects to protect infrastructure, and emergency repairs after large flood events to stabilize banks and bed. Rigid channels are common in developed areas where human investments are abundant in the river corridor. Although rigid design is effective at reducing local risks due to channel movement, under this design approach erosion problems are often transferred to downstream locations. In addition, a general homogenization of habitat results from this method and severely limits biological potential.

Unnatural rigid design is primarily based on handling large floods, and thus utilizes analytical and empirical methods to determine hydraulic capacity. Little, if any, information on the sediment transport capacity of the channel is typically used during design. Engineers have a lot of experience in rigid, open channel design, yet these installations frequently require periodic maintenance as materials are re-located during flooding. Many guidelines exist for identifying the appropriate material size for stabilization (e.g., NRCS, 1996; Fischenich, 2001) and for design principals (e.g., USACOE, 1994; Richardson et al., 2001).

Figure 2-2: Photograph of an unnatural rigid design component on the Mad River in Compton, NH that was installed with minimal planning to fortify a rapidly eroding bank (Source: DES).

2.2.1.2 Semi-Natural Form Design

Semi-natural form design, commonly referred to as natural channel design, is based on replicating channel morphology in an analogous reach where stable form is present (i.e., the analog approach). The new naming convention of semi-natural form design is presented because as the natural channel design approach became popularized over the past decade information regarding truly natural channel restoration seems to have been lost. For example, semi-natural form design typically has a partially constrained planform to limit channel migration (Figure 2-3), and thus channel evolution is stopped. It is this control that allows for a more natural design approach where site constraints and human investments are present in the river corridor. The increased hydraulic and substrate heterogeneity in semi-natural form design over rigid channel methods improves habitat and increase the biological potential with comparable channel stability.

Semi-natural form design is usually based on using the bankfull discharge as the dominant channel forming flow (e.g., Rosgen and Silvey, 1996; FISRWG, 1998). As with unnatural rigid channel design, this design strategy of using a single flow to shape a channel can be problematic since a river typically is exposed to a wide range of flows. Nevertheless, semi-

Figure 2-3: Photograph of a semi-natural form design on the Piscataquog River in New Boston, NH where a rock vortex weir (pictured above) and rock groins, or barbs, were used to limit erosion, protect infrastructure, and improve habitat (Source: MMI).

natural form design is currently one of the most popular means of river restoration (e.g., Rosgen and Silvey, 1996). Public demand for increased aesthetics and access, improved habitat in constrained project areas, and continued involvement in the restoration process have promoted this design method.

2.2.1.3 Natural Process Design

Natural process design restores channel form and processes where all dimensions remain unconstrained (Figure 2-4), and channel evolution may take place. This truly natural design approach leads to a complex and deformable channel in dynamic equilibrium. Natural process design is only possible where constraints are limited so that channel movement and floodplain inundation do not create conflicts with existing human infrastructure. Natural channel form and processes allows for the establishment of channel stability, and high quality habitat for all flow conditions and biotic life-stages leading to the potential for full biological restoration.

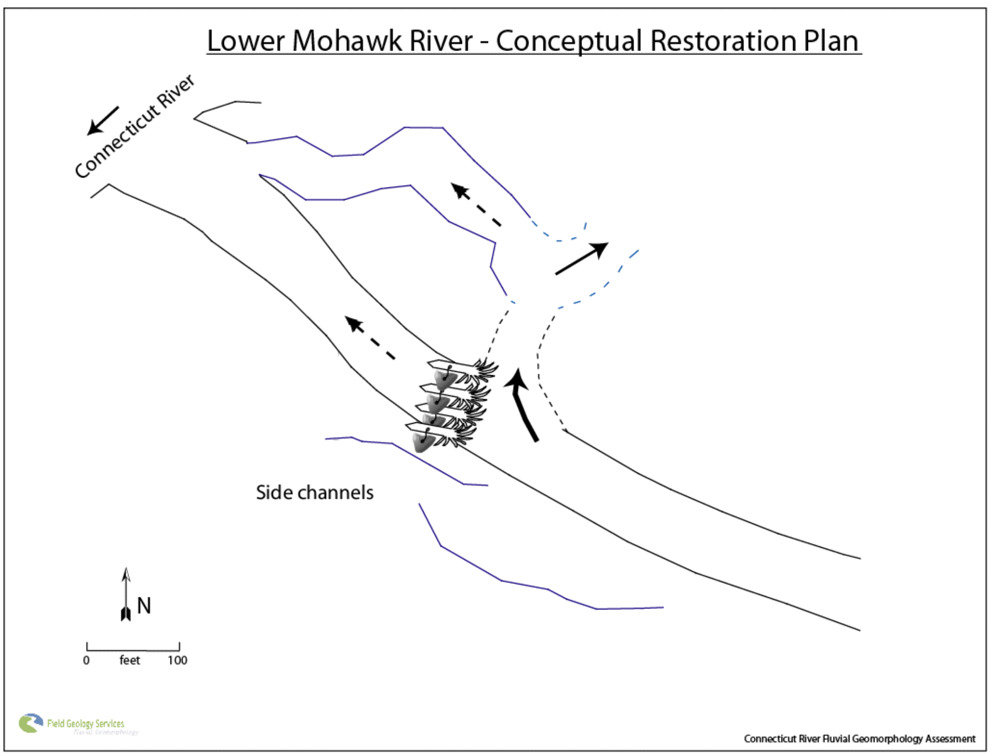


Figure 2-4: Schematic of a natural process design plan for the Mohawk River in Colebrook, NH where flow in the straightened channel is returned to abandoned side channels (Source: Field Geology Services).

Natural process channel design is comprehensive, covering a range of flows and sediment regimes, but is simplified due to the absence of physical project constraints. Empirical, analog, and analytical methods are required to understand how to establish natural process and form. If properly designed, natural process design should require little to no maintenance, create minimal risks to humans, and generate valuable flood attenuation and sediment retention to improve conditions at downstream locations.

Natural process design is usually not possible when infrastructure protection is the main project goal. In addition, there is a general reluctance to set aside land in the river corridor so that channels have enough room to move. This has resulted in limited experience and funding for natural process design projects. The benefits of natural river form and processes are widely known to include the establishment of stable channels with high quality habitat, and thus natural process design should be considered where possible.

2.3 Scope

What is the scope of the project?

- Small: Limited funds and rapid corrective action
- Medium: Moderate funding and project duration
- Large: Substantial investment and long-term project

Project scope is often dictated by the permitting requirements and level of funding, which hopefully are synchronized with the magnitude of the problem being addressed. A small project scope results from a local scale problem that can be corrected in a short period of time with limited funding. On the other hand, projects that are large in scope tend to require substantial funding, have considerable permitting requirements, and can last for a long time.

2.3.1 Regulatory Permits

Some combination of federal, state, and local permits is required for naturalized channel design and bank stabilization activities (Chapter 11.0). An understanding of permitting requirements is important for accurate project scoping as permit applications can increase project cost and time period. Regulatory authorities should be contacted during the initial project classification to identify the required permits for the project.

2.3.2 Funding Sources

Project funding in the State of New Hampshire originates from a variety of sources (Chapter 11.0). While considering project scope it is important to determine if current funds are ample to accomplish goals. Thinking about funding early in the project planning process will reduce the chances of using up the project budget before completion that can delay design, implementation, and effectiveness monitoring. Additional funds will need to be pursued if funding appears to be too low to address the problem. Expansion of project goals may also require additional funding.

2.4 Physical Site Constraints

What is the level of physical site constraints associated with the project?

- Low: No infrastructure present in floodprone width
- Medium: Infrastructure present in the floodprone width that is subject to flooding and erosion hazards
- High: Infrastructure present in the vicinity of the bankfull channel width that is frequently subject to flooding and erosion hazards

The level of risk to infrastructure and personal property is a key factor in determining the permissible type of design and the required level of detail. For example, a channel creation in a forested area where physical site constraints are absent would have a low risk of property damage due to flooding or erosion, and thus deformable boundary conditions and channel movement would be possible (i.e., a natural process design, see Table 2-2). Channel creation in a town center, on the other hand, where there is a high risk to infrastructure and personal property in close proximity to the project site, would likely require a more rigid boundary condition and immobile channel (i.e., semi-natural form design or unnatural rigid design, see Table 2-2). Project costs and scope tend to increase with the abundance of physical site constraints due to expanded design requirements to reduce the risks to the public. Although site constraints are primarily located near a specific project implementation site, they can also occur further away (e.g., downstream, distant floodplain, and even upstream) and so each project should consider potential affects on any other area.

2.5 Ecological Risk

What is the anticipated level of ecological risk?

- Low: Ecological recovery with a resilient and self-sustaining system likely. Limited chance of additional harm to ecosystem. Complementary multidisciplinary goals.
- Medium: Moderate likelihood for ecological recovery and establishing a resilient and self-sustaining system. Possibility of short-term harm to ecosystem. Multidisciplinary project goals may have some inconsistencies.
- High: Ecological recovery with a resilient and self-sustaining system unlikely. Possibility of long-term harm to ecosystem. Multidisciplinary project goals are in conflict with each other.

Manipulation of the physical components of river channels and banks create risks to aquatic habitat and biological assemblages. Issues such as habitat degradation, disruption of life-cycle requirements such as migration paths and spawning gravels, and changes to nearby wetlands are just some of the concerns to consider when planning a naturalized river channel design or bank stabilization project. Projects with low ecological risk are likely to recover, have a resilient and self-sustaining system, and have a limited chance of causing additional harm to the ecosystem. Such projects typically have biological goals that complement those in other disciplines. On the other hand, high ecological risk is associated with projects where recovery is not straight forward, resiliency and a self-sustaining system are not likely, and biological goals are in conflict with other disciplines. Ecological risk tends to decline with increasing degrees of natural channel form and processes that are permitted in created channel design (see Table 2-2).

2.6 Societal Acceptance

What is the likely level of societal acceptance of the project?

- Low: Not a priority project for the public and use of public funds not supported
- Medium: Public interested in project and willing to allocate some public funds
- High: Strong public support of project with willingness of substantial investment and involvement

The social aspects of a project are important considerations to gain public acceptance, encourage allocation of public money, and promote future stewardship. In many instances where projects take place on or adjacent to private lands, public acceptance of a project is often required for the project to take place at all. In these instances, land-owners should be involved in the project as planning begins. Low priority projects to the public are often poorly understood and thus allocation of public funds is more complicated. High priority projects have the support of a majority of the public, and the problem and solution are understood and desired. Projects with a high degree of societal acceptance tend to be relatively easy to fund. Outreach efforts can increase public awareness and acceptance of a project. Note that while the public might enthusiastically support solving a problem, education and outreach may be needed to gain support or understanding of the most responsible solution.

2.7 Project Classification

The final classification step is to place the project into one of three categories – routine, moderate, or comprehensive based on the responses to the questions outlined above (see Table 2-1 and see Figure 2-1). The project category will be referred to throughout this document to guide design and monitoring. There may be a need to change a project's classification as new information becomes available.

2.7.1 Routine Projects

Routine projects mostly have limited goals that fall under localized infrastructure protection or habitat enhancement. Some routine projects may have expanded goals that include some aspects of channel stability and local habitat rehabilitation. Project scope is small to medium, with low to medium physical site constraints and ecological risk. Routine projects take place at the sub-reach scale, and can be as small as a single geomorphic unit such as a riffle. Public acceptance of routine projects is medium to high due to public familiarity with patch fixes in the river corridor. Examples of routine projects include a local bank stabilization to protect infrastructure, small grade control applications where few structures are present, and introduction of instream features for fish cover where few structures encroach on floodprone and erosion hazard areas.

2.7.2 Moderate Projects

In addition to establishing channel stability, moderate projects include rehabilitation or habitat enhancement goals at approximately the channel reach spatial scale, typically amongst a medium degree of physical site constraints. Some moderate projects can have more site constraints. The presence of infrastructure leads to medium to high ecological risk as frequently-used rigid boundaries at this scale can have negative effects on river components such as near-bank habitat, fish movement, and connectivity. Public acceptance of moderate projects can decrease due to the larger scope, but is typically medium. Examples of moderate projects include form-based naturalized channel design, bank stabilization with a combination of hard and soft practices, and installation of habitat features over a reach where several structures encroach on floodprone and erosion hazard areas.

2.7.3 Comprehensive Projects

Comprehensive projects are medium to large in scope, and often include one to multiple reaches. The goals of comprehensive projects can range from channel stability and local habitat rehabilitation restoration of system processes. Comprehensive projects can have a high degree of risk if many physical constraints exist in close proximity to the bankfull channel width. The large project size leads to increased ecological risks as a large initial disturbance is common during installation of comprehensive projects. Relative to less-involved projects, public acceptance is typically lower for comprehensive projects since they are less common and require substantial funds to complete. An example of a comprehensive project is the restoration of an incised tributary that has unstable channel geometry causing erosion hazards to nearby homes, excessive sediment delivery to the mainstem river, and poor aquatic habitat. Solutions of comprehensive projects are often multi-faceted and for this example could include a combination of active and passive approaches such as natural process and semi-natural form channel design, application of hard and soft bank stabilization components, installation of various types of habitat enhancement features, the purchase and demolition of structures in locations that are permanently prone to flooding and erosion hazards, and the purchase of easements to preserve open space to give the river channel ample room for lateral adjustment to limit future conflicts between human investments and river processes.

CHAPTER 3.0: INITIAL ASSESSMENT AND PROJECT PLANNING

3.1 Introduction

Projects should ideally be conducted in the context of an on-going monitoring program to inform planning, design, implementation, and evaluation (Ralph and Poole, 2003). However, this is often not possible due to limited existing monitoring, especially for routine projects such as local infrastructure protection and habitat enhancement. During the early phases of project classification and planning, all pertinent existing information such as maps, photographs, and previous project reports should be assembled. An initial data and field assessment is needed to confirm accurate classification of the project as routine, moderate, or comprehensive (Chapter 2.0), and to identify important project planning components (Chapter 3.0). The initial assessment is also important for beginning to expand the understanding of the problem (Chapter 6.0). The minimum initial assessment data recommendation for all project types is outlined in Section 3.2. Note that additional data are likely needed to support the appropriate level of pre-project monitoring (Chapters 4.0 and 5.0), design (Chapters 7.0 to 10.0), and post-project evaluation and management (Chapter 12.0). The initial data collection during the early stages of projects is typically qualitative and spans the spatial scales from site to watershed (e.g., site walks and map-based exercises), while subsequent measurements and observations for design are more detailed and tend to concentrate on the primary project site up to the reach scale.

The existing planning approaches that are recommended for naturalized channel design and bank stabilization projects (e.g., FISRWG, 1998; Miller et al., 2001; OMNR, 2001) have many overlapping components that are applicable to a broad range of projects – problem identification, drafting of goals and objectives, design, implementation, and evaluation. Comprehensive projects tend to require a substantial amount of planning while routine projects can take place with limited planning.

3.2 Initial Assessment

3.2.1 Overview

An initial collection of physical, biological, and chemical data will help gain a better understanding of the problem, refine goals and objectives, identify future data collection needs, and establish baseline conditions. The initial assessment should begin with a broad evaluation of watershed, reach, and site hydrology and sediment regime. Departure from the balance between sediment and water (Lane, 1955) is often the primary mechanism leading to channel instability and degraded aquatic habitat. The channel geomorphology component of the initial assessment should produce an initial estimation of the expected river channel type for the given valley, the general planform based on longitudinal slope and discharge, likely cross section dimensions, the current stage of channel evolution, and the most likely sources of current and historical channel distress. Aquatic habitat is briefly evaluated to gain an understanding of the channel response to the stressors and how the project can have the most biological benefit. Where applicable, species targeted for recovery are also identified to establish baseline population estimates. Finally, an initial understanding of water and sediment quality can identify existing chemical impairment.

3.2.2 Core Data Requirements

Virtually all river management projects require an initial assessment that begins with gathering and reviewing existing data followed by a site visit to view field conditions. During the initial site visit, take photographs to qualitatively document existing conditions. New Hampshire Department of Environmental Services (DES) has a photo documentation procedure (Appendix B) that offers useful guidance and repeatable methods. The intent of the initial assessment is to begin to understand river and watershed conditions with available information, and to identify the type of detailed information that will be needed for design.

The following data generally exist for most rivers in New Hampshire and can be obtained from various websites, libraries, and state offices.

3.2.2.1 Existing Mapping

Site maps are necessary to identify the project location relative to watershed features and municipal boundaries, and to identify land use/cover in the watershed. Topographic maps with contour lines depict the site's elevation, land slope, relief, and cultural features. Topographic maps can also be used to delineate watersheds, measure river channel length, compute sinuosity and channel slope, and view location of wetlands, lakes, ponds, roads and bridges.

Topographic maps are available from the US Geological Survey (USGS) and can be found in libraries and selected bookstores. Digital maps are available on the Internet (Search: TopoZone, Terraserver, or Google Earth). Old USGS topographic maps can be downloaded from the University of New Hampshire Library (http://docs.unh.edu/nhtopos/NewHampshireList.htm), and are useful for observing changes to the landscape. Commercial copies of topographic maps are available in the New Hampshire "Atlas and Gazetteer" by Delorme, found in major bookstores.

Hydrologic unit code level 12 (HUC-12) watershed boundaries are available on the New Hampshire Department of Environmental Services (NHDES) One-Stop GIS website (http://www2.des.state.nh.us/gis/onestop). Directions on how to delineate a watershed and interpret a topographic map is available from the Natural Resources Conservation Service (NRCS) (http://www.nh.nrcs.usda.gov/technical/ws_delineation). In addition, a GIS watershed theme tool is also available, along with a variety of other useful data layers, at the University of New Hampshire Granit Data Mapper website (http://mapper.granit.unh.edu) that are useful for making a preliminary base map during the early planning stages of a project.

Geology and soil information is important for understanding the valley characteristics. Geology maps of New Hampshire can be obtained from NHDES (http://www.des.state.nh.us/geo1link) and soil maps can be obtained from County Soil Surveys. Electronic soil information can be downloaded from the NRCS Soil Data Mart (http://soildatamart.nrcs.usda.gov/County.aspx?State=NH) or from the Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/). Floodplain maps are available on the Internet through the Federal Emergency Management Agency (FEMA) Map Service Center (http://msc.fema.gov/webapp/wcs/stores, Digital Flood Insurance Rate Maps (DFIRMs) and Flood Insurance Studies (FIS)).

National wetland inventory maps on the US Fish and Wildlife Service (FWS) website (http://wetlandsfws.er.usgs.gov/NWI) should be reviewed to identify wetlands near the project site.

3.2.2.2 Aerial Photographs

Aerial photographs are an important source of information, especially for larger watercourses, and provide initial data on channel alignment, meander shape and size, adjacent land uses, vegetative cover, and wetlands. In some cases, photographs will show bank erosion problems, sediment bars, dams, and other features.

At the beginning of a project an inquiry should be made to state and local officials for existing aerial photographs. Current and historical photographs often exist for the entire state, or large portions of it, from previous mapping flights to study the changing landscape. New Hampshire aerial photographs (DOQ 1998 Aerial Imagery and NAIP 2003 Aerial Imagery) can be viewed on the University of New Hampshire Granit Data Mapper website (http://mapper.granit.unh.edu). Keep in mind that aerial photographs are often taken in spring before leaves appear on trees so flow can be higher than normal. In addition, digital aerial photographs are available on the Internet (Search: TopoZone, Terraserver, or Google Earth). The use of historic photographs is particularly helpful for tracking changes in river channel location, meander pattern, and land use conditions.

3.2.2.3 Hydrology and Hydraulic Information

The term hydrology is used here to refer to the frequency, magnitude, duration and timing of flow rates, ranging from short-term droughts and floods to long-term annual runoff. Hydrology information is essential for understanding river problems and solutions. The primary source of hydrology data in the United States is the USGS gage network that measures and records surface water levels and flow rates on select rivers in the country. Ground water and water chemistry data are also available for a small subset of sites.

Current and historical data, flow statistics, and other information related to the gage sites in New Hampshire can be found via an interactive map on the Internet (http://nh.water.usgs.gov/WaterData/station_map). Federal, state and local entities currently fund the operation of 41 continuous record gages as well as six partial record gages and three stage-only gages (Appendix C), all of which are operated by the USGS (NHSGTF, 2006). Olson (2003) reviewed the utility of the USGS gage network in New Hampshire and found, as in many other states, that increased data collection would lead to better estimates of regional flow conditions. Beyond gage data, USGS has other useful hydrology and flood study information.

Additional gages are operated in New Hampshire by the DES Dam Bureau and data are accessible via the Internet (http://www.des.state.nh.us/RTi_Home/). An initial look at gage data on or near the study river is helpful to get a general feel for system hydrology. Chapter 7 of this guidelines document provides information on how to use gage data.

Further information on flood flow rates, floodplain boundaries, and flood water depths is available from FEMA for larger communities. Note that FEMA undertook a complete hydraulic study of the CT River in 2000 to 2002 to revise the floodplain maps from the Massachusetts border north as far as Plainfield and Hartland. At the outset of all projects, an inquiry should be made to FEMA to see if floodway information exists at the project site as this, along with the project type, will help determine whether site specific flow measurements or temporary gages are needed. New Hampshire DFIRMs can be viewed on the University of

New Hampshire Granite Data Mapper website (http://www.granit.sr.unh.edu). Additional data can be obtained from the electronic FEMA Map Service Center (http://msc.fema.gov/webapp/wcs/stores), or via a phone or a written request. Flood information is available for some communities at libraries and municipal offices.

Hydrology and flood studies have likely been conducted on some New Hampshire rivers for specific projects and may be available from NHDES, practitioners, or non-profit groups. Other sources of existing hydrology and hydraulic data include the New Hampshire Department of Transportation (NHDOT) and the NRCS.

Hydraulics, and specifically the study of open channel flow, is central to naturalized river channel design and bank stabilization projects. Channel stability is determined from the amount of deposition and erosion taking place, which in turn is a function of the size of the particles that can be moved for a given water velocity. In addition, a mix of different water depth and velocity combinations is important for creating good aquatic habitat. As part of the initial assessment, a plan view (i.e., overhead looking down on the river) sketch of riffles, runs, pools, and glides should be made at the project site to estimate the percentage of surface area covered by each. Lack of a given type of hydraulic unit, such as pools or riffles, could be addressed during the project design.

3.2.2.4 Fluvial Geomorphology

Fluvial geomorphology refers to the shape, size, slope and patterns of river channels and their floodplains. Initial measurement of basic geomorphic variables is needed for all projects to record the river channel's existing condition, help compare it with natural regional conditions, and begin to identify specific problems. Preliminary geomorphic data requirements include channel width and depth, general alignment (straight, meandering, braided), stability (is erosion or deposition dominant?), bank conditions (vegetated, raw), size of bed material (bedrock, boulders, cobbles, gravel, sand, silt or clay) and type of profile (steep cascades, moderate pools and riffles, gentle runs). Rapid assessment tools such as the bank erosion hazard index (BEHI) (Rosgen and Silvey, 1996) are useful during preliminary site walks to estimate site conditions. Chapter 8.0 describes measurement of these and additional geomorphic variables.

Aerial photographs and USGS topographic maps are used to measure channel and valley slope, channel sinuosity, and valley width to help gain an understanding of the river valley.

3.2.2.5 Biology

Initial information on a site's physical habitat, plants and animals is needed to plan river channel design and bank stabilization projects that attempt to improve biotic integrity. An initial rapid habitat assessment such, as that available from the US Environmental Protection Agency (EPA) (http://www.epa.gov/owow/monitoring/rbp - Appendix A, Form 2 for high gradient channels and Form 3 for low gradient channels) is required for all sites to understand existing habitat conditions and how habitat might change after project completion. This habitat assessment should complement a description of current river habitat, including potential sources of impairment.

A preliminary understanding of the organisms that likely currently inhabit the project site, and that could potentially occupy local habitat after project completion is needed. Sources of such information include state biomonitoring programs, an understanding of regional ecozones from state and federal biologists, previous biological studies in the watershed, and data on rare and endangered species. Contact the New Hampshire Department of Fish and Game (http://www.wildlife.state.nh.us/), the New Hampshire Natural Heritage Bureau (http://www.dred.state.nh.us/divisions/forestandlands/bureaus/naturalheritage/), and the DES Biomonitoring Program (http://www.des.state.nh.us/wmb/biomonitoring) for assistance in approximating the biological composition at the project site and in the watershed. If a project is targeting a single species for recovery, information on its life cycle requirements, local and regional historical distribution, and current abundance in the vicinity of the project site is needed.

Information on federally listed species and the locations of their critical habitats may be obtained from the FWS Environmental Conservation Online System (http://ecos.fws.gov). The website of the Northeast Regional Office of the National Oceanic and Atmospheric Administration (http://www.nero.noaa.gov/nero/) contains information on listed freshwater and marine fisheries, as well as their habitats.

State habitat and biological information may be obtained from The New Hampshire Wildlife Action Plan on the New Hampshire Fish and Game Department website (http://www.wildlife.state.nh.us/Wildlife/wildlife_plan). Possible local sources of habitat and biological data include watershed management plans, town planning goals, local land trust review, and information on previous resource issues.

If wetlands are present a Certified Wetland Scientist may be needed for delineation, and wetland assessment is recommended where the project may influence wetland quality.

If the project includes goals of improving aquatic habitat and biological recovery, additional biological data are required to establish baseline conditions, identify if biological change takes place once the project is installed, and ultimately determine project effectiveness. The goals of the project and whether it is routine, moderate, or comprehensive, will help determine the amount of biological data that should be collected. Chapter 4.0 makes recommendations for pre-project biological monitoring and describes some important aspects of conducting a biomonitoring program as a project evaluation tool. Post-project monitoring and evaluation is addressed in Chapter 12.0.

3.2.2.6 Chemistry

Water and sediment quality are important background watershed signals and key metrics of river health – both of which can be limiting factors in aquatic habitats. Key water quality issues are basic physical parameters (temperature, pH, dissolved oxygen, conductivity, and turbidity), nutrients (phosphorus, nitrogen), toxic chemicals, and pathogens (virus, bacteria).

Salinity levels are used to determine if coastal river habitat is freshwater, brackish, or marine. For sediments, primary issues include abundance of fines, nutrients (attached nitrogen and phosphorus) and toxics (attached trace metals).

At the beginning of the project, the most recent *New Hampshire 305(b) and 303(d) Surface Water Quality Assessment State Surface Water Quality Report* should be reviewed for water quality designation maps showing the state's Clean Water Act (1972) reporting for the project river (http://www.des.state.nh.us/wmb/swqa/2004/summaryreports). Review the New Hampshire Water Quality Rules (http://www.des.state.nh.us/rules/desadmin_list) to help understand designated uses, criteria to protect the designated use, and an anti-degradation policy. Reviewing designated uses and impairments on other rivers in the watershed may help determine potential threats to water quality. Locate existing data to identify water quality trends and confirm state records of possible priority pollutants. USGS water quality data for New Hampshire are available on the Internet (http://waterdata.usgs.gov/nh/nwis/qw). New Hampshire water quality data are available via the NHDES One-Stop GIS website (http://www2.des.state.nh.us/gis/onestop/).

Existing data on sediment quality are less common than that on water quality. Seek out existing data on sediment quality from federal, state, and local officials, as well as existing studies. For example, EPA conducted two sediment quality studies in the Connecticut River in 1998 and 2000. If no data are present, review land use/cover mapping to obtain an indication if sediment and its quality are a concern for the project and justify future monitoring. If fine sediment sources exist then physical smothering and transport of pollutants is possible. Excessive phosphorus can be delivered to the river via land erosion and sedimentation so unstable and actively adjusting channels can degrade both sediment and water quality. Past industrial activities in a watershed are a concern as trace metals can attach onto fine sediment particles, be transported downstream, and create local hotspots of toxics that can degrade habitat. If any of these land use/cover characteristics exist and the project includes goals of sediment quality improvement, the chemical monitoring program should include sediment quality.

If the project includes goals of improving water and sediment quality, additional chemical data are required to establish baseline conditions, identify if chemical change takes place once the project is installed, and ultimately determine project effectiveness. The goals of the project and whether it is routine, moderate, or comprehensive, will help determine the amount of chemical data that needs to be collected. Chapter 5.0 makes recommendations for pre-project chemical monitoring and describes some important aspects of conducting a chemical monitoring program as a project evaluation tool. Post-project monitoring and evaluation is addressed in Chapter 12.0.

3.2.2.7 Previous Studies

The initial assessment should include a broad search for previous studies that are relevant to the project. Reports on any previous river management activities, geomorphic investigations, biological studies, and water and sediment chemistry studies at the project site, reach, or watershed should be reviewed. Such studies can contain important pieces of initial assessment data such as mapping, hydrology and hydraulics data, information on biological assemblages, and characterization of water and sediment quality. The search for previous studies should be broad as existing information in the watershed and region is often also valuable to project planning and design. Previous studies or completed projects may be found at government offices, universities in the region, non-profit organizations, or private consulting firms. Examples of useful documents include DES studies related to establishing reference reaches, sediment studies such as the one that exists for the entire Connecticut River watershed in New Hampshire (Hellyer, 2000), erosion inventories such as those available from the Connecticut River Joint Commissions (http://www.crjc.org/erosion.htm), and studies or inventories that college and university students or faculty have done.

3.3 Project Planning

3.3.1 Problem Identification

Problem identification is a critical component of project planning. A key to performing an effective project is to understand the mechanisms that are ultimately causing the problems being addressed (Jansson et al., 2005). Even for routine projects that are known to only address a response rather than a stressor, it is important to report on the likely causes of the problem for the benefit of future management efforts. Problem identification is not a one-time event, yet progresses throughout the project as more detailed data become available clarifying the stressors and responses that cause river channel and bank distress (see Chapter 6.0 for more details on problem identification). The spatial and temporal scale at which disturbances are operating indicates whether stressors are localized or originating at the watershed scale, and if disturbances occur at a regularly occurring time interval. A clear identification of the problem will support and enable the development of accurate goals and objectives, appropriate design, and effective implementation. Problem identification concludes with identification of the anticipated general course of action – do nothing, passive recovery after stressor elimination, active channel design, monitoring to acquire more information, or long-term management (OMNR, 2001).

River channel and bank projects generally begin when landowners, municipal officials, conservation groups, or state agencies identify an existing or potential problem. Both natural and anthropogenic change can lead to scenarios where river form and process is in conflict with community assets. River projects typically arise due to the reduction of a combination of a river's ecosystem services and cultural value. Conveyance of water and sediment, formation of aquatic habitat, and storage of water and sediment in floodplains are some of the primary natural river and floodplain processes. Typical river ecosystem services include water supply, waste assimilation, and groundwater recharge. Recreation opportunity, aesthetics, and increased property values are common cultural values associated with river systems.

After identification of a problem, the magnitude of river distress is compared to natural and acceptable conditions. River distress may occur due to activities at different spatial scales – the watershed, multiple reaches, a single reach, or smaller – and at different temporal scales. Stessors may be due to natural forces (land slides, ice jams, tree blow downs), driven by climate patterns (increased precipitation, acid rain, invasive species) or due to local human activity (bridges, dams, gravel mining, channel encroachments, artificial linings, water diversions), and may have short- or long-term impacts on river functions. Adverse impacts could include channel incision, widening, bank erosion, excessive lateral meander migration, habitat deterioration, water quality degradation, and others (see Chapter 6).

During problem identification it is important to gain an understanding of the future trajectory of river distress – a forecast of whether conditions are likely to deteriorate, stabilize, or improve over time with and without active intervention. Channel morphology and the current stage of channel evolution are used to predict how a channel is currently adjusting and how this will change in the future. This initial determination assists thinking about potential alternatives, and specifically if monitoring and/or passive approaches are possible management options. In some cases, a resilient system may begin recovery without active approaches. Intervention is appropriate when current river impacts are unacceptable or future impacts could attain undesirable levels and generate conflicts between river process and human infrastructure. It is essential that one consider "cause and effect", whether the problem is correctable, and then weigh the benefits of intervention versus construction impacts (see Chapter 11).

3.3.2 Goals and Objectives

3.3.2.1 Overview

After initial assessment and problem identification, an image of the desired river channel structure and function (i.e., 'a guiding image' after Palmer et al., 2005) is created to represent a target for after the project is complete. For more involved moderate and comprehensive projects this image should extend beyond the project site out to the reach and watershed spatial scales to understand the broader implications of the project. Watershed change, new problem areas, and additional projects should also be considered. Goals, as expanded upon from those in the initial project classification (Chapter 2.0), represent over-arching descriptions of the guiding image. Objectives represent specific characteristics of the target river channel that can be verified via monitoring and analysis.

3.3.2.2 Discussion of Goals

When creating a list of project goals and objectives expectations must be adjusted based on existing system constraints. It is important to keep in mind the potential of projects, recalling that full system restoration is often not possible and rehabilitation or enhancement of selected components is often a more realistic goal (see Table 2-2). A goal that should that should be included for every project is to avoid damaging one component of the aquatic ecosystem while implementing a project that improves another. A common example of this is the introduction of large rock vortex weirs or cross vanes to increase channel stability that inadvertently limit local fish movement under low and moderate flow conditions.

3.3.2.3 Stakeholder Involvement

Watershed partners, such as local residents, non-profit organizations, government agencies, educational institutions, and private corporations, can play an important role in the project and become a mobilized stakeholder group that supports future management activities. Opportunities for stakeholder input should be created during project planning to share information on the problem being addressed and establish widely acceptable goals and objectives. Watershed partners often bring to the table knowledge of politically popular ideas, a long-term database of historical information, and an understanding of the investments associated with on-going maintenance, all of which improve project planning. Stakeholder involvement can be limited if the group is too small or excessively complicated if the group is too large. Routine projects often have limited stakeholder involvement while comprehensive projects tend to include large stakeholder groups that have multiple opportunities for input throughout the project.

3.3.3 Design Overview

The alternatives analysis is the main feature of the project design phase. After review of existing and initial assessment data, a preliminary alternatives matrix is compiled for initial comparison in terms of how effective each is at meeting project goals and objectives with the given site constraints (Table 3-1). A project team and greater stakeholder group meeting can be held to discuss eliminated alternatives and those that are recommended for further consideration and analysis. This first step of the alternatives analysis rapidly eliminates unfeasible options allowing for the second step of the analysis to focus on more likely solutions to the problem. The initial alternatives analysis is a good time to conduct a thought exercise of identifying ways of eliminating watershed stressors via large-scale management efforts and river corridor protection initiatives while only considering how best to fix the river. However unlikely applicable, the holistic thinking promotes discussion of the mechanism of the stressors, helps to understand the current project within a larger spatial context, and identifies future management opportunities.

Alternatives that adequately address project goals and objectives, and work within constraints are confirmed for further investigation by the project team and stakeholders. A complete alternatives analysis that draws on the most appropriate tools based on the project type – routine, moderate, or comprehensive – and its goals will lead to an effective final design that includes multiple checks of findings.

3.3.4 Implementation

Regulatory permitting, funding and site access are three key aspects of implementation that should be addressed at the beginning of the project. See Chapter 11.0 for a detailed discussion of these and additional project implementation steps. Permitting requirements and

Table 3-1: Example of a preliminary alternatives matrix that is useful for exploration of project options, ruling out alternatives that are clearly not feasible, and selecting a sub-set of alternatives that should be considered for further analysis.

	Project Goals and Objectives								
Alternative	**Increase sediment continuity**	**Improve channel stability**	**Reduce bridge scour**	**Improve aquatic habitat**	**Towards natural process**	**Short or long-term solution**	**Initial relative cost est.**	**Comments**	**Rec.**
Watershed Alternatives									
No action	x	x	x	x	x	n/a	none	not desirable, many local erosion hazards, system-wide instability	
Limit sediment supply	+	+	o	+	+	long	very high	address erosion sites throughout river corridor	
Restore natural discharge	+	+	o	+	+	long	very high	not reversible, altered hydrology, developed corridor, accepted risks	
River Corridor Protection Alternatives									
Limit new encroachments	o	+	+	+	+	long	medium	decrease/prohibit future corridor conflicts	✓
Passive channel recovery	o	+	+	+	+	long	medium	space to meander, floodplain creation, decreases corridor conflicts	✓
Bridge Alternatives									
No action	x	x	x	x	x	n/a	none	not desirable, bridge prone to scour, mechanism of sediment bottleneck	
Increase bridge width	+	o	+	o	+	long	high	allow ample lateral migration, flood bench creation, increase safety	✓
Add overflow culvert	o	o	+	o	+	short	medium	reduce high-flow backwater, flood bench creation, multi-use	✓
Channel Alternatives									
No action	x	x	x	x	x	n/a	none	not desirable, unstable channel, inc. lateral erosion, poor habitat	
Passive adjustment	o	o	o	o	+	long	low	adjustment likely with bridge change, track monumented sections	✓
Adjust cross sections	o	o	x	+	+	short	medium	assist towards flood bench creation, compound stable channel	✓
Increase channel slope	+	x	x	x	x	short	medium	oppose natural process of decreasing slope	
Stabilize raw banks on site	x	o	x	x	x	short	medium	not presently working at site, need hard toe, improve flow path	✓

+ Good o Moderate to fair x Poor

Rec. = Recommended further analysis

the amount of available funding directly influence the scope of the project, and site access alone can impede implementation. Project construction can only take place once the final design is complete, permits are in hand, and site access is granted. If contractors are needed to complete the project, those with experience working in rivers and a proven track record of high quality work should be selected. All field volunteers should be adequately trained and have a clear understanding of tasks to be accomplished each field day. A member of the project team should be present to guide as much of the construction as possible to increase the accuracy and efficiency. Throughout the construction phase, an effort should be made to minimize harm done to the system so that recovery can take place rapidly. The implementation phase concludes with post-construction inspection documentation (Chapter 11.0).

3.3.5 Evaluation and Management

All projects include some level of evaluation and management (Chapter 12.0). Ideally, post-project monitoring can be coupled to a previously established monitoring effort to facilitate before-after comparisons; however, post-project data collection alone across a range of sites can be used for effective monitoring as well. Monitoring and evaluation determine if project objectives are being achieved and if adaptive management (Holling, 1978; OMNR, 2001) is needed beyond normal operation and maintenance. Limited qualitative evaluation results are often adequate for routine projects, and results should be communicated to the project team and watershed stakeholders. Outreach efforts for moderate projects, which typically require more evaluation when goals include biological and chemical recovery in addition to channel stability, should extend throughout the region to share outcomes and assist others doing similar work. The increased investment in comprehensive projects usually requires a more extensive evaluation. The outcome of comprehensive projects should be shared at the national level when possible and published in industry, government, or peer-reviewed journals to advance the science of naturalized river channel design and bank stabilization. Project reporting will continue to bring together members of government, academia, non-profit organizations, private companies, and the public to improve current management efforts.

CHAPTER 4.0: PRE-PROJECT BIOLOGICAL MONITORING

4.1 Introduction

The recommended initial assessment for all river channel design and bank stabilization projects provides preliminary information on physical habitat, the likely existing and potential assemblages of organisms, and life-cycle requirements of target fish, macroinvertebrates, and/or plants. For projects with goals that include improving aquatic habitat and biological recovery, additional data should be collected to gain a more comprehensive understanding of the system to guide the ecological aspects of design and establish baseline conditions. Findings of a biomonitoring program illustrate which expected habitat features are absent so that they may be incorporated into more naturalized designs. The level of biological monitoring is synchronized with both the primary project goals and the project classification as routine, moderate, or comprehensive (Figure 4-1). If recovery of a target species and their habitat is part of the project goals, the primary function of pre-project monitoring is to gather the appropriate level of baseline data to compare to post-project effectiveness monitoring (Chapter 12.0).

Current monitoring protocols suggest that substantial time and funding is needed in order to confirm biological change following a river management activity; however, resources are often not available to conduct this level of monitoring. Scaled back monitoring recommendations are presented here that fit into the typical duration and funding of current naturalized channel design and bank stabilization projects. The monitoring recommendations will likely expand in the future as the desire to evaluate project effectiveness through pre- and post-project monitoring continues to grow.

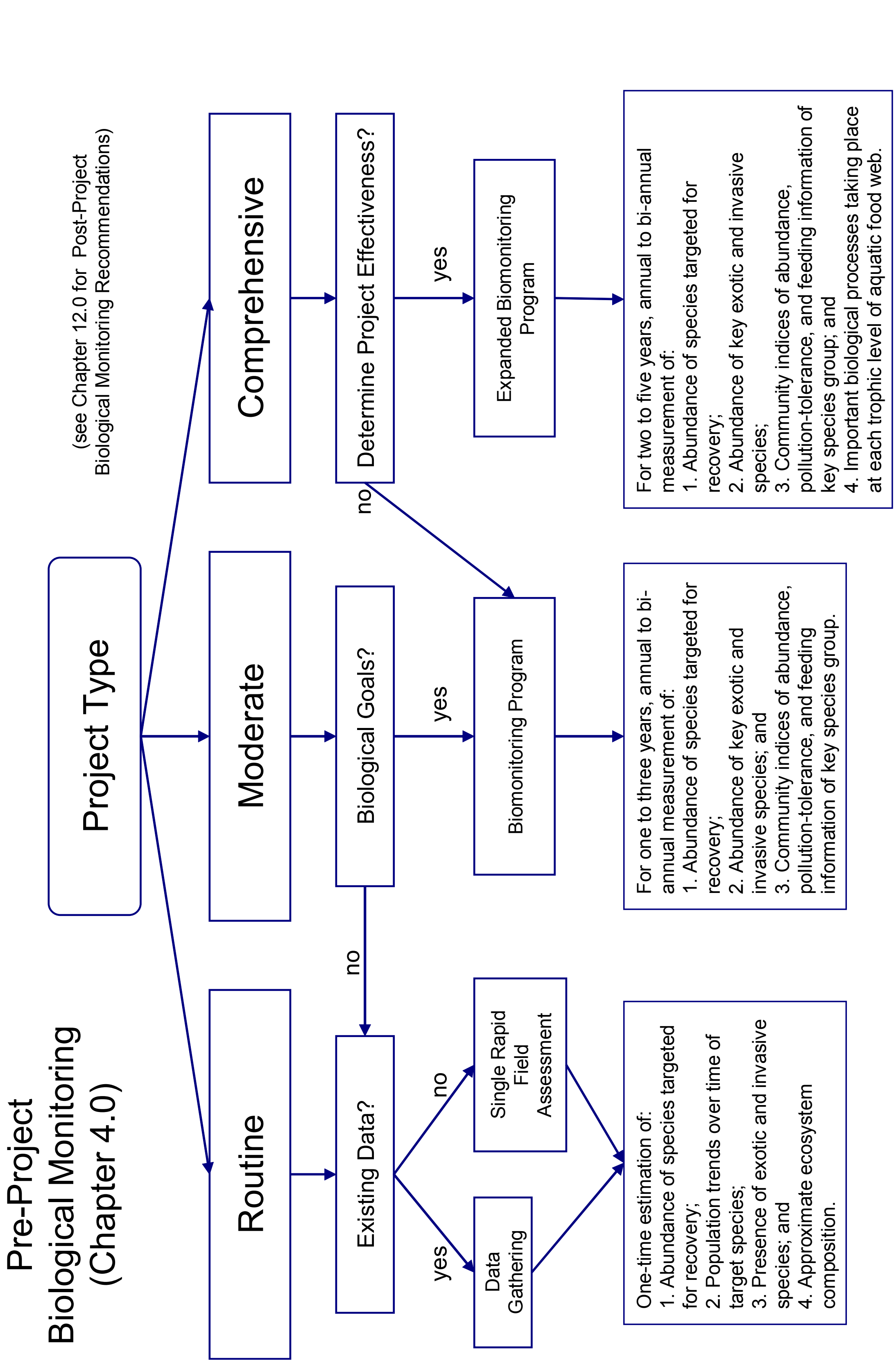


Figure 4-1: Pre-project biological monitoring recommendations for routine, moderate, and comprehensive projects.

4.2 Biomonitoring

4.2.1 Routine Projects

The recommended biological data for routine projects includes an estimation of:

- The abundance and/or relative abundance of species targeted for recovery;
- Population trends over time of target species;
- The presence of exotic and invasive species; and
- The general overall ecosystem composition.

Routine projects with limited biological goals and objectives usually do not require pre-project biological monitoring. In this case, existing data and expert knowledge gathered during the initial assessment (Chapter 3.0) are sufficient to estimate any desired biological information such as target species population estimates, relative abundances, population trends, the presence of exotic and invasive species, and the approximate composition of the ecosystem. This amount of biological data may be sufficient for routine projects having the main goal of channel stability, but which include secondary biological objectives. If existing data are limited, a single rapid field assessment is recommended to estimate the biological information. The rapid field assessment is ideally performed with local experts familiar with the system and the common regional composition of populations of different river habitats.

Popular methods for choosing sampling locations, timing and collection are available through the US EPA Rapid Bioassessment Protocols (Barbour et al., 1999) (http://www.epa.gov/owow/monitoring/rbp/). In addition, state resource managers that conduct biomonitoring programs may be contacted for guidance (http://www.des.state.nh.us/wmb/Biomonitoring/). Watershed groups should be contacted to see if data are available from volunteer monitoring.

The rapid field assessment is limited in detail. A single sampling period is common, and collections should be performed during the month when state biomonitoring programs make most of their collections to facilitate data comparisons and following trends. Avoid collections during abnormal flow, and in particular following large flood events when assemblages typically move through disturbance and recovery cycles that differ from typical conditions. The rapid field assessment should occur at, or immediately downstream of, the anticipated implementation area. Replicated collections are typically made from a single habitat type, most typically riffles. The sampling program should focus on the target species and other important members of the system.

Due to their ubiquitous nature in all stream types, their integrated response to an array of environmental stressors and the relative ease of collection, macroinvertebrates are useful for rapid bioassessment. Various texts are available to assist with biomonitoring (Rosenberg and Resh, 1993; Karr and Chu, 1999) and identification of macroinvertebrates (Pennak, 1978; McCafferty, 1983; Peckarsky et al., 1990; Merrit and Cummins, 1996). NHDES Coastal Program has a volunteer biomonitoring program with helpful methods and reports that are available on the Internet (http://www.des.state.nh.us/Coastal/Resources/). In addition, several sources of monitoring guidance and basic macroinvertebrate identification guides are available on the Internet (http://www.epa.gov/bioindicators/html/photos_invertebrates.html and http://www.umass.edu/tei/mwwp/links.html#fauna). Fish are also popular for single-effort biomonitoring as they typically are the species targeted for recovery. Data are most often collected via electro-shocking or snorkeling. Electro-shocking is likely beyond the typical level of activities associated with a routine project, yet a short snorkel survey is appropriate where fish habitat is a primary goal to get a better understanding of fish population estimates, relative abundances, and habitat use at the project site.

4.2.2 Moderate Projects

For moderate projects that do not include biological goals other than to avoid additional harm to the ecosystem, gathering existing data or a single rapid field assessment is sufficient to estimate pre-project conditions. A biomonitoring program is recommended for moderate projects that have biological goals and objectives. The decision to perform biomonitoring is not always straight forward since moderate projects often have multiple objectives including increasing channel stability and improving aquatic habitat.

Based on their larger size (i.e., reach scale) and common goals of local habitat rehabilitation or enhancement in addition to increasing channel stability, many moderate projects attempt recovery of a target species and thus biomonitoring is recommended. For one to three years, annual to bi-annual measurement of population estimates and/or relative abundances of target species, abundance of exotic and invasive species, and community indices should be made before implementation. This program translates to a total range of one to six collections, which is a function of the available funding and the specific project objectives. The biomonitoring program suggested for moderate projects focuses on the group that the target species is a part of (e.g., coldwater fish, riffle-dwelling insects, or mosses).

It is important to contact state officials, members of regional academic institutions, local watershed groups, or any others that may be biomonitoring in rivers at or near the project site. Set up a meeting to discuss the sampling locations, frequency, and methods to facilitate data exchange. Collections for the pre-project biomonitoring program associated with moderate projects will likely include investigating one or two different habitat types (e.g., riffles and snags) and be spatially distributed across the project site. Concurrent monitoring is often performed at additional locations away from the project site to track unchanged controls, a healthy reference site if available, and a remaining impaired site as a degraded benchmark.

An example of a biomonitoring program that is common for moderate projects is the replicated monitoring of trout before (and after) project implementation via electro-fishing. State and federal resource managers are typically involved in this biological monitoring given the specialized equipment and training requirements. Existing data and methods are often available via the Internet. For example, one can obtain information on fish (http://www.des.state.nh.us/wmb/Biomonitoring/fish_assess) and macroinvertebrate (http://www.des.state.nh.us/wmb/Biomonitoring/inverts) community assessment in New Hampshire from the website of the New Hampshire Biomonitoring Program.

4.2.3 Comprehensive Projects

Comprehensive projects are large in size, often spanning multiple reaches, and thus their impact on a river channel and biology is great. For this reason, and because projects of this size almost always include habitat and biological recovery goals, biomonitoring is recommended. The biomonitoring program described above for moderate projects is ample where project effectiveness does not need to be determined; however, an expanded biomonitoring program is needed for effectiveness monitoring.

For two to five years, annual to bi-annual measurement of population estimates and/or relative abundances of target species, abundance of exotic and invasive species, and community indices should be made before implementation. This program translates to a total range of two to ten collections, which is a function of the available funding and the specific project objectives. The biomonitoring program suggested for comprehensive projects can focus on the group that the target species is a part of, but can also include other groups that likely influence the target species such as its main predator and prey. The expanded biomonitoring program includes investigating multiple habitats, spatial distribution across the project site, and concurrent monitoring at a range of control, reference, and impaired sites.

When system restoration through returning important processes that form high quality habitat is a goal of a comprehensive project, an effort should be made to identify the key processes and interactions at each level of the aquatic food web. Does the system primarily rely on external inputs to drive the base of the food web (i.e., heterotrophic) or does most of the food come from instream plant production (autotrophic)? What are the primary pathways of energy through the aquatic food web, and where do potential bottlenecks exist? Biological processes such as photosynthesis, respiration, nutrient processing, and the breakdown of organic matter should be considered. If post-project monitoring is continued for a long enough time (Chapter 12.0), the expanded biomonitoring program should allow for the determination of project effectiveness.

4.3 Physical Habitat Assessment

Almost all naturalized river channel design and bank stabilization projects influence physical habitat and thus a pre-project assessment should be made. Important habitat parameters include:

- Large and small organic matter;
- Bed substrate;
- Scour and deposition features;
- Channel morphology;
- In- and near-channel hydrology;
- Longitudinal and lateral connectivity;
- River banks; and
- Riparian areas.

The EPA habitat assessment mentioned in the previous chapter (Section 3.2.2.5) is commonly used for a quick assessment. The Vermont Agency of Natural Resources is presently developing a new rapid habitat assessment (RHA) that establishes indicator variables of key habitat-forming physical processes and components essential for life-cycle requirements (VTANR, 2005). Once complete, the RHA will be available for different channel types and will be a quick and thorough habitat assessment tool. The Vermont Geomorphic Assessment Protocols, which include both a rapid geomorphic assessment and the RHA, is available on the Internet (http://www.anr.state.vt.us/dec/waterq/rivers).

For routine projects, where physical change is limited to a small part of a river channel or bank, a brief qualitative description of the listed parameters and how they may change is ample to track physical habitat. For moderate and comprehensive projects that cover larger areas and often include biological goals and objectives, a more thorough investigation of the physical habitat parameters is recommended. The following observations and measurements should be made during site walks and field sketches of habitat features, most of which are collected during the initial data assessment or readily available as data are collected to inform the design. Estimate:

- The abundance of large woody debris (LWD);
- The percentages of boulders, cobbles, gravels, and sands in approximately 10 square feet (1 square meter), as well as the degree to which the bed follows the expected riffle-run-pool-glide, step-pool, or other pattern as one moves down a river reach;
- The abundance, spacing, and quality of the main scour and depositional features (riffles, steps, pools) associated with the given channel type;
- Channel morphology variables at monumented cross sections as determined during data collection for the appropriate level of design;
- In-channel hydrology characteristics, and the presence of riparian wetlands;
- The degree of longitudinal connectivity (abundance of blockages such as dams, culverts and bedrock outcrops) and floodplain connectivity (entrenchment ratio);
- The abundance of vegetative cover, overhanging vegetation, and canopy cover, the degree of erosion on the river banks; and
- The abundance of vegetative cover and dominant land use in the riparian corridor.

CHAPTER 5.0: PRE-PROJECT CHEMICAL MONITORING

5.1 Introduction

A review of local and regional water and sediment quality data gathered during the initial assessment for all naturalized river channel design and bank stabilization projects offers information on background chemistry and potential chemical threats. For projects with water quality improvement goals, additional chemical data are needed to determine baseline conditions for comparison to post-project monitoring (Chapter 12.0). The amount of chemical monitoring is not only a function of project goals, but also project classification as routine, moderate, or comprehensive (Figure 5-1).

5.2 Chemical Monitoring

5.2.1 Routine Projects

The recommended chemical data for routine projects include an estimation of:

- Basic water quality parameters (temperature, pH, conductivity, dissolved oxygen, and turbidity) at several recent points in time;
- Watershed water quality and trends; and
- Major geologic and anthropogenic water quality signals in the watershed.

Routine projects with limited water quality goals and objectives usually do not require pre-project chemical monitoring. In this case, existing data and expert knowledge gathered during the initial assessment (Chapter 3.0) are sufficient to estimate the desired chemical information. This amount of chemical data may be sufficient for routine projects having the main goal of channel stability, but which include secondary water quality objectives. If existing data are

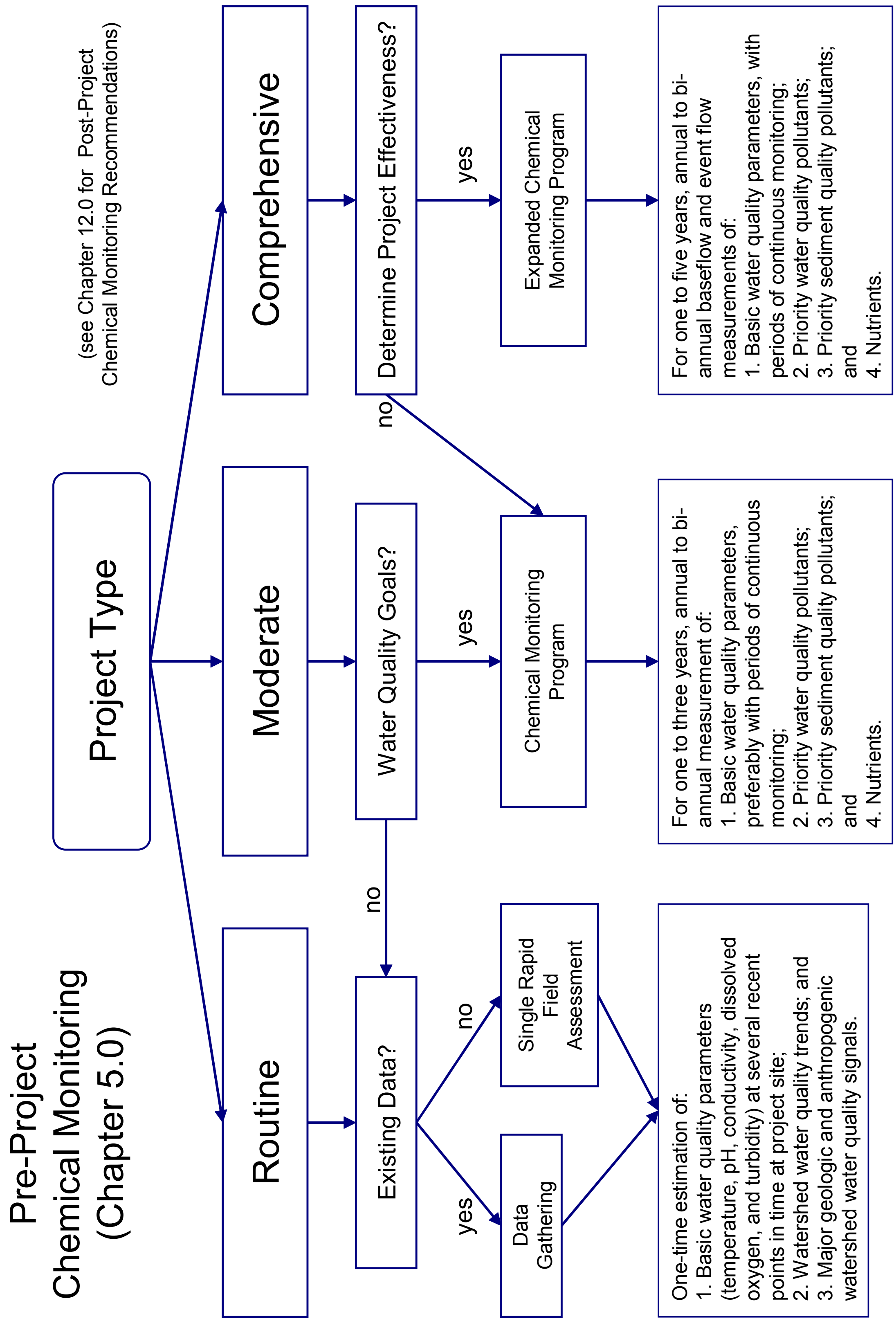


Figure 5-1: Pre-project chemical monitoring recommendations for routine, moderate, and comprehensive projects.

limited, a single rapid field assessment is recommended to estimate the chemical information. The rapid field assessment is ideally performed with local experts familiar with the system and water quality measurement and interpretation.

The one-time rapid field assessment will consist of making measurement of basic water quality parameters using portable field probes during baseflow conditions. Standard methods (Clesceri et al., 1998) should be referred to for proper measurement techniques. The New Hampshire Volunteer River Assessment Program (VRAP), which offers groups technical support and equipment loaners to conduct water quality monitoring, has many useful protocols and reports that are accessible on the Internet (http://www.des.state.nh.us/wmb/vrap/). In addition, state resource managers that regularly conduct water quality monitoring programs may be contacted for guidance (http://www.des.state.nh.us/WMB/biomonitoring/chem). Watershed groups should be contacted to see if data are available from volunteer monitoring programs. Existing data and reporting in the watershed and region should be used to estimate water quality trends and signals.

5.2.2 Moderate Projects

For moderate projects that do not include water quality goals other than to avoid additional harm to the ecosystem, gathering existing data or a single rapid field assessment are sufficient to estimate pre-project conditions. A chemical monitoring program is recommended for moderate projects that have water quality goals and objectives. For example, a chemical monitoring program would be appropriate for a moderate project where channel and bank stabilization are performed to ultimately improve water clarity. In this case, turbidity would be the priority water quality parameter monitored.

For moderate projects with water quality goals and objectives, the recommended chemical monitoring program includes measurement of:

- Basic water quality parameters, preferably with some period of continuous monitoring;
- Priority water quality pollutants;
- Priority sediment quality pollutants (where applicable); and
- Nutrients.

Annual to bi-annul data collection is recommended for one to three years, for a total range of one to six collections. The number of data collections is a function of the water quality goals and the available funding. Monitoring should be performed during the appropriate flow condition for the parameter of interest. For example, if dissolved oxygen is the issue than monitoring should take place during low flows, while bacteria or nutrient issues may require monitoring after a rainfall when the channel is conveying stormwater. The best method of investigating most basic water quality parameters such as temperature, pH, conductivity, dissolved oxygen and turbidity is by deploying continuous monitoring data-loggers to track the changes over time. Whenever possible, deploy data-loggers over the course of several weeks as they are an economical and practical way to gather good data over large project areas. Refer to standard methods (Clesceri et al., 1998) for proper sample collection, handling, and analysis.

Priority water and sediment quality pollutants can be identified from existing data or inferred from the project problem identification and the land use in the river corridor. Include sediment analysis in the monitoring program for moderate projects in watersheds where trace metal contaminants or excessive nutrients could be present. Sediment quality monitoring is important to ensure habitat for bottom-dwelling, or benthic, species is not impaired by local hotspots of deposited pollution-laden sediment.

The concentration of nutrients, and in particular phosphorus in fresh water and nitrogen in salt water, is a primary factor that determines the abundance of aquatic plants, which in turn regulate dissolved oxygen levels and pH via photosynthesis and respiration. Swings in both dissolved oxygen and pH associated with the daily, or diel, cycling between photosynthesis and respiration are factors that can limit aquatic habitat. Data-loggers are very useful for tracking diel cycling.

It is important to contact state officials, members of regional academic institutions, local watershed groups, or any others that might be participating in on-going chemical monitoring programs at rivers near the project site. Set up a meeting to discuss the sampling locations, frequency, and methods to facilitate data exchange. Several programs within the NHDES Watershed Management Bureau (http://www.des.state.nh.us/wmb/) such as River Management and Protection, Biomonitoring, and VRAP should be contacted to discuss water quality monitoring. New Hampshire sampling data and locations can be found at the NHDES OneStop (http://www.des.state.nh.us/OneStop).

For moderate projects, concurrent monitoring is recommended at a control site away from the project site.

5.2.3 Comprehensive Projects

Chemical monitoring is recommended for comprehensive projects because they are large in size, often spanning multiple reaches, and thus their potential influence on water quality is considerable. The chemical monitoring program described above for moderate projects is ample where project effectiveness does not need to be determined; however, an expanded chemical monitoring program is needed for effectiveness monitoring.

For comprehensive projects where determining project effectiveness is desired, the recommended chemical monitoring program includes measurement of:

- Basic water quality parameters, preferably with periods of continuous monitoring;
- Priority water quality pollutants;
- Priority sediment quality pollutants (where applicable); and
- Nutrients.

Note that these are the same data collected for moderate projects with water quality goals. The difference here is that the more frequent sampling is recommended to allow for determination of project effectiveness. Annual to bi-annul data collection is recommended for one to five years, where a single collection consists of both a baseflow and event flow observation, for a total range of two to twenty collections. The number of data collections is a function of the water quality goals and available funding. Again, the flow condition and duration of sampling should be set based on the water quality parameters to be measured.

An expanded chemical monitoring program often includes concurrent monitoring at a control, reference, or impaired sites, as well as monitoring of other mainstem rivers in the watershed. If post project monitoring is continued for a long enough time (Chapter 12.0), the expanded chemical monitoring program should allow for the determination of project effectiveness in terms of changes to water quality.

CHAPTER 6.0: RIVER CHANNEL STRESSORS AND RESPONSES

6.1 Introduction

River channels respond to stressors based on their vulnerability to adjustment (i.e., the level of force that the channel bed and banks can withstand before excessive adjustment takes place). Stressors may originate from both natural and human causes. Natural stressors include geologic, biologic, and meteorological conditions that are largely independent of human activity. Common stressors caused by humans include activities associated with channelization and hydrologic alteration. The response to channel stressors includes changes in conveyance of water and sediment, channel degradation (i.e., down-cutting) and aggradation, and changes in rates of erosion and deposition. Accurate identification of channel stressors and responses will guide the establishment of design alternatives.

6.2 Vulnerability

An important part of river management is being able to identify potential problems before they occur and to connect land use activities with channel changes.

River channels vary from being very resilient and stable to being vulnerable to internal and external forces that create channel distress and adjustment. Stable channels, such as those bounded by bedrock or boulders, may be virtually static and highly resistant to change. Alluvial channels, including those that are high-gradient with coarse bed material and low-gradient meandering with sand beds, are very sensitive to changes. Physically vulnerable channels can lead to widespread channel adjustment that can threaten river ecology, nearby infrastructure, and social values (Table 6-1).

Table 6-1: Examples of physically vulnerable channel types or features, and the associated threats to river ecology, infrastructure, and social values.

Physical	Ecological	Infrastructure	Social
Unconfined channels	Rare & endangered species	Roads and bridges	Historic sites
Active alluvial channels	Spawning sites	Floodprone areas	Archeological sites
Braided channels	Prime habitat	Erosion hazard areas	Aesthetics
Steep channels	Fish passage barriers	Developed floodplains	Recreation
Alluvial fans	Canopy removal	Utilities/water supplies	
Active floodplains	Food producing sites	Erodible/low dikes	
Steep/high banks		Unsafe dams	
Pools			

6.3 Channel Stressors

6.3.1 Introduction

The activities and forces that potentially affect channel stability are described herein as stressors. Stressors may be due to either natural or human activities. They may occur at various scales including the regional watershed, multiple reaches, a single reach, or on rare occasion locally. Although the response to stressors that often require management activities can take place at a very local scale, stressors tend to originate at larger scales.

6.3.2 Natural Channel Stressors

6.3.2.1 Regional and Watershed Scales

Natural channel stressors include a wide range of geologic, biologic, and meteorological activities that are largely independent of human activity. Regional and watershed scale stressors include large scale activities such as changing weather conditions and geologic uplift or subsidence (Table 6-2). Landslides and mud flows occur in mountainous areas and can provide sudden high sediment loads to watercourses. Natural stressors influencing rivers take place over a wide range of time scales, from short term events such as flash floods all the way up to the long geologic time scales of uplift.

Table 6-2: Natural channel stressors at multiple scales.

Regional and Watershed	Multiple to Single Reach	Single Reach to Local
Intense precipitation	Ice jams	Tree blow-downs
Ice storms	Floods	Bend scour
Droughts	Base level changes	Meander chutes
Floods	Channel degradation	Sediment bars
Landslides	Channel aggradation	Landslides
Climate change	Channel widening	Invasive species
Changing geology	Log jams	
Forest Fires		

Keep in mind that all of the stressors mentioned here are taking place on rivers that are continually responding to glaciation and the retreat of the massive ice sheets approximately 40,000 years ago. Rivers formed from melting glaciers deposited tons of gravel and cobbles filling some valleys, while large glacial lakes deposited layers of silt and clay in other valleys. Rivers that flow through today's New Hampshire landscape continue to erode, transport, and re-deposit these glacial sediments.

More frequent natural stressors include short duration meteorological events such as intense precipitation or rapid snow melt that create periodic floods. Peak flood flows cause erosion that can enlarge vulnerable river channels by removing bed and bank material and inundate floodplains. Flooding can be increased due to ice jams, and excessive erosion can take place in short time periods during spring ice-out. Some low energy channels are prone to sediment deposition during and following floods. Ice storms may also impact smaller rivers by dropping trees along the banks. Droughts impact rivers by reducing water depths and widths, and thus useable aquatic habitat. Low flows can also increase water temperatures, lower dissolved oxygen levels, create fish passage barriers, and increase waste water concentrations.

Climate change is a long-term stressor to rivers at the regional and watershed scale that is partly natural as earth moves further away from an ice age and partly anthropogenic as greenhouse gases increase in the atmospheric due to fossil fuel use. Depending on location, global warming may alter the hydrologic cycle, leading to changes in precipitation, evapotranspiration, runoff (i.e., river flow rates), ground water storage levels, and sediment yield. Regional and state data indicate that New Hampshire watersheds are being influenced by climate change (Rock, 2006). New Hampshire's climate displays considerable variability from year-to-year, with a trend of warming winter temperatures over the past 4 years (Wake et al., 2006). Total annual precipitation in New England has increased 3.3 inches between 1899 and 2000, with an apparent rise in frequency of more intense storm events (Markham and Wake, 2005). Larger floods, particularly in channels that are disconnected from their historic floodplains, would likely reduce channel stability. Higher flows generally lead to wider channels, which increases threats and management obligations in river corridors. As with the influence of deglaciation, the changes in the regional weather patterns associated with global climate change will have a long-term and continuous effect on New Hampshire rivers.

Coastal areas of New England already have seen increases in mean annual precipitation, with larger and more intense storms occurring more frequently. Information from the National Oceanic and Atmospheric Administration (NOAA) indicates that sea level is rising at an accelerated rate. Coastal rivers thus have an increasing base water level at their outlets that raises tide levels and upstream water surface elevations. In addition, habitats can change if the salinity wedge moves inland.

6.3.2.2 Multiple to Single Reach Scales

Natural channel stressors also occur at scales of multiple to single reaches. These stressors include activities such as seasonal ice jams, localized flash floods such as those produced by thunderstorms, and local changes in sediment loads such as from landslides or forest fires. Other intermediate scale stressors include gradual natural movement of sediment through fluvial systems that lead to localized channel degradation, aggradation, or general widening. Multiple to single reach scale stressors tend to be short duration events that occur annually or more often.

6.3.2.3 Single Reach to Local Scales

Small scale natural stressors affect a limited area such as the impacts of an uprooted tree across a small channel or a local landslide. Other local stressors include local erosion and deposition, meander chute cut-offs, and the formation of sediment bars. More often than not, small scale stressors ultimately originate at larger scales.

6.3.3 Stressors Caused by Humans

6.3.3.1 Introduction

There are many human activities that may alter river processes, ranging from watershed-wide changes in hydrology or sediment loads to direct local modification of river channels (Table 6-3). River channels in New England are presently responding to reforestation during the 20th century following widespread deforestation in the 19th century for timber and farmland creation. In addition, historic channel straightening took place in the late 19th/early 20th centuries for log drives as on the upper Connecticut River. Historical channelization has taken place to reduce local flooding and lateral movement to allow for more development in the floodplain. Changes to the landscape such as logging, farming, and urbanization have created stressors to the river by altering watershed hydrology. Land development in the river corridor can lead to excessive physical adjustment of the river channel that reduces water quality, degrades aquatic habitat, and creates long-term management obligations to protect infrastructure.

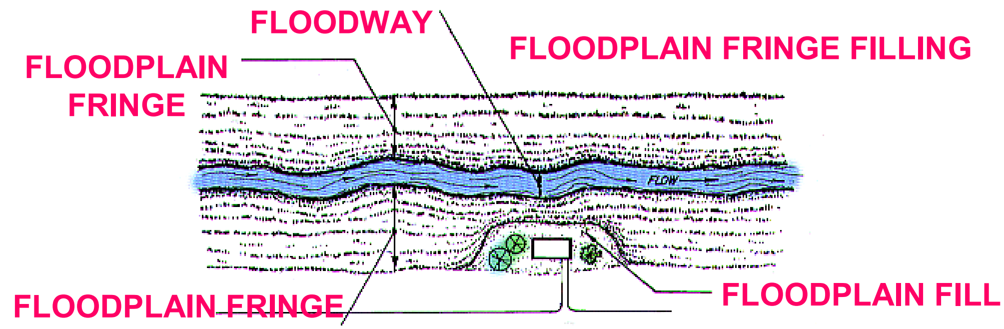
6.3.3.2 Channelization (straightening, armoring, filling, widening, deepening, clearing)

Channelization includes the collective actions of straightening, armoring, filling, widening, deepening, clearing and otherwise altering natural rivers to increase flow capacity and reduce flooding. Other reasons for channelization include protection of encroachments in the floodplain (Figure 6-1), filling of wetlands or part of the channel to reclaim land (Figure 6-2),

Table 6-3: Potential stressors caused by humans, and likely watershed and channel responses.

Scale	Stressors	Responses				
		Watershed		Channel		
		Hydrology	Sediment Load	Water Conveyance	Sediment Stability/ Transport	Water Quality
Watershed	Forest Clearing	X	X	O	O	X
	Urbanization	X	X	O	O	X
	Impervious Cover	X	X	O	O	X
	Storm Drains	X	X	O	O	X
	Wetland Filling	X	X	O	O	X
	Non-Point Runoff	X	X	O	O	X
	Drainage Ditches	X	X	O	O	X
Multiple to Single Reach	Dams	X	X	X	X	O
	Realignment	O	X	X	X	
	Channel Enlargement	X	X	X	X	
	Gravel Mining		X	X	X	O
	Floodplain Fill	X	O	X	X	O
	Flow Diversions	X	X		X	O
	Dikes & Levees	X	O	X	X	O
	Channel Clearing	O	O	X	X	O
	Thermal Exposure					X
	Waste Discharges					X
Single Reach to Local	Bridges			X	X	
	Culverts			X	X	
	Docks			X	X	
	Channel Fill	X	O	X	X	O
	Channel Enclosure			X	X	
	Hard Channel Linings			X	X	
X = Primary response, O = Secondary response						

FLOODPLAIN ENCROACHMENTS



LOCAL

ADVANTAGES:

- RECLAMATION OF LAND FOR HUMAN USES
- REDUCED FLOOD DAMAGES ON FILLED AREAS

DISADVANTAGES:

- INCREASED FLOOD VELOCITIES IN REST OF FLOODPLAIN
- INCREASED SCOUR
- POTENTIALLY IRREGULAR CURRENTS AND FLOW PATTERNS
- DESTRUCTION OF FLOODPLAIN HABITAT
- DECREASED AQUIFER RECHARGE
- POSSIBLE OBSTRUCTION OF TRIBUTARY FLOW TO MAIN CHANNEL
- BLOCKAGE OF NATURAL CHANNEL MEANDER MIGRATION
- ENCOURAGES OTHERS TO PLACE FILL
- REDUCED FLOODWATER STORAGE

COMMENTS

FLOODPLAIN ZONING USUALLY ALLOWS FILLING FRINGE AREAS. RAISING THE UPSTREAM FLOODWATER PROFILE BY THE 1 FOOT ALLOWED BY NATIONAL FLOOD INSURANCE PROGRAM REGULATIONS MAY CAUSE FLOOD DAMAGE TO EXISTING BUILDINGS.

UPSTREAM

DISADVANTAGES:

- INCREASED FLOODWATER ELEVATIONS AND FLOOD DAMAGES
- ALTERED FLOW PATTERNS
- ENCOURAGES SEDIMENT DEPOSITION

DOWNSTREAM

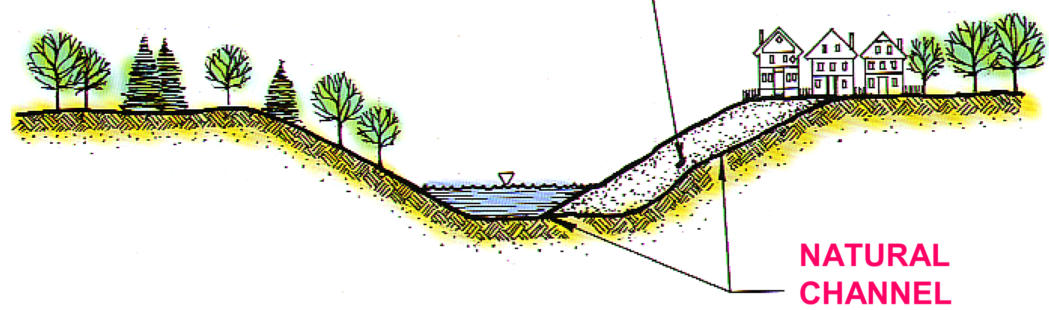
ADVANTAGES:

- POSSIBLE DECREASE IN PEAK FLOOD FLOWS

DISADVANTAGES:

- CHANGE IN FLOW PATTERNS
- HIGHER FLOW VELOCITIES
- INCREASED SEDIMENT LOAD

Figure 6-1: Schematic of a floodplain encroachment stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).



LOCAL	UPSTREAM
ADVANTAGES: • INCREASED LAND AREA FOR HUMAN USES *DISADVANTAGES:* • REDUCED CHANNEL SIZE • INCREASED FLOW VELOCITIES • INCREASED WATER DEPTH • INCREASED BED AND BANK SCOUR • DESTRUCTION OF RIPARIAN HABITAT AND ELIMINATION OF SHADE • DECREASED FLOODWATER STORAGE AND CONVEYANCE • ALTERATION OF LATERAL DRAINAGE OF RUNOFF TO RIVER • PREVENTION OF NATURAL CHANNEL ADJUSTMENTS	*DISADVANTAGES* • INCREASED WATER DEPTH AND FLOODING • POSSIBLE REDUCTION IN FLOW VELOCITIES **DOWNSTREAM** *ADVANTAGES:* • DECREASED PEAK FLOW RATES *DISADVANTAGES:* • INCREASED SEDIMENT LOAD LEADING TO REDUCED WATER QUALITY AND POSSIBLE AGGRADATION • CONCENTRATED FLOW CAUSES SCOUR AT END OF FILL AREA **COMMENTS** PLACING FILL MATERIAL IN RIVER CHANNELS OFTEN CAUSES AN INCREASE IN FLOODWATER LEVELS.

Figure 6-2: Schematic of a channel filling stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

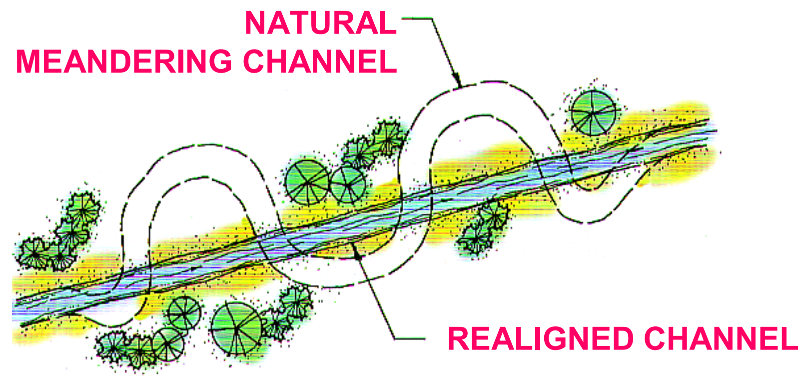
and navigation improvement. Channelization can cause severe disruption of local river morphology and ecology. In addition, channelization and the resulting increased sediment transport can have strong implications for channel behavior downstream when mobilized sediment is deposited.

Straightening channels (Figure 6-3) reduces their length but not the vertical drop; hence the channel slope is increased. This leads to higher flow velocities and greater sediment transport. The channel will erode sediment and degrade unless artificially stabilized or an additional sediment load is supplied. Changing the channel slope can induce a change in channel pattern. Degradation is common on steepened channels, and can progress upstream and into tributaries. The material eroded may form sediment deposits downstream of the straightened reach.

Armoring channel banks and bottom via rock riprap (Figure 6-4), rigid lining (Figure 6-5), walls, or other hard materials is performed to prevent a river channel from moving. Bank armoring prevents side-to-side movement, and is typically applied to protect infrastructure near the rive channel by changing local erosion and deposition patterns. Armoring the channel bed stops vertical movement, and is often used to prevent severe erosion or match grades near infrastructure such as bridges and culverts. Armoring affects the up- and downstream channel, where changes to erosion and deposition rates can lead to changes in meander pattern, the amount of degradation and aggradation, and channel dimensions that can lead to additional problems with infrastructure protection, alignment at bridges, and habitat quality.

Other components of channelization such as widening (Figure 6-6), deepening (Figure 6-7), or clearing (Figure 6-8) all are performed primarily to increase flow capacity and reduce the depth of flooding. Widening and deepening result in a greater volume of water in the channel, while clearing results in a smoother channel that can move water downstream faster. These activities can seriously degrade the channel morphology, water quality, and aquatic habitat in a river. Widening and deepening can lead to excessive deposition in the channel as the water

CHANNEL STRAIGHTENING



LOCAL

ADVANTAGES:

- **INCREASED CONVEYANCE CAPACITY**
- **RECLAMATION OF LAND**
- **POSSIBLE REDUCTION OF FLOOD DAMAGE**

DISADVANTAGES:

- **SHORTER CHANNEL LENGTH, INCREASING SLOPE**
- **HIGHER FLOW VELOCITIES**
- **INCREASED SCOUR**
- **REDUCED FLOODPLAIN STORAGE**
- **ELIMINATION OF POOLS AND RIFFLES**
- **REDUCED BANK HABITAT AREA**
- **REDUCED AQUATIC HABITAT AREA**
- **CHANNEL SCOUR PROTECTION REQUIRED**

UPSTREAM

ADVANTAGES:

- **LOWER FLOOD STAGES**

DISADVANTAGES:

- **POTENTIAL CHANNEL DEGRADATION**

DOWNSTREAM

DISADVANTAGES:

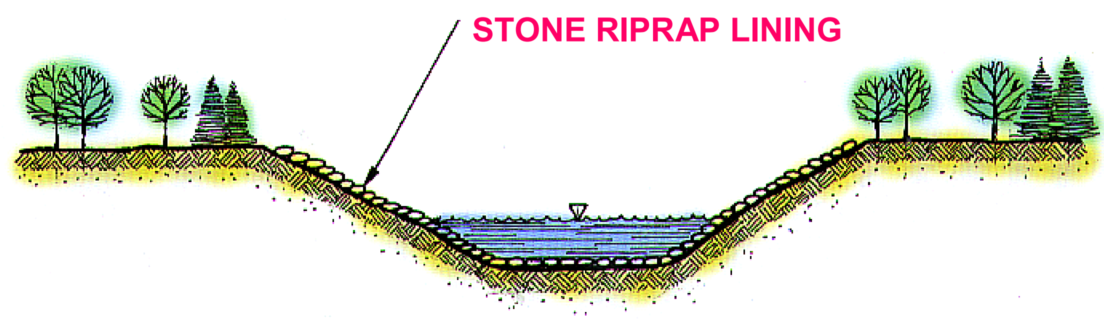
- **INCREASED FLOOD FLOW RATES AND STAGES**
- **INCREASED SEDIMENT LOADS**
- **INCREASED SEDIMENT DEPOSITION; IF EXCAVATED AREA IS NOT ARMORED, MAY BURY BED HABITAT**

COMMENTS

THE REALIGNMENT AND RELOCATION OF CHANNELS IS USUALLY ASSOCIATED WITH LAND DEVELOPMENT AND HIGHWAY PROJECTS.

Figure 6-3: Schematic of a channel straightening stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

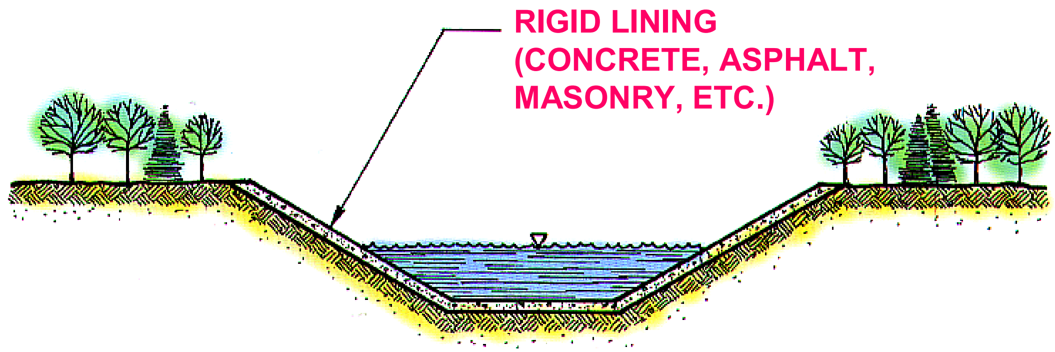
RIPRAP CHANNEL LININGS



LOCAL	UPSTREAM
ADVANTAGES: • MINIMAL EROSION • INCREASED FLOW CONVEYANCE • ALLOWS FOR STEEPER BANKS AND BED SLOPES *DISADVANTAGES:* • PREVENTION OF NATURAL CHANNEL ADJUSTMENTS • POLLUTION FROM LEACHING MINERALS • DESTRUCTION OF NATURAL VEGETATION, WILDLIFE HABITAT AND FISH SPAWNING SITES • POOR AESTHETIC VALUE	*DISADVANTAGES:* • SCOUR POTENTIAL AT TRANSITION • IMPEDIMENT TO FISH MIGRATION **DOWNSTREAM** *DISADVANTAGES:* • INCREASED FLOW VELOCITIES • POTENTIAL FOR SCOUR • HIGHER WATER TEMPERATURE **COMMENTS** IN AREAS WITH LOW VELOCITIES, TOPSOIL CAN BE PLACED OVER THE RIPRAP AND PLANTED WITH RIPARIAN SPECIES TO MITIGATE VEGETATION LOSSES.

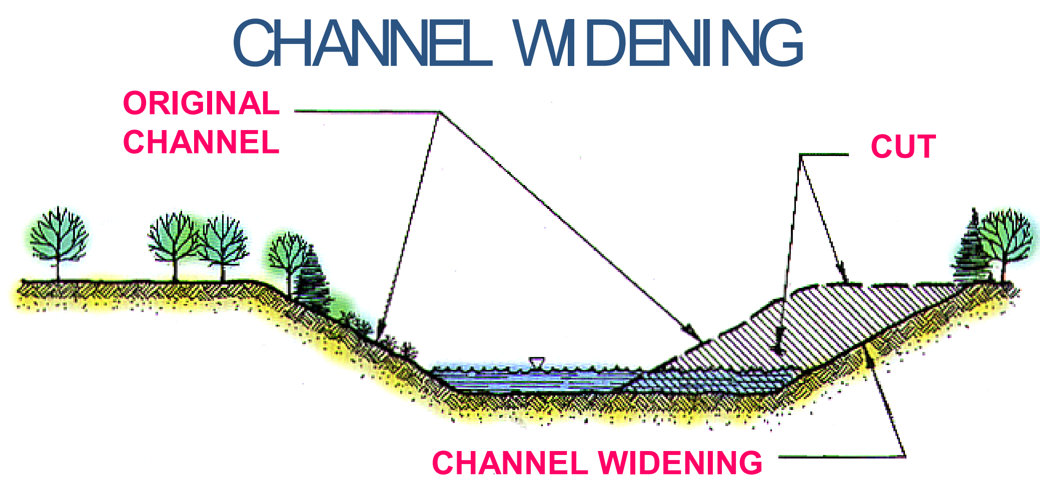
Figure 6-4: Schematic of a riprap armoring stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

RIGID CHANNEL LININGS



LOCAL	UPSTREAM
ADVANTAGES: • PREVENTS EROSION • LOW MAINTENANCE COST AT OUTSET • INCREASED FLOW CAPACITY • ALLOWS FOR STEEPER BANKS AND BED SLOPES *DISADVANTAGES:* • INCREASED SEDIMENT TRANSPORT CAPACITY • DESTRUCTION OF RIPARIAN HABITAT • HIGHER WATER TEMPERATURE • POOR AESTHETIC APPEAL • LACK OF HABITAT DIVERSITY • DECREASED CHANNEL STORAGE • DECREASED STREAM-GROUNDWATER INTERACTION • DESTRUCTION OF FISH SPAWNING SITES • PREVENTION OF NATURAL CHANNEL ADJUSTMENTS • REDUCES RUNOFF RENOVATION, QUALITY	*ADVANTAGES:* • MAY LOWER FLOODWATER ELEVATIONS *DISADVANTAGES:* • MAY HAVE HIGH VELOCITIES AND SCOUR AT TRANSITIONS **DOWNSTREAM** *DISADVANTAGES:* • SCOUR AT TRANSITION • DIMINISHED WATER QUALITY • CAUSES MORE CONCENTRATED PEAK FLOW RATES • HIGHER WATER TEMPERATURE **COMMENTS** CAN CREATE A STERILE RIVER WITH NO LIFE.

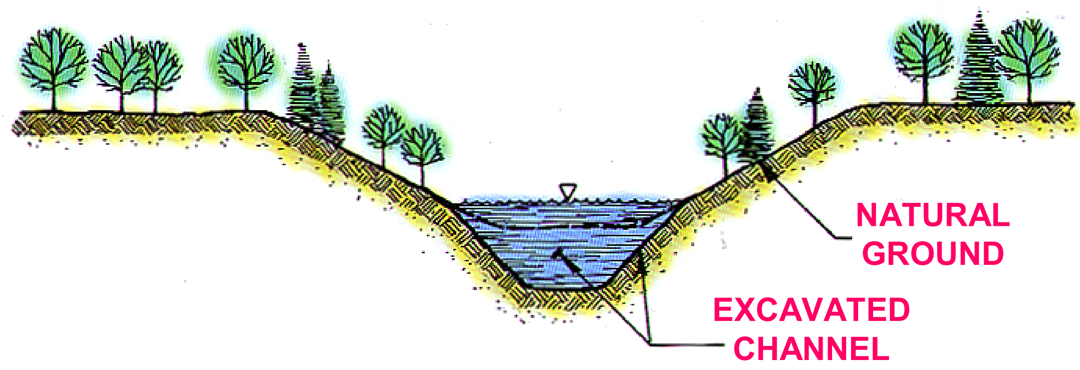
Figure 6-5: Schematic of a rigid lining stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).



LOCAL	UPSTREAM
ADVANTAGES: • INCREASED FLOOD FLOW CAPACITY • DECREASED FLOOD FLOW DEPTH • INCREASED CHANNEL STORAGE *DISADVANTAGES:* • DECREASED FLOW VELOCITIES • INCREASED SEDIMENT DEPOSITION • DESTRUCTION OF RIPARIAN HABITAT • INCREASED WATER TEMPERATURE • POTENTIALLY UNSTABLE BANKS • REDUCED FLOW DEPTH **COMMENTS** TRY TO SAVE VEGETATION ON ONE OR BOTH BANKS.	*ADVANTAGES:* • REDUCED FLOOD FLOW DEPTHS *DISADVANTAGES:* • POSSIBLE CHANNEL AGGRADATION • SCOUR AT TRANSITION **DOWNSTREAM** *ADVANTAGES:* • COULD DECREASE PEAK FLOWS BY INCREASING STORAGE VOLUMES *DISADVANTAGES:* • COULD INCREASE PEAK FLOWS • INCREASED SEDIMENT LOAD DURING EXCAVATION • MAY CAUSE CHANNEL DEGRADATION

Figure 6-6: Schematic of a channel widening stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

CHANNEL DEEPENING



LOCAL

ADVANTAGES:

- INCREASED CHANNEL FLOW CAPACITY
- INCREASED ALLOWABLE FLOW DEPTH
- REDUCED FLOW VELOCITIES
- INCREASED CHANNEL WATER STORAGE
- DECREASED WATER TEMPERATURE
- REDUCED FLOOD DAMAGES

DISADVANTAGES:

- REMOVAL OF NATURAL STREAMBED COBBLES AND ARMOR
- INCREASED EROSION
- POSSIBLE REDUCTION OF BANK STABILITY
- POSSIBLE DEGRADATION OF TRIBUTARIES
- REMOVAL OF VEGETATION
- DISTURBANCE OF SPAWNING AREAS
- POSSIBLE LOWERING OF GROUNDWATER

UPSTREAM

ADVANTAGES:

- LOWER FLOOD ELEVATIONS

DISADVANTAGES:

- POSSIBLE STREAMBED DEGRADATION

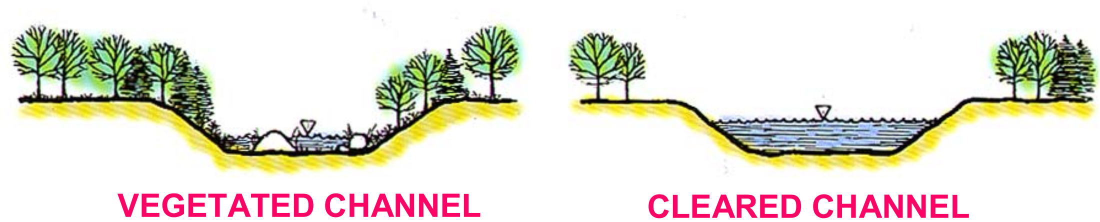
DOWNSTREAM

DISADVANTAGES:

- INCREASE IN SEDIMENT LOADS AND DECREASE IN WATER QUALITY DURING EXCAVATION
- COULD INCREASE OR DECREASE PEAK FLOW RATES

Figure 6-7: Schematic of a channel deepening stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

CHANNEL CLEARING



LOCAL

ADVANTAGES:

- INCREASED FLOW CAPACITY FOR STORMS OF FREQUENT RECURRENCE INTERVALS
- REDUCED FLOODWATER DEPTHS
- REDUCED FLOOD DAMAGE
- REMOVAL OF EXCESS DEBRIS

DISADVANTAGES:

- INCREASED FLOW VELOCITY
- INCREASED EROSION POTENTIAL
- INCREASED WATER TEMPERATURE
- DECREASED WATER TURBULENCE AND AERATION
- DISTURBED HABITAT
- REDUCED INSTREAM COVER AND SHELTER FOR FISH

UPSTREAM

ADVANTAGES:

- LOWER FLOODWATER DEPTHS

DOWNSTREAM

DISADVANTAGES:

- INCREASED SEDIMENT LOAD AND DEPOSITION
- INCREASED WATER TEMPERATURE
- DECREASED DISSOLVED OXYGEN LEVELS
- REDUCED INPUT OF LEAF AND WOODY ORGANIC MATTER

COMMENTS

EXCESS CHANNEL CLEARING ELIMINATES THE NATURAL SHELTER AND ORGANIC DETRITUS THAT CONTRIBUTE TO THE AQUATIC HABITAT. THE NATURAL RIPARIAN VEGETATION AND CHANNEL IRREGULARITIES SHOULD BE PRESERVED.

Figure 6-8: Schematic of a channel clearing stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

velocity is reduced in the bigger channel. On the other hand, clearing a channel can cause excessive erosion as water velocity increases.

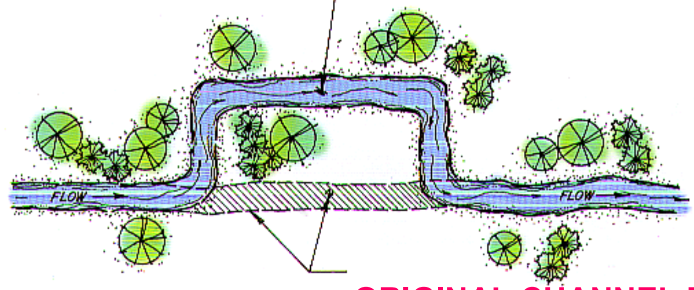
Straightening channels can affect the ecology of a river by eliminating the natural sequence of riffles, runs, pools and glides that normally provide a varied habitat. The elimination of refuge areas in meander pools, oxbows, and low velocity flow areas reduces habitat quality. Unstable banks or beds that are subject to erosion reduce habitat quality.

Channel realignment, or relocation, (Figure 6-9) can increase passage of waters to downstream reaches and alter the peak rate of runoff and sediment transport. Upstream areas will drain quicker, and recharge of water into the soil decreases. This is most pronounced on porous soils, or where floodplain inundation becomes less frequent.

6.3.3.3 Hydrologic Alteration

Large scale human activities alter watershed responses to precipitation, increasing the total volume of surface runoff and the peak flood flow rates. Removal of forest canopy, tilling fields, smoothing and paving land surfaces, and compacting soil contribute to decreased water infiltration into the soil. Filling or draining wetlands reduces the temporary storage of surface runoff, contributing to higher runoff (i.e. river flow) rates.

Drainage ditches and storm drainage systems are constructed to protect transportation systems, small roads associated with logging roads, agricultural fields and infrastructure associated with urban areas, from excess stormwater and/or groundwater. These local drainage systems collect and convey water to larger man-made channels or natural rivers accelerating the movement and concentration of runoff that leads to increased runoff rates. Altered hydrology is a permanent feature of the developed landscape as our transportation systems and developed areas need to have drainage facilities to protect them from flooding and erosion.



LOCAL	UPSTREAM
ADVANTAGES: • OLD CHANNEL RECLAIMED FOR HUMAN USES • INCREASED FLOOD STORAGE IF OLD CHANNEL NOT RECLAIMED *DISADVANTAGES:* • INCREASED CHANNEL LENGTH • DECREASED CHANNEL SLOPE • DECREASED FLOW VELOCITY • DECREASED FLOW CAPACITY • AGGRADATION DUE TO INCREASED SEDIMENT DEPOSITION • DESTRUCTION OF CHANNEL HABITAT **COMMENTS** CAREFUL DESIGN AND CREATION OF NATURAL CONDITIONS IN NEW CHANNEL CAN MITIGATE NEGATIVE IMPACTS.	*DISADVANTAGES:* • AGGRADATION • SCOUR AT TRANSITION • POSSIBLE INCREASE IN WATER ELEVATION • POSSIBLE CHANGE IN CHANNEL PATTERN, ALIGNMENT **DOWNSTREAM** *ADVANTAGES:* • DELAY OF PEAK FLOOD FLOWS *DISADVANTAGES:* • DECREASED SEDIMENT LOAD, LEADING TO DEGRADATION

Figure 6-9: Schematic of a channel relocation stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

6.3.3.4 Dams

Dams (Figure 6-10) alter the flow of water and sediment to the point that natural river form and process is an unrealistic objective of restoration unless dam removal is considered. Dams reduce fish populations by blocking both migratory and resident species from historic spawning grounds.

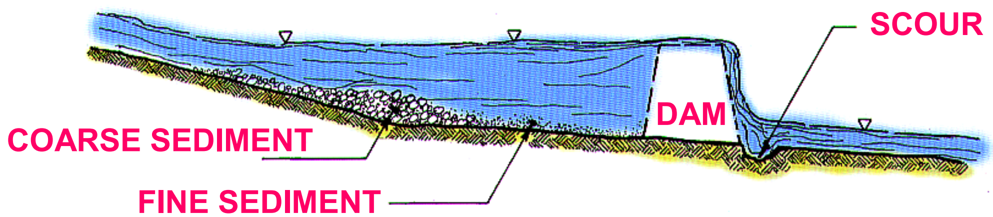
Small dams alter flow, reduce sediment transport, increase downstream water temperatures due to solar heating in the upstream impoundment (Lessard and Hayes, 2003), and serve as physical barriers to fish migration. The collective impact of the many small dams scattered across virtually every river system is extensive. The removal of small dams is becoming a popular restoration option given that many of the structures are obsolete, safety hazards, and key sources of habitat impairment.

Large dams cause large departures from a natural flow regime, particularly downstream of hydro-electric power plants. Unnatural flow regimes alter channel morphology and sediment regime (Assani and Petit, 2004), reduce the overall quality of river habitat making a river uninhabitable for some organisms, and eliminate many of the natural services provided by rivers (Postal and Richter, 2003). Large dams trap most of the sediment moving downstream, and substantial erosion is common on tailwater reaches due to the release of sediment-starved water from the widened upstream impoundment (Kondolf and Swanson, 1993).

6.3.3.5 Urbanization

Urbanization and other forms of land development are accompanied by removing vegetative ground cover, smoothing the land surface, and increasing the area of the watershed covered with impervious or compacted surfaces. Impervious surfaces include roof tops, roadways, driveways, and parking lots. Larger impervious areas increase the amount of surface runoff,

DAMS



LOCAL

ADVANTAGES:

- CREATION OF LAKE OR POND HABITAT
- RECREATIONAL SITE
- POTENTIAL POWER-GENERATION SITE
- LOWERS WATER TEMPERATURE
- MAY STORE RUNOFF
- STORES WATER FOR HUMAN USES

DISADVANTAGES:

- DECREASED TURBULENCE AND INCREASED ORGANIC SEDIMENTS LEAD TO LESS DISSOLVED OXYGEN
- INCREASED FLOOD STAGE
- FLOODS NATURAL RIVER BANKS
- POSSIBLE FLOODING OF TRIBUTARIES
- HIGHER GROUNDWATER LEVELS
- ELIMINATES SHALLOW HABITATS
- BLOCKS FISH PASSAGE, SEGMENTS RIVER

UPSTREAM

ADVANTAGES:

- MAY PROVIDE AREAS FOR BOATING, FISHING, SWIMMING

DISADVANTAGES:

- BED AGGRADATION
- HIGHER WATER LEVELS
- BARRIER TO FISH MIGRATION
- FLUCTUATING WATER LEVEL CAUSES BANK SLOUGHING

DOWNSTREAM

ADVANTAGES:

- MAY DECREASE PEAK FLOWS, INCREASE LOW FLOWS

DISADVANTAGES:

- DECREASED SEDIMENT LOAD
- INCREASED SCOUR
- DAM FAILURES WOULD CAUSE DOWNSTREAM FLOOD WITH CATASTROPHIC FLOW AND SCOUR

COMMENTS

LARGE DAMS MAY PROVIDE RECREATION, FLOOD CONTROL AND WATER SUPPLY STORAGE. LARGE IMPOUNDMENTS MAY BE USED TO REGULATE DOWNSTREAM FLOW RATES.

Figure 6-10: Schematic of a dam stressor, and the anticipated responses as categorized by advantages and disadvantages (Source: MacBroom, 1998).

decrease infiltration and decreases the time water remains in its watershed, altering natural flows (USEPA, 1997) (Figure 6-11). The USGS study (2006) on impervious cover in the New Hampshire seacoast watershed indicated impacts at less than 10% imperviousness. The 10% level is a common watershed development threshold often cited in the scientific literature (e.g., CWP, 2003), beyond which impacts to hydrology, fluvial geomorphology, water quality, and aquatic habitat take place. In addition, the presence of storm sewers and curbs increases the velocity of surface runoff, decreases residence time in the watershed, and allows runoff to rapidly concentrate in rivers.

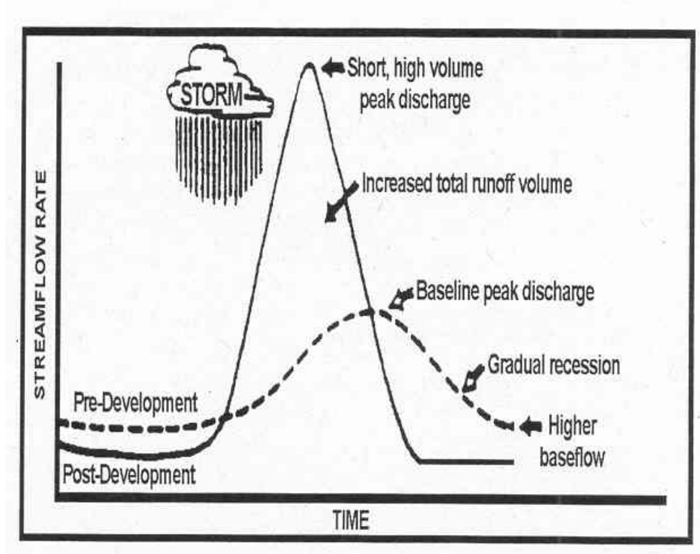


Figure 6-11: Pre- and post-development hydrographs that show an increase in runoff and higher peak flows following a change in land use (Source: EPA, 1997).

The combination of larger runoff amounts and faster concentration times can drastically change the flow rates in rivers. Urbanization will also increase the magnitude and frequency of mean annual and bankfull flows in the river. Urbanization also reduces the infiltration of water into the soil and the storage of surface water leading to a long-term reduction in low flows. As a result of higher peak flow rates and the greater frequency at which they occur, alluvial river channels in urban areas often tend to enlarge by horizontal widening and vertical degradation.

Modern stormwater management practices help reduce the hydrologic impact of urbanization. The use of detention basins, infiltration systems, low impact development, and erosion controls are an important part of river management.

6.4 Channel Response

6.4.1 Introduction

River channels can respond to natural events and human activities locally, over a single or multiple reaches, and throughout a watershed. Some of the general trends of river channel response are discussed below. Note that the text accompanying the schematics of human disturbances to river channels (MacBroom, 1998) in the preceding figures in this chapter includes information on likely responses to these stressors.

6.4.2 Change in Water Conveyance

Activities that increase channel flow capacity usually decrease floodwater levels and reduce flood damages. However, increasing channel conveyance by channel clearing and smoothing (i.e., reducing flow resistance) will increase velocity and the risk of bank or bed erosion unless rigid linings are used. Channel straightening usually results in steeper bed slopes and higher flow velocities, which may widen or deepen the local channel, and accelerate the flow of water downstream, raising flood levels.

Some activities may decrease channel size, restricting flow and raising upstream water surface elevations (i.e., creating a backwater). In addition, reducing the width of a floodplain by placing fill material or constructing levees increase velocities at the site and immediately downstream. As channels degrade relative to historic floodplain elevations, flood flows cannot spread out on the floodplain and are more confined to the channel, and thus local and downstream water velocities are higher.

Undersized bridges and culverts also restrict flow, raising upstream water levels and reducing water velocity that leads to increased sediment deposition (Figure 6-12). Undersized structures also tend to increase local and downstream water velocity, which in turn increases

Figure 6-12: Excessive aggradation upstream of an undersized bridge on the West Branch of the Little River in Stowe, VT (Source: MMI). The photograph is taken looking downstream. The bridge opening is smaller than the current bankfull width of the channel. Hydraulic modeling indicates that backwatering takes place in this location under bankfull and larger storms.

the amount of erosion, as water is concentrated into and through the structure. High velocities at structures may create scour holes that endanger the foundations, or prevent fish passage.

6.4.3 Change in Sediment Transport

Changes in sediment transport rates combined with the boundary conditions of the bed and banks ultimately determine channel stability (Figure 6-13).

Activities that increase water conveyance often increase the channel's ability to transport sediment. If the competency (i.e., the size of erodable particle) exceeds the critical threshold of the bed or bank material, increased erosion and aggradation can occur. Long-term increases in channel erosion lead to removal of finer sub-threshold particles and bed

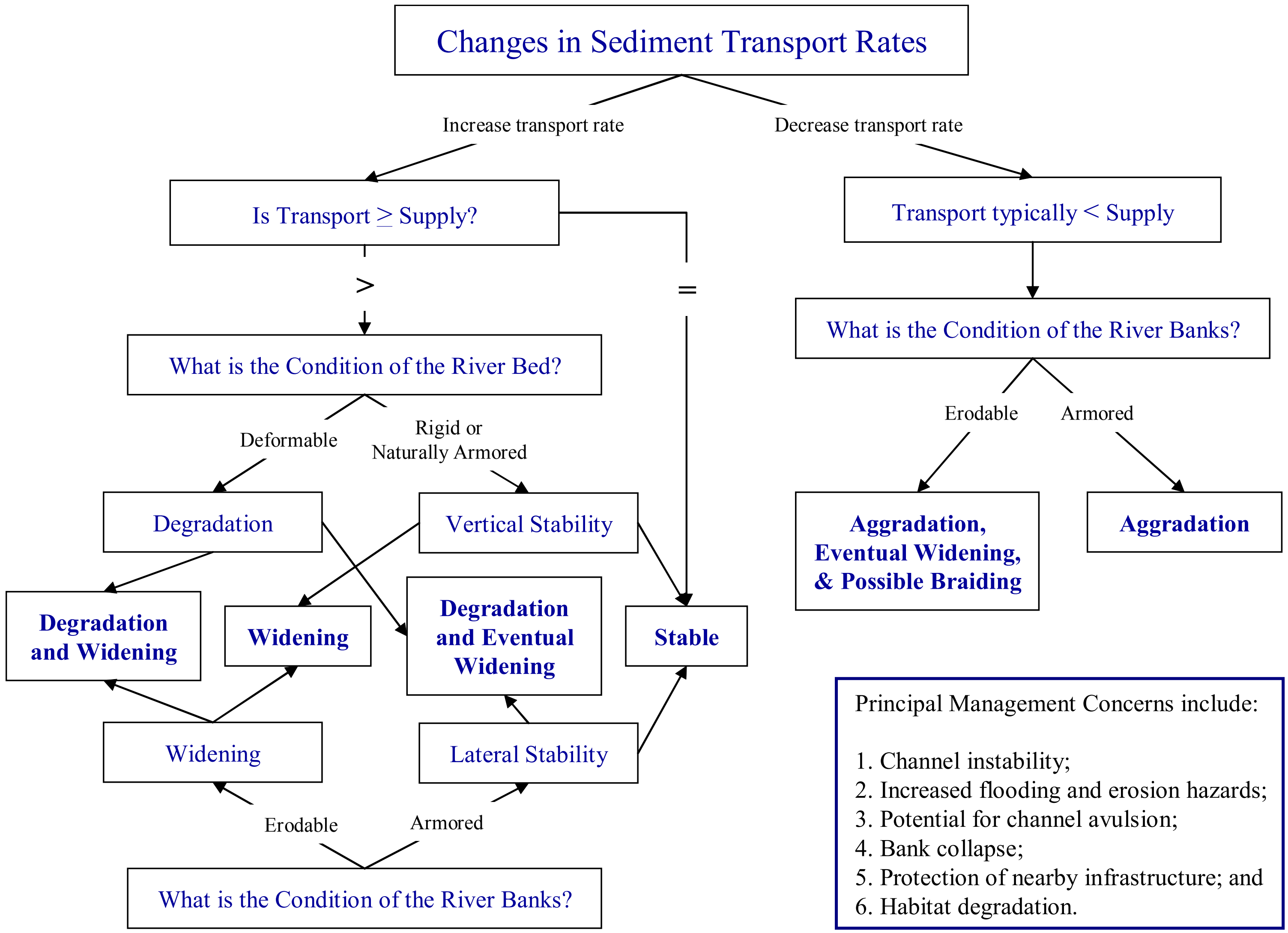


Figure 6-13: The affects of altered sediment transport rates and channel boundary conditions on stability. Bold text indicates most likely processes influencing the river channel.

degradation. If sufficient large particles remain, the river bed may become naturally armored and stabilize, leaving just the banks still subject to erosion and channel widening.

Reducing the river's ability to transport sediment by reducing its slope or diverting water (i.e., lowering water velocity) can lead to sediment deposition and channel aggradation.

6.4.4 Channel Degradation

Degradation is the general long-term lowering of a river bed or the rapid down-cutting of a channel during floods (Figure 6-14). It occurs where the channel's slope, discharge, and substrate size allow for the transport of more sediment than is supplied to a river reach. The river will erode its bed until the slope and velocity are reduced to a point where the river bed erosion no longer produces additional sediment.

Degradation can occur as a uniform lowering of the bed if the factors inducing the erosion are consistent throughout a channel reach. In other cases, the degradation can occur in the form of upstream migration of small erosion fronts called head cuts. In effect, two graded portions of the river are separated by a local steep point, or a nick point, where active degradation

Figure 6-14: Photograph of channel degradation and widening on Warren Brook in Alstead, NH (Source: Horizons Engineering, LLC).

occurs. The steep point continuously erodes its base and thus travels upstream. (Note that an analogous feature is also possible on an aggrading front that is called a steep riffle.)

Natural degradation can be the result of geologic uplift, climatic changes that increase runoff, or even an increase in watershed and bank vegetation that reduces the natural supply of sediment. Degradation of the river will usually continue until a new equilibrium condition is reached, unless the channel bed is naturally armored. Natural grade control (i.e., falls or cascades) and dams can stop the upstream movement of a head cut, reducing upstream channel degradation.

Channel degradation that occurs in the absence of natural bed armoring can lead to deep channel incision. As the channel down-cuts the banks get taller and may eventually be subject to collapse. Channel incision and bank collapse often lead to channel widening and increased sediment loads. High steep banks are prone to collapse by either exceeding the slope's safe angle of repose or by being undermined by scour at their base (Figure 6-15). Incision ceases when either the channel slope is decreased to equilibrium conditions or channel widening leads

Figure 6-15: Photograph of an eroding bank associated with channel degradation on Warren Brook in Alstead, NH (Source: Horizons Engineering, LLC). Inset photograph shows the same bank following stabilization with riprap and grass.

to decreased flow depths and lower shear stress. In addition, if incision leads to head cuts that migrate up a coarse-grained channel, the upstream degradation can add to the downstream sediment supply and slow the downstream incision.

Incision results in lower water levels in the channel relative to the top of bank and also can lower nearby ground water levels. Incision also decreases the frequency and depth of floodplain inundation, and gradually the river is disconnected from riparian wetlands and the floodplain.

6.4.5 Channel Aggradation

Aggradation is the general increase in elevation of a long reach of a riverbed over a long-term period (Figure 6-16). It is a process of deposition in which sediment is continually added to the riverbed, and possibly even to the floodplain. Aggradation occurs when the river does not have sufficient slope, velocity, or flow rate to transport the sediment load of a given size distribution. The riverbed and floodplain elevations will increase until equilibrium is reached with sediment transport being equal to sediment supply rates.

Figure 6-16: Photograph of an aggradational feature at the confluence of Bowers Brook and Cold River in Acworth, NH taken in August 2006 (Source: Horizons Engineering, LLC).

The reach downstream of an aggrading reach may have an increase in slope as the aggrading reach is raised above the previous bed level. This new steeper slope will increase the channel's sediment transport rate until a new equilibrium is reached.

The slope of the riverbed upstream of an aggrading reach is reduced by the downstream deposits. This reduction in slope reduces sediment transport and hence the area of deposition will migrate upstream, with progressively finer material being deposited due to the lower transport capacity. The sediments will be segregated by weight into stratified layers sloping downstream.

The aggrading channel often becomes wide and braided as it fills with new sediment and the water carves out multiple flow paths through the deposits. If the channel is not too incised overbank flows on the floodplain will take place more frequently leaving sediment deposits on the floodplain's surface. Thus, the floodplain surface may rise with the river, but at a slower rate. Aggrading channels often tend to widen in order to maintain their cross-sectional area.

Among the factors that lead to increased sediment deposition and channel aggradation are: a decrease in watershed vegetation leading to increased surface erosion (e.g., logging, development in the river corridor); climatic changes reducing runoff rates; and excessive infiltration in coarse alluvium.

6.4.6 River Bank Erosion

River bank erosion is one of the most common responses to external changes in water conveyance or sediment loads. Excessive bank erosion causes economic losses such as loss of land and private property damage. The sediment caused by excessive bank erosion can degrade water quality and reduce habitat quality.

Alluvial channels that have formed in erodable soils, and even some formed in more compacted glacial till, often have natural bank erosion on the outside of meander bends, in reaches where the channel width is narrows, in areas where the banks have been compromised by ice abrasion, and in areas subject to high flow velocity. Extensive bank erosion and general channel enlargement occurs during floods.

Excessive sediment loads may also contribute to bank erosion. Deposition of coarse gravel and cobble sediments in the channel reduces cross-sectional area, and may encourage erosion of the banks when bank materials are finer than deposited bed materials resulting in channel widening. Braided channels, with many mid-channel bars and islands, are notoriously unstable.

Bank erosion may consist of the detachment and removal of local particles, mass failures of larger areas of soil that are undermined at or below the water line, and loss of river bank trees and roots. The assessment of both gradual bank erosion and mass failures is complex because these processes occur naturally resulting from normal channel adjustments. In many cases the river bank will adjust its shape and naturally re-vegetate. However, stressors can cause excessive bank erosion that release large volumes of new sediment that may require corrective action. In addition, the presence of infrastructure and private investments often leads to the desire to reduce even normal rates of bank erosion, which would typically heal on their own given ample space and time. Typical methods of bank stabilization are presented in Chapter 10.0 of this manual.

6.4.6.1 Channel Widening

Channel widening is used to describe situations where there is bank erosion occurring on both sides of a river channel. Unlike simple bank erosion which naturally occurs in limited areas such as along bends or contractions, channel widening implies a net increase in the waterway's width over a sizeable length.

Channel widening may occur naturally due to major floods or it may be encouraged by the increased peak flood flow rates attributed to watershed changes. Widening is also associated with excessive channel degradation and aggradation, such as that common near a dam. Unlike common local bank erosion problem that often do not call for management, channel widening suggests the river channel is undersized for the modern flow rates.

Widened channels that convey large flood flows typically have featureless (i.e., plane) beds and shallow water depths under normal and low flow conditions that have poor aquatic habitat. The breaks in the forest canopy on over-widened channels tend to allow excessive growth of invasive plants such as Japanese knotweed (*Fallopia japonica*), tartarian honeysuckle (*Lonicera tatarica*), and garlic mustard (*Alliaria petiolata*).

6.4.7 Channel Avulsion

Channel avulsion occurs when there is a rapid and dramatic change in the river's alignment. Avulsions usually occur during floods when waters overtop the banks and scour a new flow path, generally across a low floodplain. Classic examples of channel avulsion occur on sinuous alluvial rivers when floodwaters carve a new straight channel across a meander bend, creating a meander chute cut-off that bypasses the original channel. An oxbow can form if the river channel migrates away from and isolates the meander bend that has been short circuited.

Human activities can lead to channel avulsion. Clearing riparian forest cover from low floodplains reduces roughness and encourages higher overbank flow velocities that can lead to meander chute cut-offs. Channel avulsions are also possible where sand and gravel material is excavated from floodplains. Long linear floodplain ponds associated with former gravel extraction sites are typically often subject to avulsion as they provide a low resistance pathway that captures the river. Three relatively recent New Hampshire examples of channel avulsion are the Suncook River in Epsom (Figure 6-17), Pemigewasset River near I-93 Exit 31, and Mad River near I-93 Exit 28.

Figure 6-17: Aerial photograph of the 2006 Suncook River channel avulsion in Epsom, NH (Source: USACOE).

CHAPTER 7.0: HYDROLOGY

7.1 Introduction

Hydrology is one of the primary variables that determine the dynamic shape of a river and its physical processes. Flows and their pattern of variability are also the foundation of the aquatic and riparian zone ecosystems. Naturalized river channel and bank stabilization projects should be designed with consideration of a range of flows that determine the physical stability, ecological integrity, and chemical composition of a river system. Designs that consider a range of flows are likely to perform as planned over longer periods of time than traditional designs that rely on a single flood event (e.g., 100-year or bankfull floods). Good hydrology practice is to determine a range of design flows via several methods and compare results. For all but the simplest of projects, direct flow measurements are compared to estimations that are generated from either simple calculations or more involved models. Current estimates of system hydrology are also compared to any initial project hydrology data (Chapter 3.0) such as found in existing Federal Emergency Management Agency (FEMA) flood insurance studies, past projects, and watershed studies.

The level of recommended hydrology analysis is a function of whether a project is classified as routine, moderate, or comprehensive (Figure 7-1). Simple design flow estimation is adequate for routine projects that are small in scope and have low site constraints. In this case a range of flows can be approximated from hydraulic geometry curves, basic regression-based models, or using regional flow estimations based on watershed size. More involved projects generally require additional analyses to expand the determination of hydrology at the project site – instantaneous measurements of flow and gage analysis. If the gage happens to be located on the river where the project is taking place data can be directly used; however, more frequently flow statistics are approximated from surrogate gage data by scaling via watershed area or data correlation. Multiple flow calculations and measurements are used to compare design flows estimations.

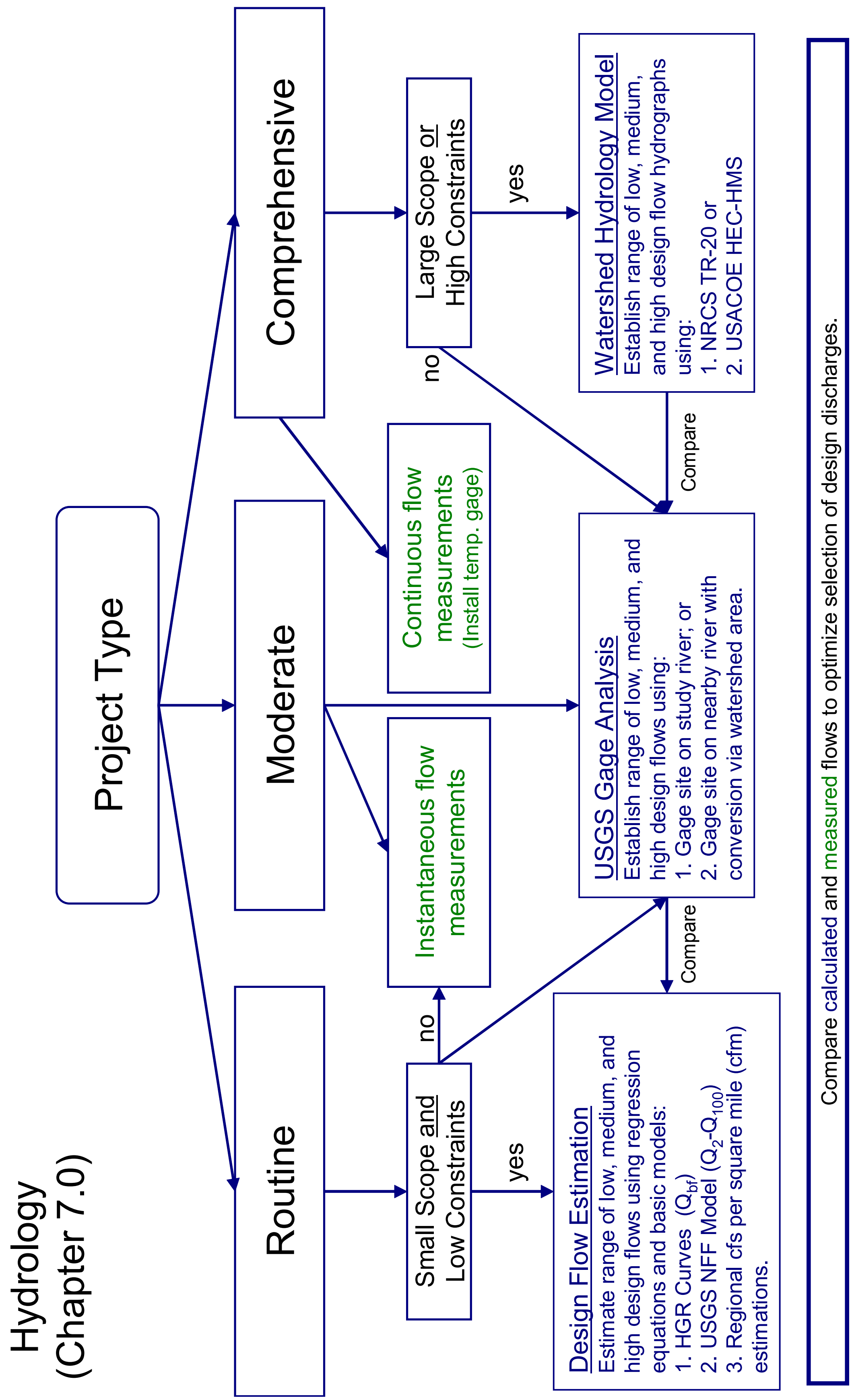


Figure 7-1: Hydrologic calculation (blue text) and measurement (green text) recommendations for routine, moderate, and comprehensive projects.

Comprehensive projects require an increased understanding of the full range of hydrologic conditions at the project site, and thus installation of a temporary gage is recommended. For projects where the scope is large or there are considerable site constraints a watershed hydrology model should be created. Models are useful for simulating changes in flow due to past and future watershed land use changes, flow diversions, and flow storage. At this highest level of analysis peak flows from regression equations, nearby gage records, continuous project-specific flow measurements, and modeled watershed hydrographs are typically compared to determine the peak and timing of a range of design flows.

7.2 Designing for Multiple Flows

7.2.1 Introduction

Use of multiple design flows allows naturalized river channel design and bank stabilization projects to meet a broader range of objectives and increase overall performance. Avoid reliance on a single design flow to increase the chances of more successful projects. In addition to designing designs based on the anticipated peak flow of the desired return frequency, consideration of low, bankfull, flood, and other ecologically significant flow magnitudes can greatly improve the success of a project in terms of channel stability and ecological integrity (Table 7-1). Other flows that should be considered where appropriate include those associated with the presence of hydropower facilities.

Table 7-1: Key function and appropriate design flow for each element of a natural(ized) channel.

Channel Element	Key Function	Hydrology / Design Flow
Thalweg	Low flow concentration	Mean dry season flow
Low Flow (Inner) Channel	Aquatic habitat	Mean spring flow
Bankfull (Main) Channel	Convey flood and sediment loads	Channel forming dominant discharge
Floodplain	Convey & store flood pulses	Over bank flood flows

Designing for multiple flows can help avoid common pitfalls with projects such as under- or over-sizing channels. Dimensions determined solely from the bankfull discharge are a common problem because culverts are undersized for large floods with relatively low return interval, such as the 10-year or 25-year storms. Relying on only large design storms, such as the 100-year flood, can lead to over-sized channels that have limited habitat quality during low flows. Attention to a range of flows is necessary to avoid limiting life cycle functions (e.g., access to spawning grounds) by not including appropriate flows occurring during critical times of the year (e.g., spring or fall fish migration). Most river channels naturally develop a compound cross section (Figure 7-2) to accommodate different flows. Designs should identify low, medium, and high flow components of each cross section at the project site.

In addition to the size of the flood, the duration and frequency of flow events is an important consideration for channel stability and ecological health. The proper amount of short-term, seasonal, annual, and long-term flow variability is essential for healthy aquatic habitat (Richter et al., 1996). Information on the occurrence of different sized floods can reveal system disturbances that can create a mechanism for altered sediment transport and channel instability, as well as a habitat bottleneck in developed watersheds. Comparing measurements and calculations of a range of flows increases the chances of being able to identify which of the many potential types of hydrologic modification (Figure 7-3) are present at the study site.

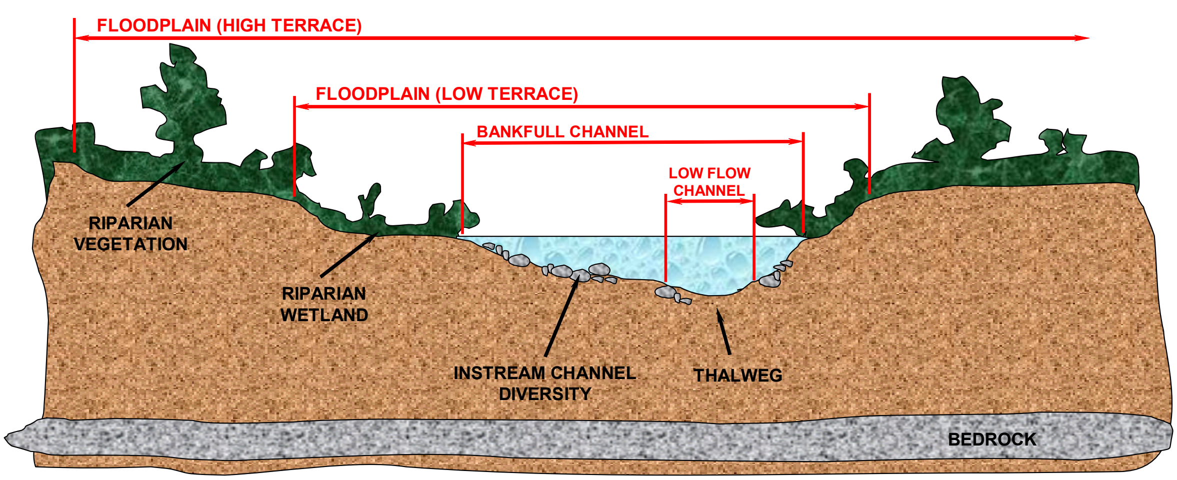


Figure 7-2: Typical schematic of a natural(ized) channel with compound features including low-flow channel, bankfull channel, and the low and high terraces of the floodplain.

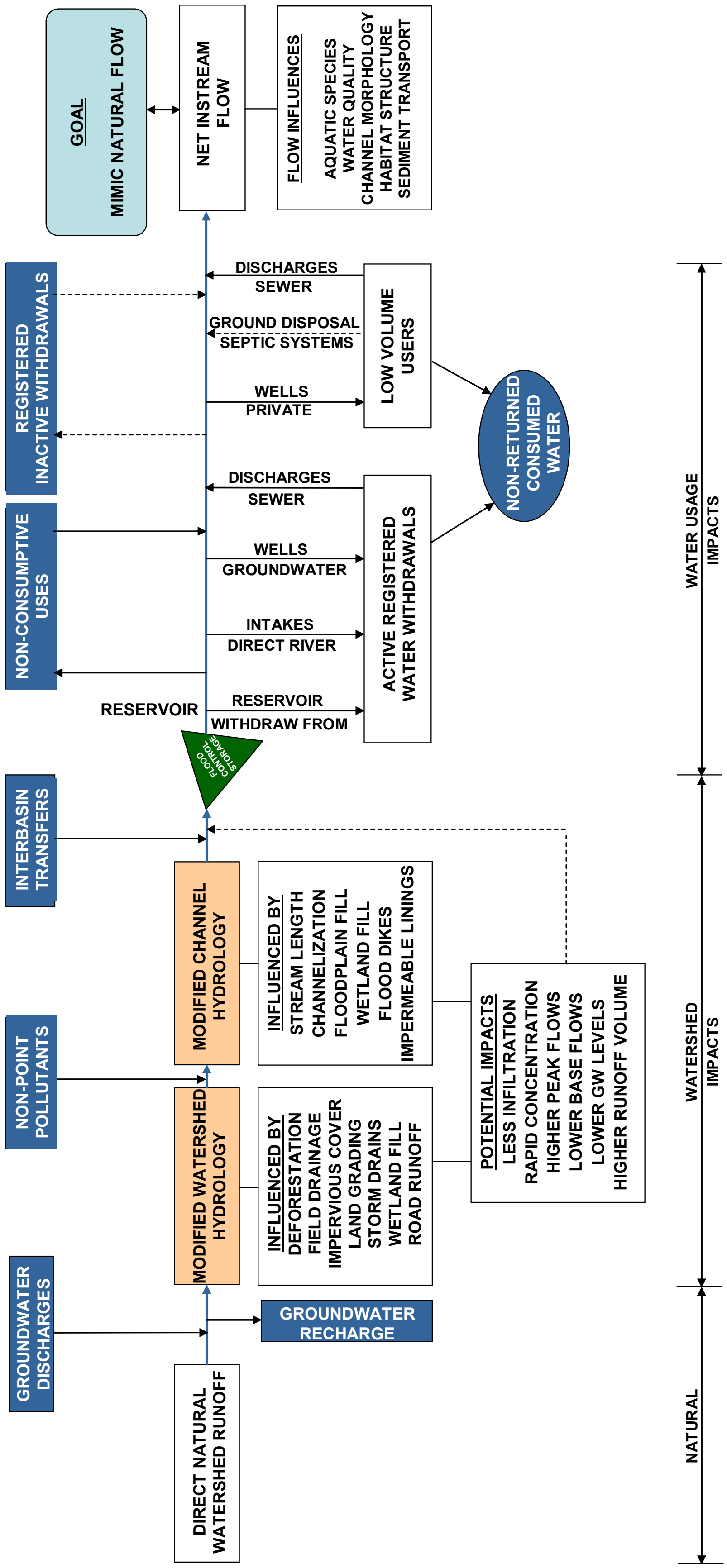


Figure 7-3: Factors, both natural and caused by humans, that influence river hydrology.

7.2.2 High Flow

The traditional approach to single-discharge design of river channel and bank stabilization projects is based on the peak 100-year discharge (Q_{100}) due to the common goal of flood mitigation and regulation of the 100-year floodplain by the FEMA. While effective at sizing projects for large floods, many designs that only consider the peak 100-year flow have little useable aquatic habitat during moderate and low flows due to shallow flow depths, and over-sized channel and bank materials. Understanding project performance during high flow is typically required by federal and state government agencies to ensure that flood elevations are not increased as a result of implementation. High discharge designs should always be used in conjunction with designs considering other flow levels.

7.2.3 Bankfull Flow

Bankfull flow (Q_{bf}), which takes place approximately once every one to two years, has become a popular design discharge due to its importance in determining the dimensions of meandering channels (Wolman and Miller, 1960). Bankfull flow in New Hampshire has been found to be best approximated by the flood that takes place every 1.5 years ($Q_{1.5}$), especially for smaller and steeper river channels (NHST, 2005). The widespread use of bankfull flow in naturalized river channel design and bank stabilization projects follows the increasing popularity of dominant discharge – one flow is most responsible for creating stable channel morphology (FISRWG, 1998). The dominant discharge is used as a surrogate to describe the flow that transports the most sediment over the long term, or the effective discharge (See discussion in Schiff et al., 2006). The bankfull flow is an approximation for a single design discharge and thus it is important to consider additional design discharges.

7.2.4 Ecologically Significant Flows

Based on the species present, variability of flows should be considered during design to address habitat conditions during the year when important life cycle functions are taking place such as migration and spawning, for example. The Natural Flow Regime (Poff et al., 1997) suggests that maintaining the natural flow variability that supports habitats for native species are the key to sustaining ecosystem functions. This concept states that flood flows and drought conditions are both important to sustaining the ecosystem. Investigate at a minimum the monthly median and range of flows. Design should accommodate the entire range of flows so that habitat availability is maintained across this range.

If no gage data are present, regression equations can be used to determine flows, and compared to surrogate flow data from a similar river. Surrogate flow data should be selected from rivers where watershed area, slope, elevation and climate conditions are similar. Translation of gaged flow values into flow per square mile of watershed area (cubic feet per second per square mile or cfsm) allows for translation of the gaged flows to an ungaged location of a different watershed size. This translation should be limited to target watersheds ranging from 0.3 to 1.5 times the gaged watershed area (Ries and Friesz, 2000). Methods are also available through the US Geological Survey (USGS) for extending partial surrogate gage records of rivers with similar watershed area, slope, elevation, and climate conditions.

7.2.4.1 Bankfull Flow

Habitat availability is largely a function of channel form and substrate material. Every flow that transports sediment affects channel form. Maximum sediment transport usually occurs at relatively moderate flow events rather than large flow events since moderate flows occur much more frequently than larger events (Wolman and Miller, 1960). The dominant discharge is used as a surrogate to describe the flow that over the long term transports the most sediment, or the effective discharge (See discussion in Schiff et al., 2006).

In channels at or near dynamic equilibrium, the dominant discharge is approximately equal to the bankfull flow (Leopold et al., 1964). Bankfull flow (Q_{bf}) is approximately the flow that occurs once every one to two years ($Q_{1.5}$). Bankfull flow has become a popular design discharge due to its importance in determining the stable dimensions of meandering channels.

Although a river channel restored using a design based on bankfull flow is likely to achieve a dynamic equilibrium, it is important to consider other design discharges such as peak and low flows.

7.2.4.2 Low Flow

Channel design for low flow conditions should attempt to provide habitat that is similar to the natural low flow condition. Low flows have important ecologic functions. Low flows are naturally occurring conditions that native species are adapted to withstand when natural habitat conditions are present to provide refuge. Non-native species may be restricted by low flow conditions. During low flows aquatic habitat quality and abundance is often reduced and higher flow dependent organisms experience stressed living conditions. Limited access to food and refuge areas is common during low flows as connectivity between suitable habitats is reduced or eliminated and fragmentation occurs. Increased water temperature and reduced dissolved oxygen harms coldwater species. These effects on higher-flow dependent species are balanced by improved conditions for other species such as invertebrates and oppressive conditions for invasive species. Naturally occurring low flows should not be prevented, but channel design for low flow conditions should strive to provide habitat availability, abundance, and connectivity similar to natural reaches. Low flow statistics have been developed for New Hampshire (Flynn, 2003) and are available on the Internet (http://pubs.usgs.gov/wri/wri02-4298/).

Establishing conditions that result in dynamic equilibrium may play the largest role in the maintaining availability of habitat during low flows. A constructed low flow habitat that has been poorly designed is unlikely to persist. Low flow habitat is likely to occupy the deepest part of the river channel, or thalweg. As such it may be subject to sediment deposition following floods. It may not be possible to construct permanent habitat for low flow conditions, but it should be possible to design the channel such that its slope, width, depth, and substrate material will continue to recreate low flow habitat. Appropriate design parameters will take into consideration substrate material and channel competence, the maximum size particle that a river can transport at a given flow, when determining channel slope, width and depth. The bankfull flow may be used to identify the minimum size substrate that will remain stable at flows up to the bankfull flow, which is the most frequent sediment transport flow. Particles larger than the channel competence size at this flow can be used to create more permanent refuge for fish, but flows higher than bankfull flows may dislodge even these. Large particles will increase channel roughness and thereby slow average water velocity and increase depth. The tradeoffs between parameters like depth and temperature change with increased channel roughness should be evaluated.

7.3 Flow Measurement

7.3.1 Introduction

Flow measurements are recommended for all but routine projects that are both small in scope and have low site constraints. Instantaneous flow measurements at cross sections are recommended for more involved routine projects and moderate projects to get a snapshot of current baseflow conditions. These measurements are used to check calculations (routine projects) and for gage analysis (moderate and comprehensive projects), and offer a current point of reference during baseflow conditions.

Installation of a staff gage is recommended in the event that flow measurements are desired during frequent regular visits to the project site. In this case, between five and ten flow measurements are made at the cross section over a range of flow levels and a depth-discharge rating curve is established. Flow can then be readily obtained by simply recording the gage reading on the depth and conversion using the rating curve. This approach to flow monitoring is particularly appealing if long-term monitoring is planned since no instrumentation is needed once the rating curve is created.

Installation of a temporary continuously monitoring gage is recommended for comprehensive projects. This procedure requires installation of a pressure probe to record water depth and five to ten instantaneous flow measurements at the cross section during various flow conditions to create a rating curve to convert depth to discharge. If a total station survey is planned for the project, survey the probe installation so that depths can be converted to water surface elevations.

7.3.2 Instantaneous Flow Measurements

Instantaneous flow at a cross section is most commonly measured via the velocity-area-integration method (Roberson et al., 1988). The channel cross section is divided into flow cells, and in each cell the depth is recorded and water velocity is measured using a current velocity meter. USGS recommends measuring the velocity at 0.6 times the water depth for shallow flows (depth < 2.5 feet), while the velocity in deeper flows is the mean of measurements at 0.2 and 0.8 times the depth. The flow through each segment in the cross section is determined via the continuity equation (Q=VA where Q is discharge (cfs), V is velocity (fps) and A is cross sectional area (sq ft)). Finally, the flow in each cell is added to obtain the total flow at the cross section ($Q_T=\Sigma Q_i=\Sigma V_i A_i$).

Installing a staff gage and developing a rating curve (Leopold, 1994) is an efficient and economical approach to making many (> 10) repeated flow measurements. After firmly pounding a staff gage into the river bed, between five and ten instantaneous flow measurements are made over time at the cross section during a range of low, medium, and high flows. During each measurement the gage reading is recorded so that a relationship between the gage and discharge is established – the rating curve of that staff gage (Dunne and Leopold, 1978). Once the rating curve is established, flow measurements can readily be determined from reading the gage and converting to flow as long as the gage remains in its original location and the channel cross section remains stable.

A USGS traditional crest-stage gage (CSG) is a simple and efficient instrument that is used to record the maximum flood stage during an event (http://pubs.usgs.gov/fs/2005/3136/fs2005-3136-text.htm). The major benefit of the CSG is that it can take a measurement while unattended. The instrument generally consists of a piece of wood inside of a steel casing with shredded cork in the bottom cap of the casing. During the flood, the shredded cork from the bottom cap floats. As the flood recedes, the pieces of cork adhere to the wood, forming a line at the maximum water surface elevation. The peak stage is then recorded from the piece of wood during the next visit to the site.

7.3.3 Continuous Flow Measurements

When continuous flow records are needed for designing comprehensive projects and no suitable gage data are available a temporary gage is installed for monitoring. Pressure gages that record water depth at set time intervals are deployed on the river in some sort of housing to protect the probe and maintain the probe location at a constant elevation. This is analogous to an automated CSG. A perforated plastic pipe is a common housing for a temporary gage that can be fixed to two metal rods driven into the river bed or stationary infrastructure such as a bridge (Figure 7-4). The top of the pipe is surveyed so that water surface elevations can be determined by measuring the distance the probe head sits below the top of pipe. The pressure gage is then retrieved and data are downloaded to a computer for plotting and analysis. Recall that between five and ten flow measurements are made at the cross section over a range of flow levels to establish a depth-discharge

Figure 7-4: Photograph of an instrument housing that contains a temporary, continuous monitoring river gage (Source: MMI).

rating curve to convert water depths to flow measurements. It is useful to obtain local precipitation data to help with the interpretation of the gage data. Typical analyses include determining peak, timing, and shape of storm hydrographs, as well as trends in baseflow.

7.4 Design Flow Estimation

7.4.1 Introduction

For all projects, begin with design flow estimation using regression equations, basic models, and regional estimations. These tools offer a quick way to determine the flow at the project site with limited site information. For routine projects that are small in scope and have low constraints, the basic estimations are often adequate for design. For most projects, however, the estimations are compared to flow statistics from measurements, a gage analysis or a watershed hydrology model.

7.4.2 Hydraulic Geometry Relationships

Hydraulic geometry relationships (HGR) are empirically-derived power relationships that are useful for rapidly estimating discharge at a given return frequency, water velocity, channel width, depth, or cross sectional area as a function of watershed area (Leopold and Maddock, 1953). The State of New Hampshire currently has provisional HGR curves that include the relationship between watershed area (sq mi) and Q_{bf} (cfs) (Figure 7-5). Note that the New Hampshire curves are slightly skewed towards smaller river channels in steeper terrain as a result of including data from channels in the White Mountains to create the curves. For larger rivers such as those in the Connecticut River Basin, it is more appropriate to use Vermont's HGR curves (Appendix J in VTANR, 2005) to determine bankfull flow. It is typically useful to compare HGR calculations with results from other empirical studies in nearby states or other regions (Dunne and Leopold, 1978).

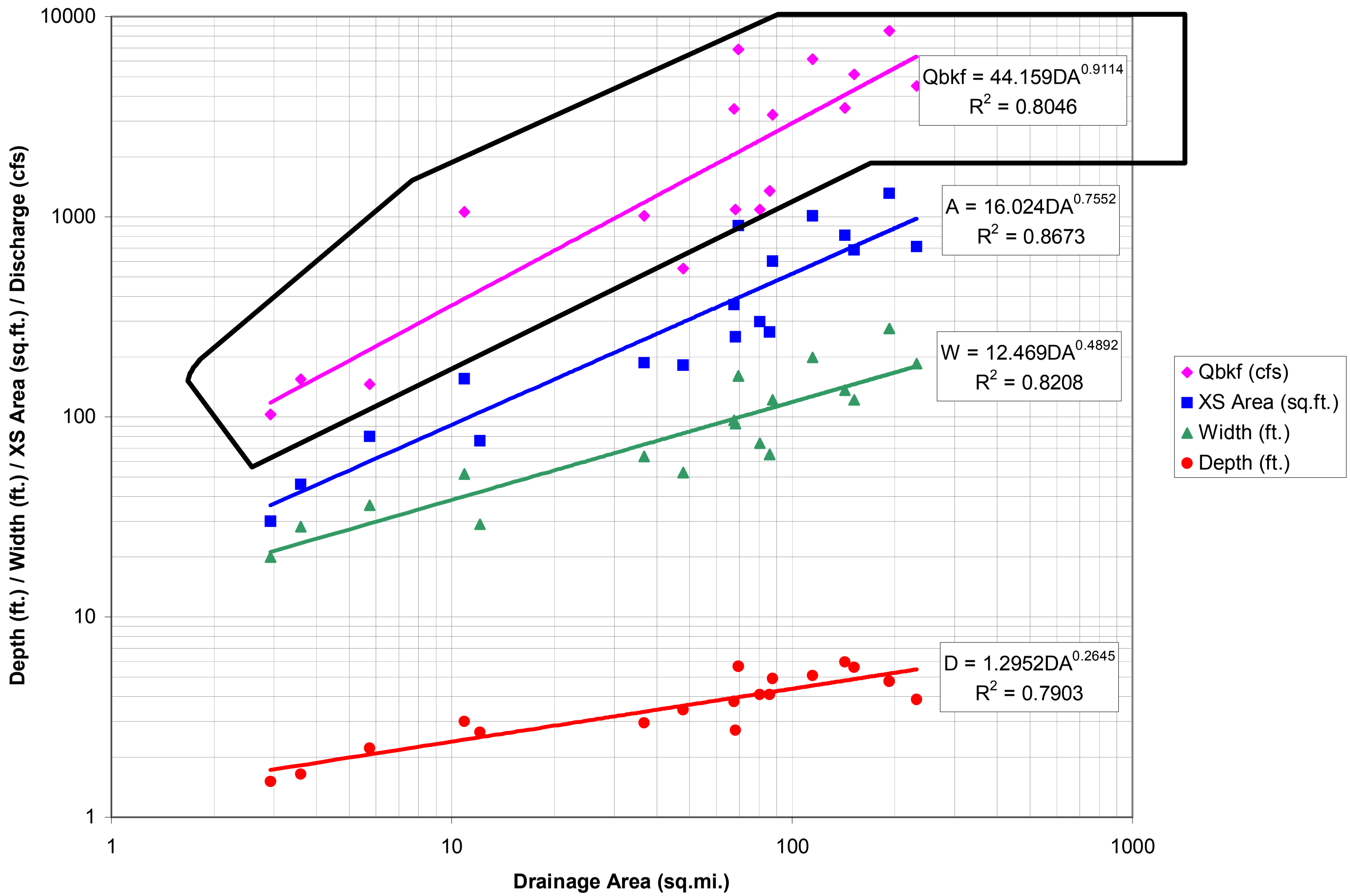


Figure 7-5: New Hampshire 2005 regional hydraulic geometry curves (provisional), which are particularly useful for smaller channels in steeper terrain (Source: NHST, 2005). Outlined curve is used to estimate bankfull flow.

7.4.3 National Flood Frequency Model

The National Flood Frequency Program (NFF) provides regression-equation estimates of peak discharges for unregulated rural and urban watersheds, flood-frequency plots, and plots of typical flood hydrographs for selected recurrence intervals for every state in the US The Program also provides weighting techniques to improve estimates of flood-peak discharges for gauging stations and ungaged sites (Ries and Crouse, 2002).

The NFF model for the State of New Hampshire allows for calculation of peak flows of storms with recurrence intervals of 2, 5, 10, 25, 50, and 100 years (LeBlanc, 1978). Inputs into the model include watershed area (sq mi), channel slope (ft/mi), and the 2-year, 24-hour precipitation (in). A detailed description of the New Hampshire NFF model and a map of the 2-year, 24-hour precipitation is presented in Appendix D. The NFF model can be downloaded from the Internet (http://water.usgs.gov/software/nff.html).

Note that the NFF regression equations for New Hampshire were established in 1978. With 30 years of additional flow data collected since then, the equations are outdated and in their current form are recommended as a rough approximation of peak flows and a source of data for comparison to other design flow estimations. USGS and New Hampshire Department of Transportation may be updating the regression equations in the near future so check the NNF website listed above for more recent information.

7.4.4 Regional Approximations

Regional approximations of the amount of flow for the given watershed area (cfsm) are useful guides to verify other estimates of design flows and help guide calculations and design. Relationships exist to estimate of a variety of flow scenarios for the northeast US (Table 7-2). A previous analysis of river gages in New England has also led to establishment of a generic hydrograph (cfsm versus month) that also can be used for gaining a rough estimate of typical seasonal flows (Figure 7-6) (Lang, 1999).

Table 7-2: Common discharge per watershed area (cfsm) for different flow scenarios. Bankfull flow estimates calculated from the New Hampshire hydraulic geometry relationships (HGR) are shown for comparison to regional flow ranges.

Flow Scenario	Flow per Watershed Area (cfsm)	Comments
7Q10	0.02-0.3	
Mean August flow	0.2 - 0.6	varies with amount of stratified drift
Median annual flow	1	
Mean annual flow	1.6-2.0	
Mean March flow	2.5-5.0	
Median annual flood	20-40	watershed area 100 sq mi
Median annual flood	30-50	watershed area 10 sq mi
Median annual flood	40-60	watershed area 1 sq mi
Bankfull flow	29	watershed area 100 sq mi, determined from NH HGR
Bankfull flow	36	watershed area 10 sq mi, determined from NH HGR
Bankfull flow	44	watershed area 1 sq mi, determined from NH HGR
100-year flood	5-10 times median annual flood	varies with location, soils, slope, storage, land use
Typical flood	200-500	
Extreme flood	500-1,000	

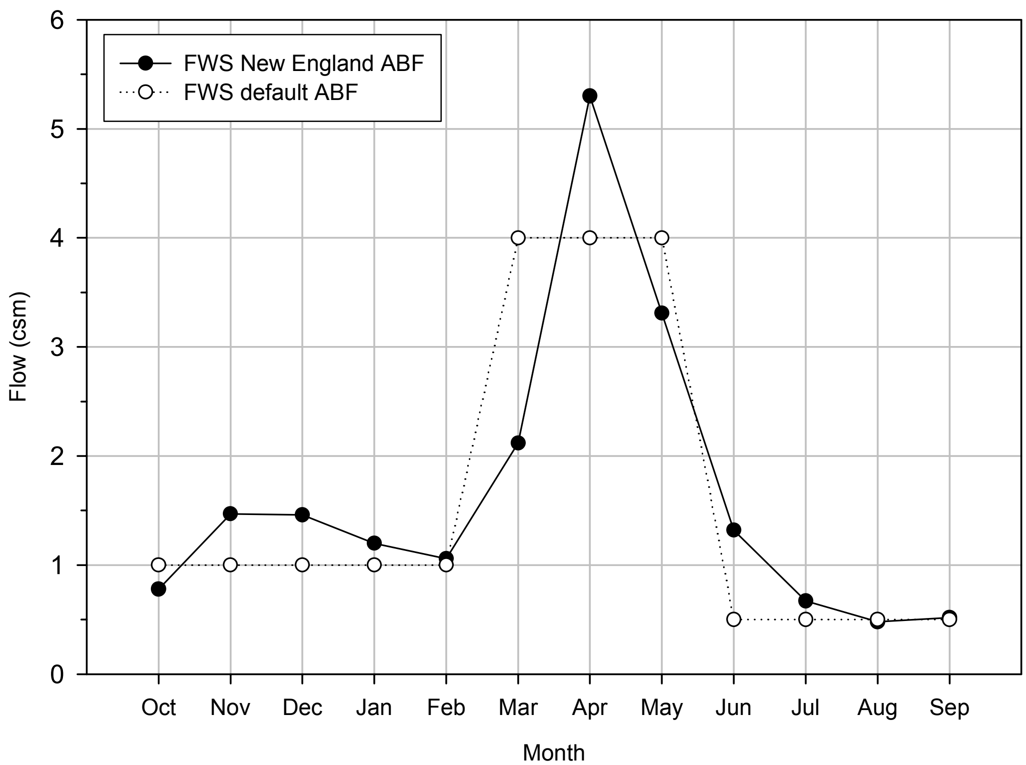


Figure 7-6: The U.S. Fish and Wildlife Service (FWS) generic New England aquatic baseflow (ABF) flow hydrograph and default flow (Source: Lang, 1999).

7.4.5 Rational Method

The rational method, Q=CIA (Q is discharge in cfs, C is the runoff coefficient, I is rainfall intensity in inches per hour, and A is watershed area acres) is used to predict peak flow rates of runoff from a simple watershed with only a single channel (ASCE, 1970). The method applies only to small watersheds having area less than 200 acres and for urban or roadway drainage systems. The rational method is seldom used for naturalized channel design and bank stabilization projects.

7.5 Gage Analysis

7.5.1 Introduction

The network of USGS river gages in the United States is an important tool for determining hydrology for designing river channel and bank stabilization projects. Analysis of gage data is recommended for all but the most basic routine projects. Unfortunately, the sparse and declining coverage of the USGS gage network and the limited number of long-term data records (10 to 20 years) required to accurately determine flow statistics complicates gage analysis. The ideal scenario is that a gage exists at the project site with ample data to directly use the existing USGS analyses and perform additional calculations as needed (Figure 7-7). More typically, the gage is located at another site on the same river or in a nearby watershed and flow measurements must be adjusted based on watershed size, the amount of urbanization, and the amount of watershed storage.

Federal, state and local entities currently fund the operation of 41 continuous record gages as well as six partial record gages and three stage-only gages (see Appendix C), which are operated by the USGS (NHSGTF, 2006). Current and historical data, flow statistics, and other information related to the gage sites and hydrology in New Hampshire can be downloaded from the Internet (http://nh.water.usgs.gov/). Olson (2003) reviewed the utility

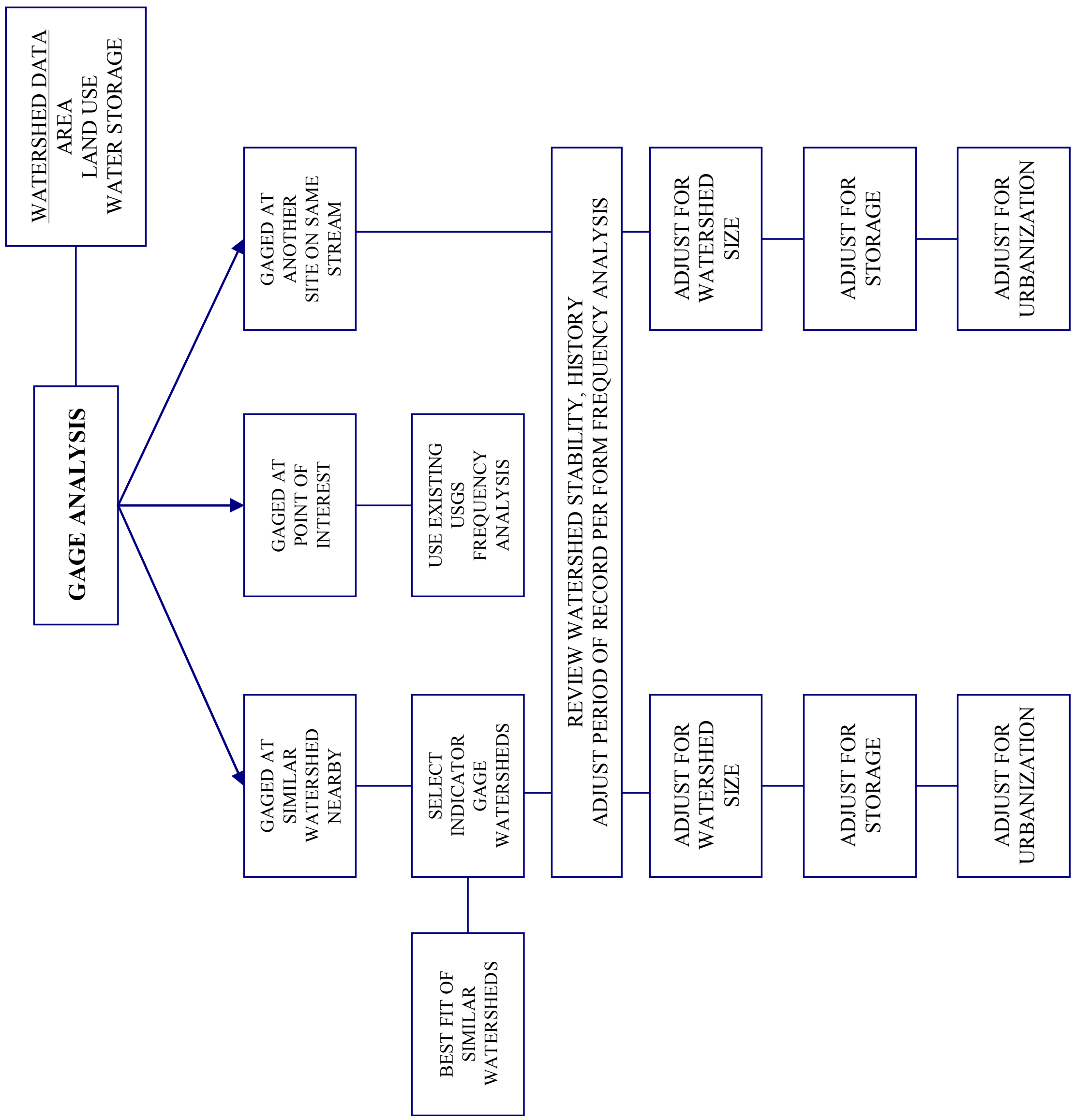


Figure 7-7: Flow chart summarizing the procedure for gage analysis.

of the USGS gage network in New Hampshire and found, as in many other states, that increased data collection would lead to better estimates of regional flow conditions.

Additional gages are operated in New Hampshire by the Department of Environmental Services (DES) Dam Bureau and data are accessible via the Internet (http://www.des.state.nh.us/RTi_Home/).

7.5.2 Gage Located at Project Site

When a USGS gage is located at the project site flow statistics that are directly available from the Internet can be used to estimate the magnitude of various design flows. Daily, monthly, annual and peak flow statistics are available for download, and are referenced based on a water year beginning on October 1 and ending September 30. Low flow statistics are typically based upon the climatic year of April 1 to March 31. Curves that indicate flow duration, the percentage of time a given flow was equaled or exceeded over a period of time, and flow frequency, the chance that a given flow is exceeded in a year, are the main products of gage analysis (Dunne and Leopold, 1978; Leopold, 1994, 1997; FISRWG, 1998). In addition, other flow statistics may be investigated such as minima and maxima for a given number of days and number and duration of high and low flow pulses that are important to the ecological integrity of the river system (Richter et al., 1996; Richter et al., 1998).

7.5.3 Gage Located at Nearby Site or Neighboring Watershed

If a gage exists on the same river as the project site or in a neighboring watershed, a surrogate gage may be used following a comparison of watershed size, the degree of urbanization, and the amount of storage is required. For the surrogate gage watershed, area within 50%, comparable amounts of urbanization, and similar storage is preferred. In this case flow measurements need only be scaled based on differences in area. If required, peak runoff estimates can be adjusted by a correction factor for watershed storage and impervious cover (Leopold, 1968).

Correlating flow measurements at a project site to flows at a nearby gage is another useful technique for estimating design flows. If a correlation exists, flows and flow statistics can be estimated at the project site using the USGS technique called MOVE.1 (Nielsen, 1999). This method works well with lower flows, base flows, or when flows are fairly steady at unregulated sites. Although more time intensive, a correlation method will provide better results than the simple scaling of drainage area.

7.6 Watershed Hydrology Models

7.6.1 Introduction

For naturalized river channel design and bank stabilization projects in ungaged watersheds that are large in scope or have high site constraints, a watershed hydrology model is recommended to obtain a range of design flows and hydrographs. The Natural Resource Conservation Service (NRCS), formerly known as the Soil Conservation Service (SCS), curve number method (Dingman, 1994) is the most popular means of modeling storm hydrographs. The Computer Program for Project Formulation Hydrology (TR-20) (SCS, 1992) and the Hydrologic Modeling System (HEC-HMS) (USACOE, 2001) are two computer models that are commonly used to perform hydrologic modeling.

7.6.2 TR-20

TR-20 is a physically based watershed runoff model that computes runoff and develops unit hydrographs from synthetic or natural precipitation. Developed hydrographs can be routed through reaches, storage areas and structures. The most recent version of the program and documentation can be obtained from the Internet (http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr20.html). Many manuals, tables, and worksheets are also readily available to assist with each step of the TR-20 modeling procedure. The current version of

TR-20 is a Windows-based application, while previous versions that are still widely used have text input/output files.

Area, soil types, and land use are determined to establish a curve number for each subwatershed. The curve number is then weighted by area to calculate a composite curve number for the entire watershed. The travel time in each subwatershed is determined based on the presence of sheet flow, shallow concentrated flow, and channel flow, and then each is added to get the time of concentration that represents the longest possible flow path through the watershed. Stage-storage-discharge relationships are needed for each reservoir or structure that stores water. If precipitation data are not available, estimates for the eastern United States are typically obtained from the National Weather Service Rainfall Frequency Atlas (Hershfield, 1961) to simulate the storm event. Antecedent moisture condition is input to estimate the infiltration capacity of the soil. Outputs from TR-20 include the size and timing of the peak flow as well as the full flood hydrograph.

Note that TR-55 (SCS, 1986) is a simplified version of TR-20 that enables a rapid manual or interactive desktop solution of peak flows in urban watersheds. Because its use is limited to watersheds having areas less than 2,000 acres and homogenous runoff conditions, TR-55 is rarely used for naturalized channel design and bank stabilization projects.

7.6.3 HEC-HMS

HEC-HMS is the US Army Corps of Engineer's version of a physical watershed hydrologic modeling program. This Windows-based program replaced the Flood Hydrograph Package (HEC-1) (USACOE, 1990) and is a graphical means of representing a dendritic network to simulate runoff processes. Model elements include subwatersheds, reach, junction, reservoir, diversion, source, and sink. The SCS Curve Number Method is commonly used when performing hydrology modeling with HEC-HMS, yet some other options are available for unit hydrograph calculation. The most recent version of the program and full documentation can be obtained via the Internet (http://www.hec.usace.army.mil/software/hec-hms/).

CHAPTER 8.0: GEOMETRIC DESIGN CONCEPTS

8.1 Introduction

Naturalized channel design and bank stabilization projects are planned in order to create a river that has adequate hydraulic capacity, is dynamic over the short term yet stable over the long-term periods, has good aquatic habitat, and is an attractive community asset. The project classification system described in Section 2.0 of this report is used prior to design to establish project goals and what type of channel is to be considered.

Valley and cross section measurements are taken to inform project design, and the level of detail of the measurements is primarily a function of whether a project is routine, moderate or comprehensive (Figure 8-1). For simple routine projects such as local bank stabilization or small culvert installations, geometric design can consist of a few site measurements with a tape measure and basic calculations. For comprehensive projects on the other hand, detailed project design could require an extended cross section survey at the reach scale and topographic mapping across the floodplain on the valley floor. Design procedure is also influenced by whether the channel is going to be a non-alluvial rigid boundary channel or an alluvial channel (Table 8-1).

This chapter discusses specific concepts to establish the size, shape, and pattern of the channel and floodplain for naturalized river channel and bank stabilization projects. This step in the design sequence follows the review of the initial assessment data that is used to generally understand the hydrology and hydraulics, sediment transport characteristics, and channel morphology of the river. In addition, channel and bank management techniques are presented to promoted channel stability, create diverse habitats and improve aesthetics.

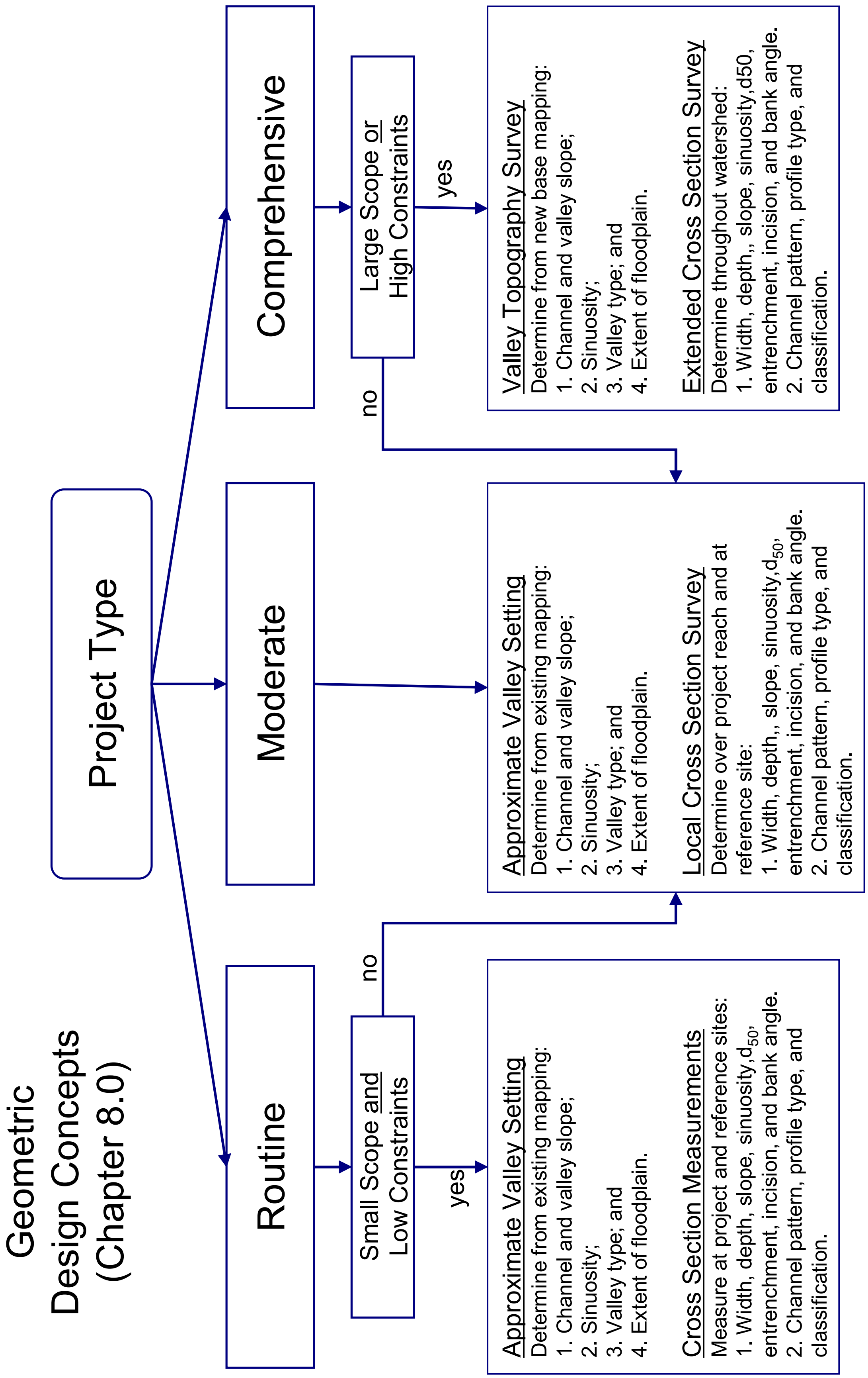


Figure 8-1: Geometric design concepts recommended for routine, moderate, and comprehensive projects.

Table 8-1: Design recommendations for non-alluvial and alluvial channels.

Task	Non-Alluvial	Alluvial
Channel Classification	X	X
Watershed Hydrology	X	X
Bankfull Discharge		X
Topographic Survey	X	X
Geomorphic Survey		X
Valley Slope	X	X
Equilibrium Slope		X
Channel Alignment	X	X
Channel Profile form	X	X
Channel Pattern form		X
Soils & Geotechnical Investigation	X	X
Cross Section Peak Capacity	X	
Cross Section Stable Form		X
Non-Uniform Flow Hydraulics	X	X
Channel Stability & Lining	X	
Dynamic Channel Equilibrium		X
Habitat Design		X

Additional information on common definitions, measurement techniques and quality assurance guidance for New Hampshire projects can be found in the *Generic Quality Assurance Project Plan for Stream Morphology Data Collection* (Sweeney and Simpson, 2003), which is available in the accompanying electronic reference library.

8.2 Site Survey

8.2.1 Introduction

All projects require local estimates, measurements, or survey to determine channel dimensions and other geomorphic variables. Basic measurements with a tape measure or estimates are adequate for simple routine projects, while more accurate survey is recommended for more involved projects with a larger scope. Data collection tasks for naturalized river channel design and bank stabilization projects include:

1. Define the upstream and downstream project limits;
2. Define the limits of local river reaches – stretches of river with common physical conditions, such as slope, width, substrate, and bank conditions.
3. Use of a classification system to better understand the channel type;
4. If an alluvial channel is to be designed using analog methods (see Section 9.3), or if the project site is extensively disturbed, find a similar stable reference reach;
5. Select the cross section locations to be surveyed at the project and reference sites. Preferred locations are at the upstream end of a riffle or stable runs. Use pools only if new pools are to be created. Mark cross section locations for the survey;
6. Identify and flag the bankfull indicators for width and depth at each cross section;
7. Survey the cross sections to record their shape, bankfull indicators, and edge of water using a long tape and rod, or using professional survey equipment;
8. Survey the river bed profile, riffles, runs, glides, and pools;
9. Survey the channel thalweg and banks to record river alignment and meanders.
10. Measure the size particle distribution of the substrate at cross sections. This may include pebble counts for course substrate or sieve tests of sandy material.

Collectively, this information documents pre-project conditions and is essential for the design of stable naturalized channels.

Beyond regional and site location mapping that is part of the initial assessment data (Chapter 3.0), most projects will require a drawing or map of existing site conditions and one or more drawings of the proposed modifications to be used for project planning, permitting, and construction. Drawings for routine projects such as bank plantings, bank slope reduction, or in-channel habitat features may use simple sketches, while moderate and comprehensive projects and those affecting long reach lengths require detailed professional surveys and plans.

8.2.2 Site Measurements for Simple Routine Projects

For simple routine projects that are both small in scope and have low site constraints, local measurement of channel dimensions with a tape measure are usually adequate for design. Hand-drawn sketches based on field measurements and observations are appropriate when:

- Property boundaries are not needed;
- Utilities are not present;
- Channel fill or excavation does not occur; and
- Channel vulnerability is low.

Typical projects of this type include planting vegetation on river banks and in the riparian buffer, reducing the slope of the river banks above the water line, and garbage removal (tires, shopping carts, etc...).

A 100-foot long tape can be used to measure the length and width of the proposed project, location of the channel banks, channel width, and physical features. A typical cross section of the channel near the project site is required. This information can be sketched to scale with reasonable accuracy on graph paper. Basic sketch maps of this type will not have ground elevations or contour lines.

For simple routine projects, valley setting (i.e., multi-reach slope and sinuosity, valley type, and floodplain width) can be approximated from mapping collected during the initial assessment.

8.2.3 Local Survey and Geomorphic Assessment

Local survey in conjunction with a geomorphic assessment is recommended for more involved routine projects, moderate projects, and comprehensive projects that are not both large in scope and have high site constraints.

Channel cross section dimensions and local river bed slope are determined from the survey in the vicinity of the project site, and typically over the project reach. If the reference reach approach is being used, the survey will include a stable reference site. Reference sites, however, are often not available so empirical and analytical approaches to channel sizing are used (Chapter 9.0).

The local cross section survey is done in conjunction with a geomorphic assessment. Field indicators of bankfull water surface elevation (e.g., the top of point bars on the inside of meanders, the limit of woody vegetation on the banks, and a well-formed bench on the bank where some sediment deposition is evident) are marked and surveyed. Substrate particle sizes are determined via a pebble count. A field estimate of the percentage of bed mobility can be determined by determining the largest particle that appears mobile (i.e., unconsolidated and clean of aquatic vegetation) on a local depositional feature such as a bar and the percentage finer than a particle of that size as determined from the pebble count. This measurement is called the riffle stability index (Kappesser, 2002), and is an indicator of the percentage of the bed that tends to be mobile during bankfull flows.

Although a range of professionals with specialized training can perform the geomorphic assessment, it is often helpful to have a licensed land surveyor perform the site survey to geo-reference the site, prepare detailed plans, and provide accurate horizontal and vertical coordinate systems that allow use of computer assisted drawing (AutoCAD) and accurate hydraulic modeling. The field work requires a tripod-mounted level, transit, or theodolite; plus a stadia rod and 100-foot tape measure.

The rapid field assessment, or Phase 2, of the Vermont Geomorphic Assessment protocols (http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro) offers excellent information on methods and useful field forms to guide data collection. In addition, the appendices in the Vermont protocols offer valuable background information on a variety of topics such as channel evolution, channel classification, bridge and culvert assessment, bankfull indicators, and regional hydraulic geometry curves. Several other references provide user-friendly descriptions of how to do a geomorphic assessment (Harrelson et al., 1994; Rosgen and Silvey, 1996; Doll et al., 2003). Sketches and spreadsheets are useful for data storage and calculations, and geomorphology-specific spreadsheets (e.g., STREAM Modules: Spreadsheet Tools for River Evaluation, Assessment and Monitoring - http://www.dnr.state.oh.us/soilandwater/streammorphology) are available on the Internet.

Ultimately, the above field work is used to determine the mean and range of the channel's bankfull widths, depths, riffle and pool geometry, channel slope, percent riffle-run-pool-glide, particle size distribution, and percent substrate types (cobble, gravel, sand, silt, clay).

For more involved routine projects, moderate projects, and comprehensive projects that are not both large in scope and have high site constraints, valley setting (i.e., multi-reach slope and sinuosity, valley type, and floodplain width) can be approximated from mapping collected during the initial assessment.

8.2.4 Extended Topographic Surveys

Extended cross section surveys over multiple reaches and a full valley topographic survey is recommended for comprehensive projects that are large in scope or have high constraints. Topographic surveys present a detailed image of physical features and landscape data that depict changes in elevation and slope. Land and riverbed elevations may be represented by both spot elevations and contour lines. Topographic maps may be based upon either ground surveys or aerial photogrammetric data. The more detailed mapping of the land surface is particularly important for large sites and those with high degree of site constraints where flooding and nearby infrastructure protection is a concern.

Data collection needs are the same as for the local survey and geomorphic assessment described in Section 8.2.3 (e.g., cross sections, profile, bankfull indicators, and hydraulic features). In addition to contour lines, maps should show buildings, roads, all river channels, subsurface and aerial utilities, fences, driveways, stone walls, large or isolated trees, bedrock outcrops, edges of lawns, fields, and wooded areas, wetland boundaries, water supply wells, and septic systems. In developed areas, topography maps should include property boundaries.

For more involved comprehensive projects that are either large in scope or have high site constraints, valley setting can be approximated measured from the extended topographic mapping.

The New Hampshire Joint Board of Licensure defines the types of surveys that must be prepared by and certified by a licensed Professional Engineer or Land Surveyor.

8.3 Design of Channel Slope and Pattern

8.3.1 Introduction

Channel slope, pattern, profile, cross section, bed features and hydraulic capacity are closely related (Table 8-2) and should be considered together during design. The slope of the river valley can be considered as an independent variable that can not be modified. The slope of the existing and proposed channels are then determined and compared to the valley slope. A sinuous channel has a longer length and lower slope relative to its valley, while a straight channel (sinuosity = 1) often has a similar length and slope to its valley.

Table 8-2: Typical ranges of channel slopes for different profile forms, and the expected dominant particles on the bed (Source: Montgomery and Buffington, 1997; Rosgen and Silvey, 1996).

Profile Form	Typical Slope Range (ft/ft)	Typical Substrate
Cascades	0.1 - 0.3	Boulders
Rapids	0.05 - 0.1	Bedrock
Step Pools	0.03 - 0.1	Boulder/cobble
Fast Runs	0.01 - 0.04	Cobble, gravel
Pool & Riffles	0.001 - 0.02	Cobble, gravel
Mild Runs	0.001 - 0.005	Sand, gravel
Flats	<0.001	Silt, clay

Natural channels have regularly occurring bed features (i.e., riffle-run- pool-glide) along the channel profile that can be replicated for use in the design of created channels. Bed features are based upon channel gradient, substrate, and roughness. Cascades and rapids have steep channel slopes and high water velocities where only boulders and bedrock will stay in place. Riffles occur in channels of intermediate steepness, and often have coarse substrate. Pools are relatively flat and consist of finer particles.

8.3.2 Equilibrium Slope and Channel Pattern

Channels that have a large sediment load or mobile boundaries will have an equilibrium slope that is the optimum condition for conveying water and sediment with limited scour or deposition. The corresponding flow rate is the channel-forming discharge (see hydrology, Section 7.6). The equilibrium channel slope can be determined from basic sediment transport equations (Table 8-3) and charts (Appendix E), empirical regional data, or from stable slopes at an appropriate reference reach.

The equilibrium channel slope should be compared with the mean valley slope. If the equilibrium channel slope exceeds the valley slope than the channel will be prone to erosion. To reduce erosion, the channel slope can be reduced by increasing the channel length by using

Table 8-3: Sediment transport equations and charts for estimating equilibrium channel slope.

Name	**Determine from…**
Sheild's resistance to motion	$\tau=\gamma*R*S*304=5*d_{50}$
USACOE - Lacey graph	$S=[0.00021*d_{50}*W_{bf}/Q_{bf}]$^0.75
USACOE (1994) stable channel	charts for Q_{bf}, d_{50} v S, W_{bf}, D_{bf} (see Appendix D)

definitions

τ = shear stress (lbs/ft^2)

γ = specific weight of water = 62.4 lbs/ft^3 at 60 ^oF

R = hydraulic radius (ft) = area / wetted perimeter

S = channel slope (ft/ft)

d_{50} = median particle size (mm)

W_{bf} = bankfull width (ft)

Q_{bf} = bankfull flow (cfs)

D_{bf} = bankfull depth (ft)

a sinuous alignment. Irregular sinuous or regular repeating meandering patterns will increase channel length and decrease slope.

If the equilibrium channel slope is less than the valley slope than the channel will be prone to deposition. To reduce deposition, sediment transport can be increased by increasing the channel slope, and thus water velocity, by straightening the channel. This management activity is typically not recommended as it can increase downstream flooding, severely impair local aquatic habitat, and work against natural channel evolution.

In some cases it may not be possible to create the desired pattern when excess slope is present. In these cases, the mean channel slope may be reduced by providing one or more riffles or vortex weirs to lower the bed at a fixed point that is protected from scour.

In summary, one should identify the equilibrium slope, identify the likely pattern for the given slope found in a natural channel of the given type, and then set the length, grade changes, and thalweg location to provide the appropriate slope and pattern.

8.3.2.1 Non-Alluvial, Rigid Boundary Channel

The design of non-alluvial, rigid boundary channels is common practice for local drainage, flood control, and transportation-related projects. Channel alignment is often constrained by topography, developed land, or infrastructure including highways, utilities, or even property boundaries. Channel alignment has to consider its end junctions with existing channels up and downstream. The overall length is then measured and the available slope determined. Rigid boundary channels often use compact trapezoidal cross sections that convey water in an efficient manner but consequently sacrifice environmental quality and habitat. They usually have relatively steep banks at angles ranging from one to four parts horizontal to one part vertical, and commonly have artificial linings or smooth earth perimeters. It is recommended that artificial linings be avoided and that the natural river bed be maintained in all designs, including those in an urban landscape.

The natural analog to the constructed non-alluvial and rigid boundary channel is the natural sediment source channel in steep terrain. The two channel types behave in a similar manner, although the constructed channel is often located on more gently sloping terrain in a developed landscape. Non-alluvial and rigid boundary channels often have high sediment transport rates, and their banks and beds are relatively insensitive to scour. As a result, they are less vulnerable to excessive sediment deposition and are not very dependent on an equilibrium slope. Their preferred slope allows them to be slightly prone to scour to discourage deposition, and accept that their erosion-resistant banks prevent excessive scour. Their pattern can be independent of slope.

8.3.2.2 Alluvial Channels

Naturalized created alluvial channels should have a pattern compatible to the bed slope and discharge rates if long-term stability is desired with minimal erosion and deposition. Determine the equilibrium slope, profile bed features, and then the appropriate pattern that a natural river would have. In general, the overall vertical change in alluvial bed elevation of the proposed channel is controlled by existing geologic and topographic conditions and cannot be changed. However, the length of channel and its alignment may be adjusted by altering the sinuosity to establish the desired channel bed slope. Knowing the bankfull discharge, the range of stable slope estimates for each pattern can also be estimated from sediment transport equations or reference reaches.

8.3.3 Channel Pattern

The desirable channel patterns are typically sinuous or straight in order to avoid the instability and large width of braided channels (Figure 8-2). However, sometimes slope and bankfull discharge dictate a braided channel pattern. The meandering pattern has advantages in that it is conducive to a wide range of habitats. The straight channel requires little land and is easy to construct. The disadvantage of meandering channels is that lateral and downstream

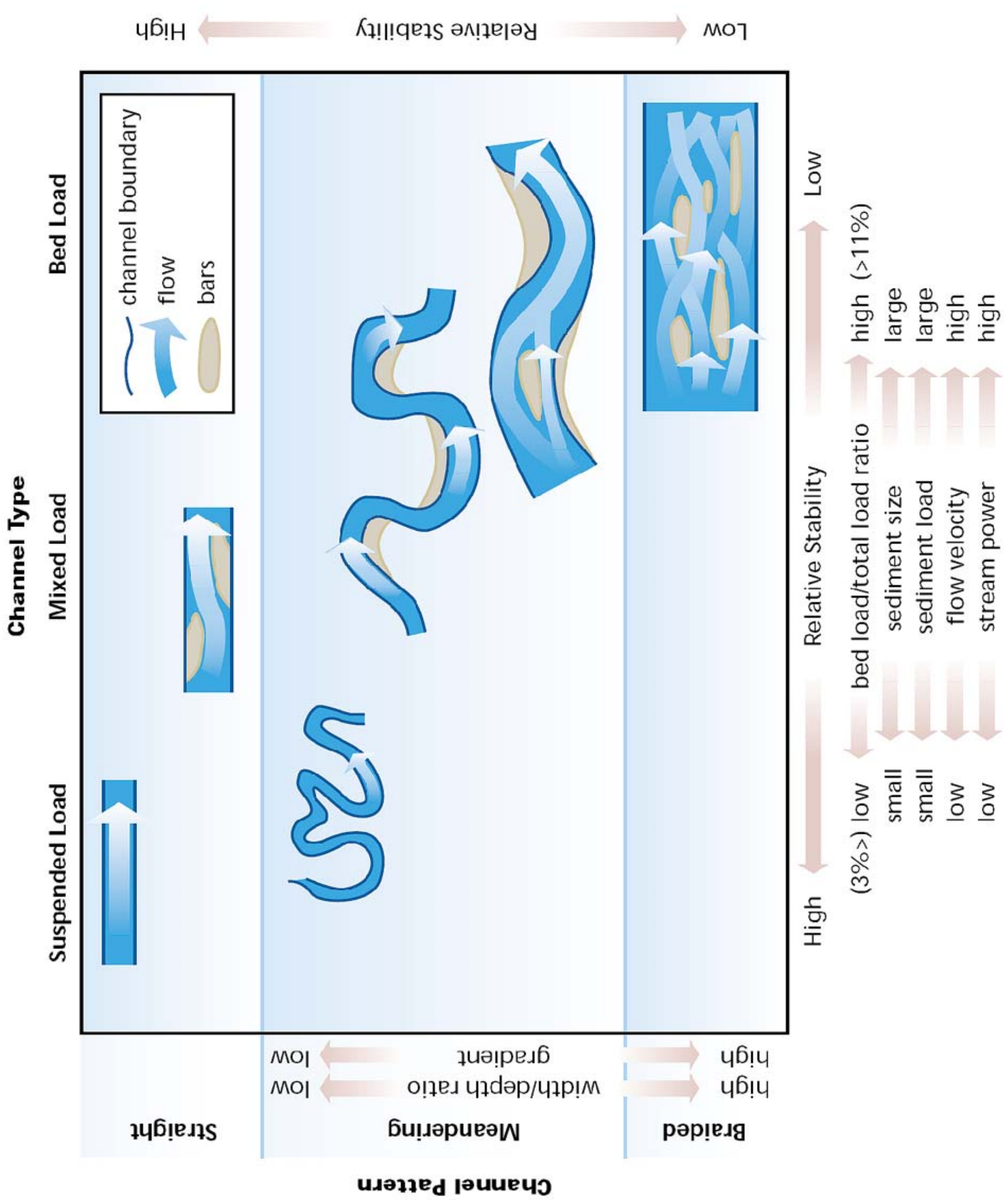


Figure 8-2: The relationship between pattern, size, stability, and sediment type for alluvial channels (Source: FISRWG, 1998 as adapted from Schumm, 1977).

movement of meanders on active rivers can consume valuable land and cause problems at bridge approaches.

8.4 Design of Channel Sinuosity

Many naturalized created channels will have a sinuous alignment that corresponds to its stable slope and plan form pattern as described in Section 8.3. Sinuous channels may have irregular alignments that are controlled by natural constraints such as narrow valleys, bedrock, or topography. Other irregular alignments are constrained by community development, highways, and infrastructure. The presence of existing hydraulic structures such as bridges, culverts, dams, and storm drains create fixed locations that created channels must connect to.

Classic geometric data on the shape and form of repeating meandering channels can be used to replicate the meander wavelength (L), amplitude (M_A), radius of curvature (r_c) from the mean bankfull channel width (w) for natural patterns (Figure 8-3) (Soar and Thorne, 2001).

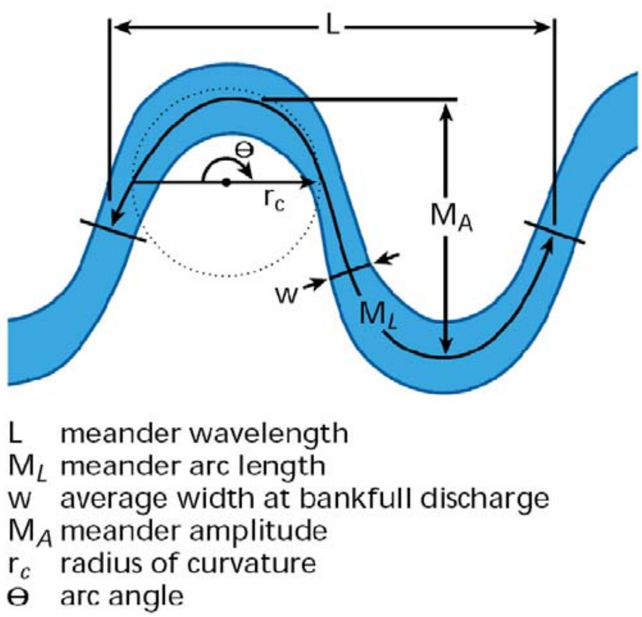


Figure 8-3: Variables used to describe and design meander geometry (Source: FISRWG, 1998).

$$L = 10.9(w)^{1.01}$$

$$M_A = 2.7(w)^{1.1}$$

$$L = 4.7(R)^{0.98}$$

The meander bend radius typically varies from 2.3 to 25 times the bankfull channel width. Local river characteristics obtained from reference reaches must also be considered. Guidance on determining mender geometry can be found in the Vermont Geomorphic Assessment Protocols (see Appendix H in VTANR, 2004). Williams (1986) provides information on the meander geometry and many rivers in North America.

8.5 Design of Channel Cross Section

The mean channel depth, width, and side slope conditions are established after determining the design discharges and slope for the desired pattern. Engineers can readily determine the required typical cross section geometry based on rigid boundary hydraulics for a given discharge and slope, and then include features to mimic the naturally stable reference reach such as a low flow channel and small low flood plain, or flood bench. The short- and long-term channel roughness must be estimated based on anticipated bank vegetation, substrate, and bed features. The tendency has been to use relatively compact cross sections that minimize the perimeter length, excavation, costs, and land. Details on cross section design for rigid boundary channels are contained in Section 9.4.2.

Keep in mind that the design of stable cross sections is not a precise practice due to the highly variable river environment. Flow that exerts force on the river bed and banks, and its ability to change rapidly, complicates construction of specific cross section dimensions. The main objective of cross section design is to approximate stable dimensions so that once constructed the channel will recover towards and achieve a stable equilibrium more rapidly than if the project is not installed. Designing the shape of the cross section at each location to match the channel plan and profile (Figure 8-4) will likely speed the return to equilibrium.

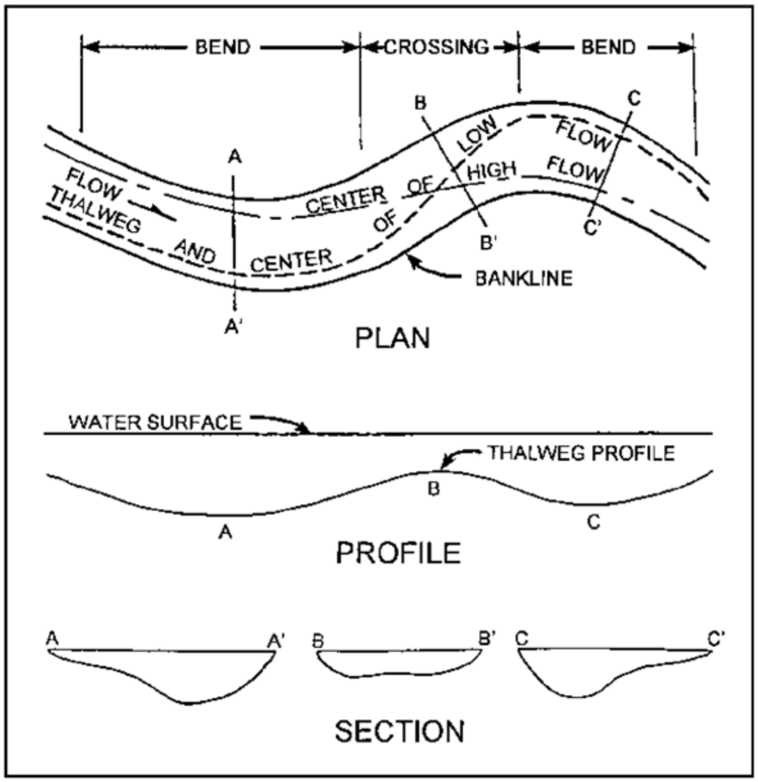


Figure 8-4: The relationship between channel plan, profile, and section (Source: Watson, 1999).

It is recommended that the width-depth ratio of alluvial rivers that are subject to both erosion and deposition be similar to those of stable rivers. The relation between the width and depth of channels with moderate sediment loads should be based on regional reference reaches and confirmed with regime or tractive stress equations, with the actual dimensions set by the hydraulic criteria for the acceptable water surface profile. For more involved moderate and comprehensive projects, the initial cross section size and shape is checked for stability and sediment transport as per Chapter 9.

The values of width and depth should be considered as mean values, with both plus and minus dimensions being used at various points to provide for converging and diverging flow along the meandering thalweg. The width, depth, and side slopes should vary to provide diverse aquatic habitat, and interesting topographical features for aesthetics. Channel widths should vary from riffles to pools based on their dimensionless ratios from reference reaches or literature.

The optimum channel width where floodplain flows are to be avoided is the maximum size that can exist without the formation of excessive sediment bars at normal flow rates. If the channel is too narrow, it will be subject to excessive scour and degradation. This is undesirable particularly in urban areas as it may undermine structures and is environmentally unsound. Channels that are too wide will have a tendency for sediments to settle, forming unstable bars and collecting debris.

Where the channel changes in width due to irregular flow patterns, erosion, deposition, and energy losses, special attention is required in the design details of transition sections. At points where the channel contracts, the decrease in width will be accompanied by an increase in velocity that may scour the bed. Therefore, the depth must be increased or the channel must be lined to resist erosion. At channel expansions, the decrease in velocity will encourage the formation of sediment bars. If these are unacceptable due to flow obstructions, then the channel depth should decrease towards the banks with a well-defined thalweg to concentrate normal flows at a scouring velocity.

8.6 Design of Profile Details

The naturalized created channel is often constructed to include a series of riffles and pools with a meandering thalweg (Figure 8-5). This creates the irregular geometry of the natural channel, without having to wait for the channel to create its own pattern. The geometry of the thalweg meanders and the location of the pools and riffles can be based upon reference reaches or published data. The spacing between pools is typically between 5 and 7 times the channel width (Rosgen and Silvey, 1996; Thompson and Hoffman, 2001), and pools are located on the outside of the meander bends (or thalweg bends in straight channels).

In straight channels, the meandering thalweg may be created by having asymmetric banks, varying width to converge flow, or artificial sills or point bars to force flows to cross the

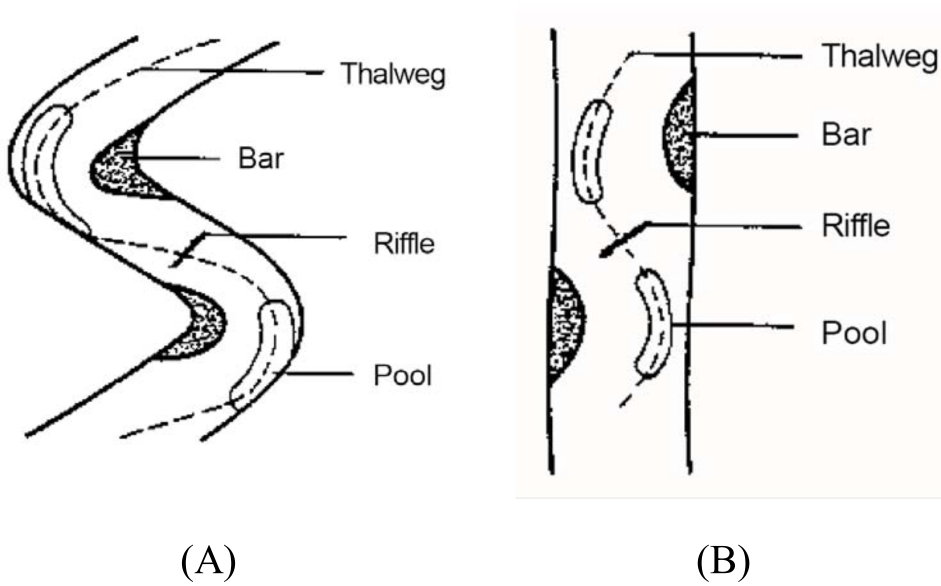


Figure 8-5: Distribution of riffles and pools along a meandering thalweg in a meandering (A) and straight (B) channel (Source: Watson, 1999).

center of the channel. Clean gravels and cobbles may be used to control the bed elevations in areas designated to be riffles.

8.6.1 Control of Aggradation

The aggrading channel fills with sediments due to a sediment load greater than the sediment transport capacity. Aggradation of existing channels can be controlled where necessary by reducing the sediment load or by increasing the sediment transport capacity. The sediment load may be reduced by use of sediment traps or reservoirs, bank stabilization, debris basins, and land use policies in developed areas to discourage erosion. The measures can often be readily applied on small watersheds, but are difficult to implement on large watersheds.

The sediment transport capacity can be increased by reducing the cross section flow area either by making the river narrower or shallower that results in higher velocities that will carry more sediment. This may be accomplished by changing channel geometry alone or by using training structures such as deflectors, vanes, or groins. Other ways to increase sediment transport include increasing slope and reducing hydraulic friction to increase mean velocity.

For some channels where sediment capture and storage is the dominant natural phenomena such as braided channels, enough room is needed across the valley to accommodate a channel that is likely to widen. Sometimes this may necessitate relocating or removing infrastructure such as roads or buildings.

8.6.2 Control of Degradation

The degradation of channels occurs when the rate of sediment transport exceeds sediment supply. The degradation may be controlled by decreasing the sediment transport of the river, increasing supply, creating vertical barriers, or lining the channel.

The transport rate can be reduced by decreasing the slope to reduce velocities. The slope of small rivers is often reduced by using a series of weirs to establish a fixed bed profile at an equilibrium slope, or by using a longer sinuous alignment. Larger rivers have their peak velocities reduced by impounding reservoirs that store large quantities of water for gradual release over a period of time. Widening the channel can increase friction and in that way decrease the scouring velocities, but is only practical where sufficient land is available.

Increasing the sediment load is rarely done to control degradation because of the concern for increased sediment loads to downstream areas and impairment to aquatic habitat.

Creating vertical barriers, also known as grade control, is a popular way to control channel degradation. The ability to control the channel bed is largely a function of channel size, the existing and predicted level of down cutting in the channel (i.e., how incised the channel is and will attempt to become), how unstable the bed is at the time of installation, and how energized the channel becomes during flood events and the degree of channel adjustment that typically takes place. As each of these factors increases, effective grade control is more difficult to accomplish.

Although channel lining can potentially control degradation, this extreme management activity is not recommended as it is very harmful to the aquatic ecosystem.

8.7 Design of Channel Banks

The design of stable channel banks includes consideration of their angle and cover materials. Both hydraulic and geologic factors influence the natural bank condition.

River banks can be separated into three parts – low, mid, and upper (Figure 8-6). The low bank is typically submerged saturating the soil, reducing pore pressures, and limiting the growth of vegetation. High flow velocities next to or directed into the low bank can lead to

Figure 8-6: Photograph of a river bank on Warren Brook in Alstead, NH with approximate locations of the low, mid, and upper bank (Source: Horizons Engineering, LLC).

scour and erode individual particles or undermine the entire bank causing collapse. The mid-bank is the portion of the bank from the bankfull elevation down to the low bank, and typically only has perennial, non-woody vegetation. The mid-bank can collapse if it becomes saturated and cannot support its weight, fails due to removal of the low bank, or is removed following a slide from the upper bank. The upper bank is above the bankfull level to the physical top of the bank or just beyond. Woody vegetation is naturally present in the upper bank, and bank failure occurs at this location when vegetation is absent or when support is lost when lower portions of the bank collapse.

Bank angles, stability, and cover materials are strongly influenced by the underlying soils. The strength of cohesive soils (silt, clay, some poorly sorted soils) is based on their shear stress. The strength of non-cohesive soils, largely coarse grain material such as loose sand, gravel, and cobbles, is based upon their internal angle of repose. New Hampshire Geologic Survey surficial geology maps are available through the Department of Environmental Services (DES) (http://www.des.state.nh.us/geo1link). In addition, USGS surficial geology maps and NRCS County Soil maps provide valuable information on regional soil types that are helpful for identifying bank materials.

Project design should include soil investigations to identify local river bank materials, presence of shallow ground water, and soil strength. Soil augers and hand shovels can be used to explore the texture and cohesiveness of surficial soils, while mechanical excavators or boring rigs are used to test deeper soils. Look for visual signs of seeps and the presence of mottling in sub-surface soils to indicate the presence of groundwater. The existence of near-channel riparian wetlands is also a good indicator of the potential for bank strength to be influenced by local hydrology. Investigations should identify the location of geologic deposits plus the soil profile to a depth of two feet below small channels and five feet below active alluvial or large channels.

Table 8-4 summarizes general recommendations for the maximum bank slopes based on geologic conditions. Areas with high velocities, high exposure (outside of bends, contractions) and non-cohesive or soft soils need individual evaluations. Shear and penetration testing is recommended for cohesive soils, while sieve testing is used for non-cohesive soils.

Bank slopes are also influenced by their height, ground water seepage, and rapid changes in water elevation. Geotechnical computations can be used to perform site specific evaluations of stable bank slopes versus bank heights. The slope of river based composed of cohesive soils and over four feet high should be evaluated individually.

8.8 Channel Flow Capacity and Floodplain Creation

Large channels that are designed to carry the total flow of major floods within their banks will tend to be unstable because the normal flows will not be able to transport the sediments in excessively large, wide channels. Channels that are undersized and unlined will erode badly and be unstable until enlarged. The flow capacity of new channels should be set to maintain

Table 8-4: Recommendations for maximum bank angles.

Material Type	**Suggested Maximum Bank Angle**	
Bed rock	0.2	Near vertical
Weathered rock	0.5 – 1.0	
Loam mixtures	1.5	
Loose silty sand	2	2
Sandy soil	2	
Fine sand	3	3
Compact clay	1.5	1
Riprap	2	
Muck or peat		0.25
Earth, small ditches		1.5
Sandy loam		3
Grass, mow		
Reference	Simons, 1977	Chow, 1959

stable equilibrium, unless special conditions warrant the frequent sediment removal to prevent erosion.

Flows in excess of the bankfull discharge are normally conveyed by floodplains. If the floodplain is not available or accessible for conveying flow, perhaps due to development in the river corridor and channelization, design should consider returning floodplain usage or at least mimicking the channel-overbank dual conveyance system with a smaller floodplain (see Figure 7-2). These features that convey overbank flow outside of the main channel yet within the active river channel are often referred to as flood benches, and are a common element in naturalized channel design. In situations where natural floodplains are disconnected due to channel incision or have been developed and filled in, a low or high terrace floodplain can be excavated to carry overbank flows. Floodplain dimensions are sized based on a reference reach or the desired flow velocity and particle transport, and the main challenge is to find areas near the river channel where there is ample room to re-establish floodplain.

Floodplain creation is a form of naturalized flood control projects where the cross section of the main channel is sized to convey normal flows and floods with average return frequencies of up to about two years. The normal flow channel is thus relatively narrowed compared to traditional flood channels, and can have sufficient concentrated flow to maintain adequate water depth for aquatic life and sediment transport (Figure 8-7). This helps improve both the environmental quality, physical stability, and the appearance of the channel.

After setting the size of the main channel to carry normal flows, the floodplain is sized to convey flood flows. The surface of the floodplain is above the typical flow elevation of the main channel and therefore the floodplain surface is often dry. The large size, relative to the main channel, and dry surface of the floodplain allow for the planting of ground covers, shrubs, and trees. In addition to its important roles for the rivers, the floodplain serves as open space, can be used for recreation, and is a green belt corridor serving as a buffer between the main channel and adjacent land uses. The floodplain may be on either or both sides of the main channel, and can be designed to vary in width to mimic a natural system, fit into a

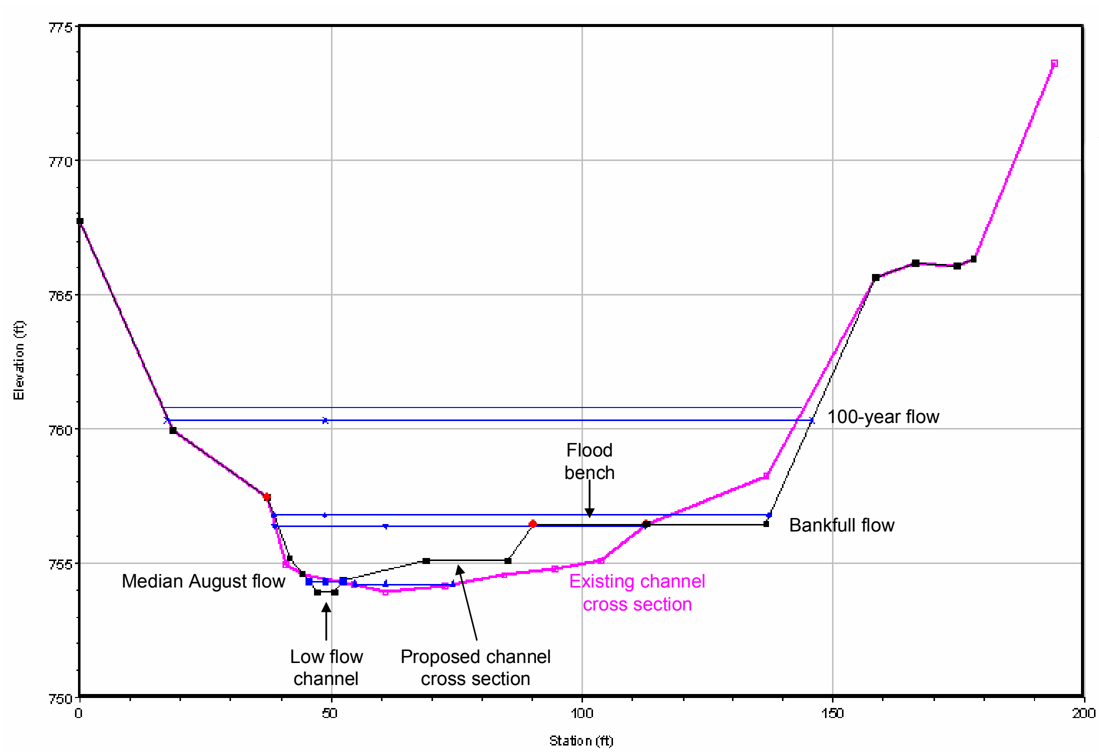


Figure 8-7: Example of a cross section design in HEC-RAS to concentrate low flows, increase sediment transport in the bankfull channel, and establish a flood bench within an incised channel.

developed river corridor, and offer aesthetic variation. Where the existing channel is adequate to convey normal flows, additional capacity for flood flows may be obtained by creating a floodplain without disturbing the natural channel.

The concept of re-establishing a floodplain is an attractive alternative to conventional flood control projects, and works with a river's natural tendency to naturally form floodplain. Applicable areas have been in town centers and other low density urban areas where structural improvements are cost effective and land can be acquired. Note that in rural areas structural type flood control projects are often not cost effective, while in highly urban areas there may be difficulties in acquiring sufficient land or in relocation of residents or business.

8.9 Ecological Considerations

Improving aquatic and nearby terrestrial habitats is an important part of many river management projects. Providing productive and diverse habitats can be done using concepts of fluvial geomorphology to replicate natural channels. This helps to simulate the characteristics of a natural channel and provide the necessary physical stability. In addition, practices that improve habitat can be used in the channel and riparian areas (see Chapter 11.0).

Key habitat features include:

- Cover such as large woody debris, undercut banks, and turbulent flow;
- Coarse bed particles such as boulders, cobbles, and gravels;
- The abundance, spacing, and quality of riffles, steps, and pools;
- In-channel hydrology characteristics, and the presence of riparian wetlands;
- The degree of longitudinal connectivity and floodplain connectivity;
- The width of vegetated riparian buffers;
- Diversity of velocity-depth combinations associated with a distribution of riffles, runs, pools, and glides; and
- The abundance of vegetative cover, overhanging vegetation, canopy cover, and erosion on the river banks.

CHAPTER 9.0: COMPUTATIONAL DESIGN TOOLS

9.1 Introduction

Methods used for naturalized river channel design and bank stabilization projects can be grouped into one of three types of general approaches: empirical, analog, and analytical.

- **Empirical** – Stable channel dimensions at the project site are predicted using regression relationships established from extensive data sets of channel geometry and flow characteristics measured at relatively healthy rivers.
- **Analog** – Stable channel dimensions and a single dominant design discharge at the project site are determined from observation of the geomorphic characteristics of a nearby healthy reference reach with similar slope and substrate.
- **Analytical** – Project site characteristics such as discharge, stable channel dimensions, or sediment transport rates are approximated via physical-based equations or models.

Typical outputs of these approaches include stable channel dimensions, elevations to place instream and bank structures, and anticipated sediment erosion and deposition (continuity). Each of the three design approaches has advantages and limitations, and alone none is universally applicable. Effective designs use components of empirical, analog, and analytical methods to allow for comparison of findings and generating a design solution that is validated by multiple approaches. The increased initial investment in design expands the likelihood that installed projects will meet project goals, and not be prone to common failures such as dislocation during large flood events or reduced habitat quality during low flows. This comprehensive design approach is ultimately more economical as project failures require costly repairs and maintenance.

The computational tools used in river channel design and bank stabilization projects is mainly determined by whether a project is routine, moderate, or comprehensive (Figure 9-1).

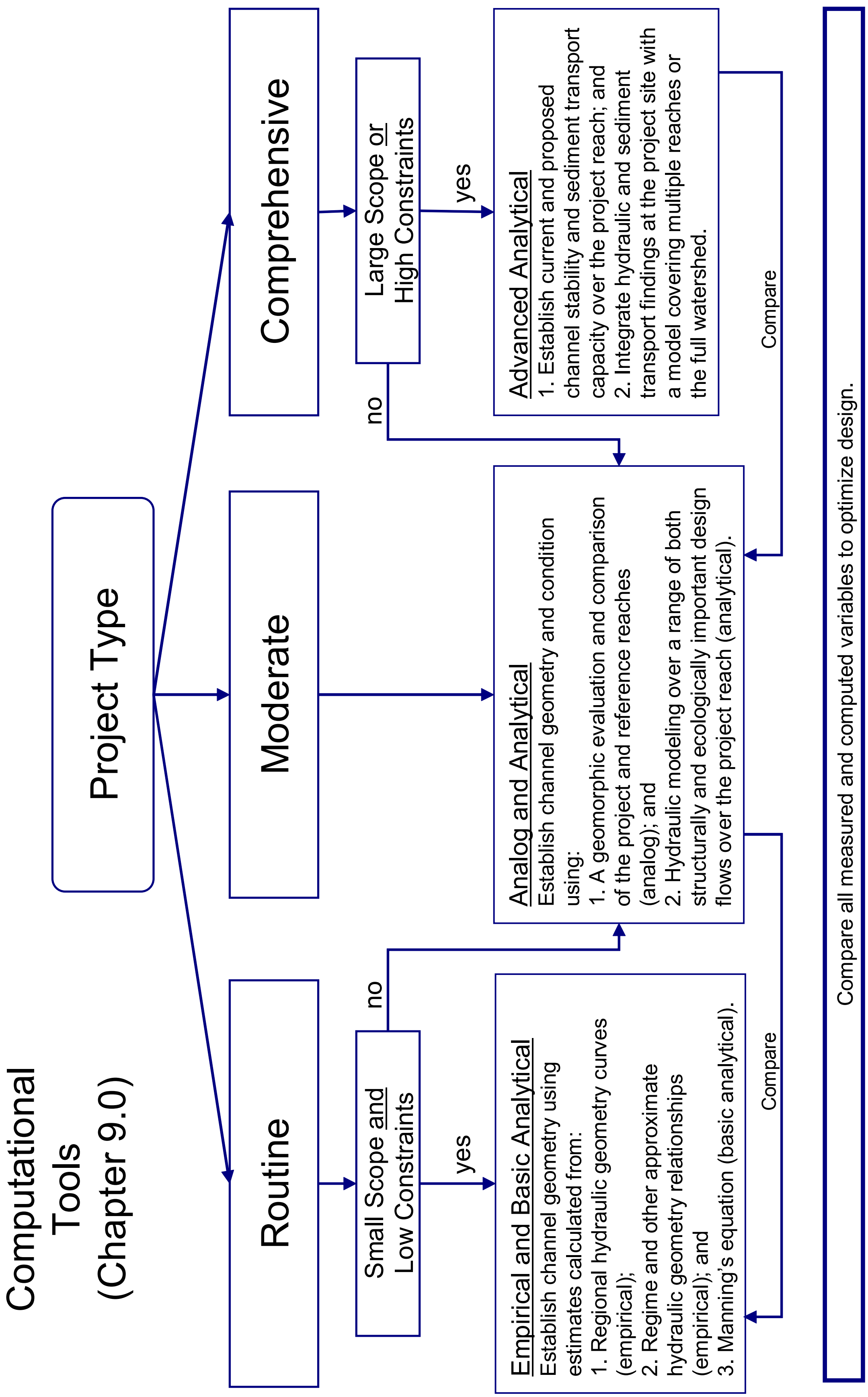


Figure 9-1: Computational tools recommended for routine, moderate, and comprehensive projects.

Routine projects that are both small in scope and have low site constraints typically are designed by a combination of existing empirical relationships (regional curves or generalized Regime theory) and basic analytical techniques such as the Manning's and continuity equations. The approximation of stable channel dimensions and water surface elevations associated with a design discharge using these rapid methods is appropriate for the low level of risk and minimal funding associated with routine projects. Such approaches can also be useful for temporary, emergency repairs where rapid response is needed. Routine projects that are larger in scope or have more risk and projects that are classified as moderate require more detailed analysis and thus more computational tools are recommended for design. Analog and analytical methods such as hydraulic modeling are used to establish stable channel dimensions, often with reference to a locally stable site. In addition, hydraulic modeling offers insight into how the site operates before and after implementation over a range of flows. This level of analysis is also applicable for comprehensive projects that are not large in scope or have high constraints. For large or high risk projects, channel stability calculations and sediment transport modeling are added to the recommended computational approaches to increase the chances of meeting projects goals and objectives over a larger site with challenging physical constraints. In this situation, hydraulics and sediment transport analysis should be integrated and scaled up to the river system or watershed level to understand the influence of the proposed project.

The selection of computational tools for river channel design and bank stabilization is also influenced by project goals. For example, if the main project goal of a moderate project is to limit the delivery of eroded sediments to downstream locations, sediment transport calculations are added to the list of recommended computational tools.

The broad geomorphic characterization of a channel reach as alluvial or non-alluvial also guides selection of computational tools (Figure 9-2). Analog and empirical approaches have been established for alluvial channels, or those that are self-formed by deposited sediments under the present hydrology, and thus their application is most appropriate on this river type. Analytical approaches are most suited for non-alluvial channels, which are typically straighter,

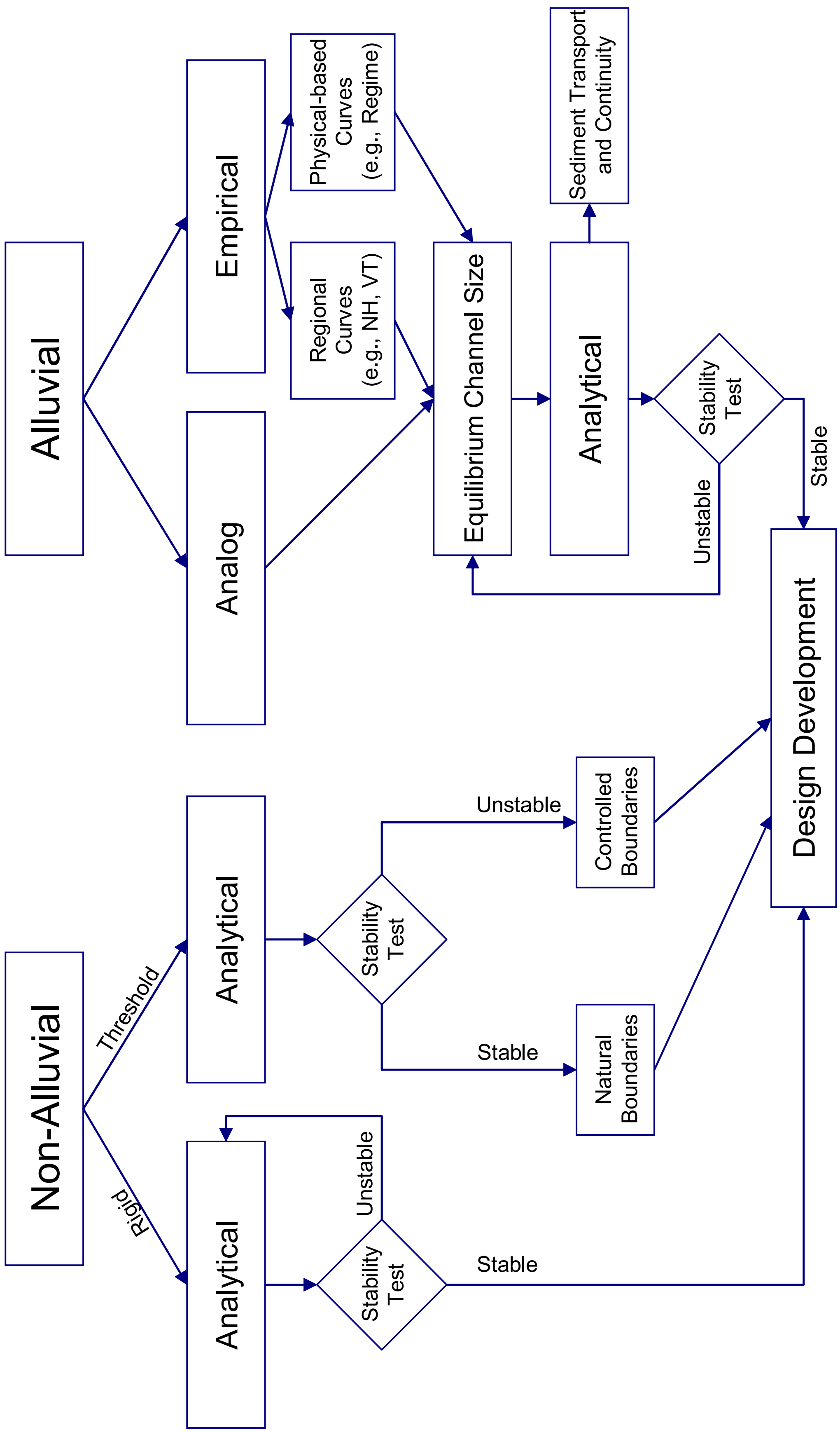


Figure 9-2: General guidance for creating a stable naturalized channel for non-alluvial and alluvial channels.

steeper, and smaller than alluvial channels. Nevertheless, analog and empirical approaches are often used today to design naturalized channels and bank stabilization projects in non-alluvial rivers. An understanding of the limitations of application of each computational tool discussed in this chapter is essential for accurately comparing and selecting results obtained from different methods.

9.2 Empirical Techniques

9.2.1 Introduction

Hydraulic geometry relationships (HGRs) for designing stable river channels are a rapid empirical design tool. Once formulated, relationships can be used to quickly estimate stable channel dimensions, discharge and velocity, channel slope and Manning's roughness coefficient (N) (see review by Singh, 2003). This empirical computational tool has been refined to the point that regional curves of the geometry of river channels are established from many local measurements of channel dimensions.

The empirical approach to river channel design and bank stabilization projects relies on extensive data sets to develop regression relationships to predict stable channel dimensions at new sites. Setting channel dimensions based on regional curves is a common empirical technique that is readily applied to a range of projects when curves exist. Many other hydraulic geometry relationships exist that are available to double check regional estimates of channel dimensions.

9.2.2 Regional Hydraulic Geometry Curves

The State of New Hampshire currently has provisional HGR curves (NHST, 2005) to estimate the bankfull channel width (ft), depth (ft), and cross section area (sq ft) based on watershed area (sq mi) (Figure 9-3). Note that the New Hampshire curves are slightly skewed towards

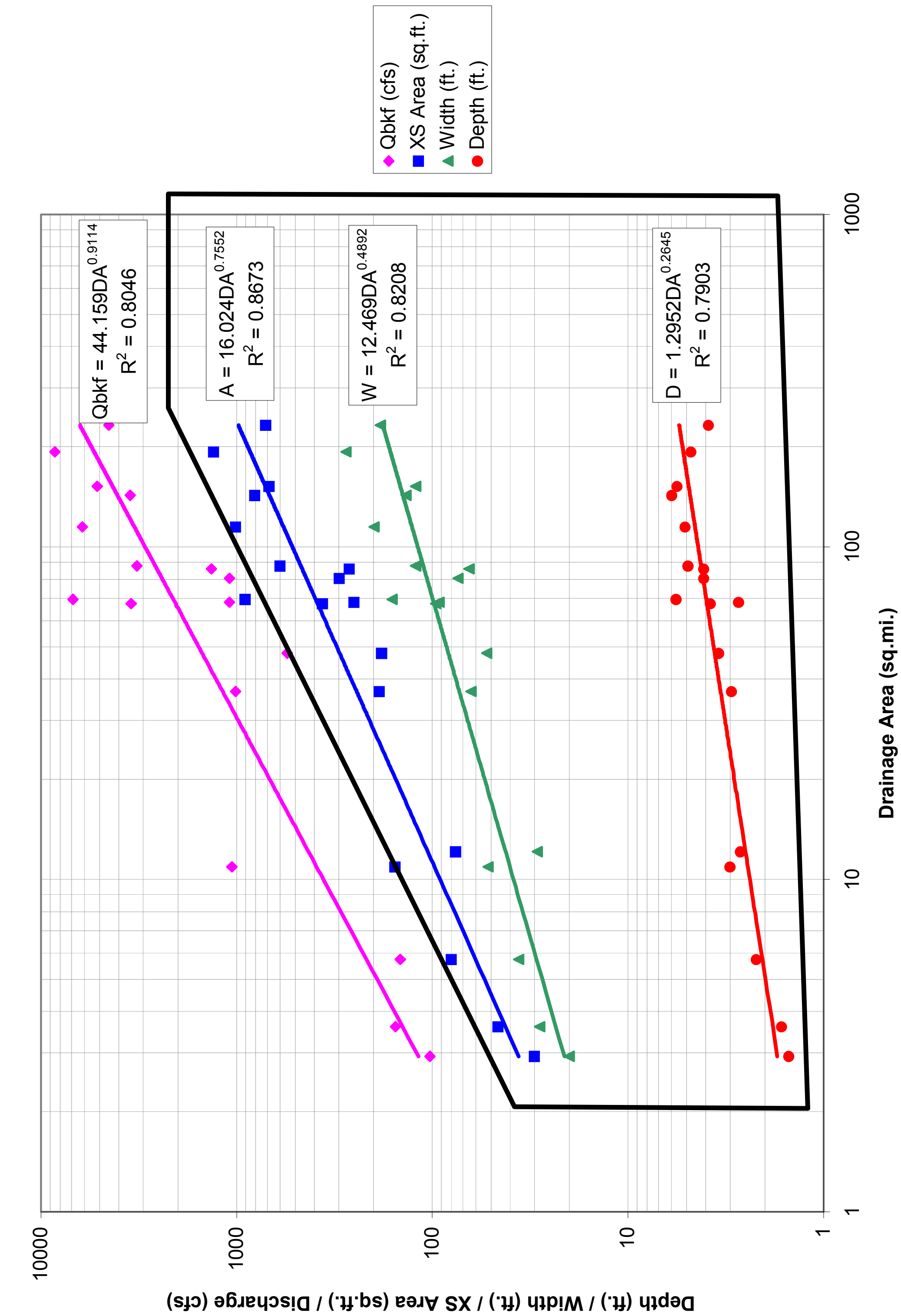


Figure 9-3: New Hampshire 2005 regional hydraulic geometry curves (provisional), which are particularly useful for smaller channels in steeper terrain (Source: NHST, 2005). Outlined curves are used to estimate bankfull width, depth, and cross sectional flow area.

smaller river channels in steeper terrain as a result of including data from channels in the White Mountains to create the curves. For larger rivers such as those in the Connecticut River Basin, it is more appropriate to use Vermont's HGR curves (Appendix J in VTANR, 2005) to determine bankfull width, depth, and cross sectional area. The New Hampshire curves will be periodically updated, so check with the Rivers Management and Protection Program in the Department of Environmental Services (DES) (http://www.des.state.nh.us/rivers) to ensure that the most recent curves are being used.

Due to the limited time it takes to calculate stable channel dimensions using HGRs it is useful to compare other regional estimates of channel dimensions with those from other empirical studies. The Natural Resources Conservation Service has a growing archive of existing HGRs and several have already been prepared for the New England Province of the Appalachian Highlands (http://wmc.ar.nrcs.usda.gov/technical/HHSWR/Geomorphic). Other regional curves (ME - Dudley, 2004; VT - VTANR, 2004; NY - Westergard et al., 2005) are useful to validate estimates with the New Hampshire HGR curves.

9.2.3 Regime Equations

Regime equations (Lacey, 1930), which are the precursor to HGRs, can be used to size a stable channel while directly considering discharge, channel slope, and substrate particle size. Because the only dependent variable in modern HGR curves is watershed area, without expressions for actual discharge, channel slope, or substrate, the regional curves often have considerable data scatter. Regime equations are particularly useful if the project is in a reference channel type that is substantially different than those used to create the HGR curves. For example, regime equations would be useful for designing a low-gradient sand bed channel in the seacoast region of New Hampshire as the regional HGR curves for steeper channels would not apply. There are several sets of regime equations (e.g., Simons and Albertson, 1963; Henderson, 1966; Julien and Wargadalam, 1995; Soar and Thorne, 2001; Lee and Julien, 2006) that can be regularly used to estimate the size of stable channels in naturalized channel design and bank stabilization projects (Table 9-1).

Table 9-1: Examples of regime equations that are useful in naturalized channel design and bank stabilization projects to estimate stable channel dimensions.

Regime Equations	K_1	K_2	K_3	m	Notes	Source
$W=0.9P=0.9K_1Q^{0.5}$	3.5	0.52	13.9	0.33	sand bed and banks	
if $R\leq 7$ft than $D=1.21R=1.21K_2Q^{0.36}$	2.6	0.44	16.0	0.33	sand bed, cohesive banks	(Simons and Albertson, 1960
if $R>7$ft than $D=2.0+0.93R=2+0.93K_2Q^{0.36}$	2.2	0.37	-	-	cohesive bed and banks	as modified by Henderson, 1966)
$V=K_3(R^2S)^m$	1.75	0.23	17.9	0.29	coarse, non-cohesive	
	1.7	0.34	16.0	0.29	sand bed, cohesive banks, high sediment load	

Regime Equations	a	b	Notes	Source
$W=aQ^b$	2.34	0.5	all sand-bed channels studied in N. America	
	2.86	0.5	sand bed with <50% tree cover	(Soar and Thorne, 2001)
	1.83	0.5	sand bed with >50% tree cover	
	2.03	0.5	all gravel-bed channels studied in N. America	

Regime Equations	Notes	Source
$W = 3.004Q^{0.426}d_{50}^{-.002}S^{-0.153}$	W in m, Q in cms, d_{50} in m, S in m/m	(Lee and Julien, 2006;
$D = 0.201Q^{0.336}d_{50}^{-0.025}S^{-0.060}$	D in m, Q in cms, d_{50} in m, S in m/m	Julien and Wargadalam, 1995)
$S = 4.981Q^{-0.346}d_{50}^{0.955}\tau^{*0.966}$	S in m/m, Q in cms, d_{50} in m, and τ^* is the dimensionless Shield's number	

definitions

W = mean bankfull width (ft); P=wetted perimeter (ft); Q=bankfull width (cfs); R=hydraulic radius=A/P (ft); D=mean bankfull depth (ft); V=mean velocity (fps); S=channel slope.

9.2.4 Limitations and Applicability of Empirical Approaches

The rapid design tools that are established from empirical methods are useful for establishing estimates of stable channel dimensions. Nevertheless, empirical approaches have some limitations that may require the use of other computational tools under certain conditions. The limitations of empirical methods include the following.

- Large regional data requirements to establish relationships
- Relationships must be used in similar systems
- Outlier observations can skew data patterns during relationship calibration
- Most appropriate for alluvial channels
- Not readily applicable to developed watersheds
- Braided channel types typically not included in relationship calibration
- Not appropriate for regulated rivers
- Variable river bed slope can influence relationships
- Limited opportunity for understanding watershed processes
- Insufficient to evaluate floodplain impacts

If empirical relationships exist for a project site yet unfavorable application conditions are present, other approaches are needed for data validation. Stable channel dimensions determined from physical-based analytical methods are often more appropriate when empirical relationships may have limited use.

9.3 Analog Techniques

9.3.1 Introduction

The analog approach to river channel design and bank stabilization uses a reference reach as a template for stable form and a single dominant design discharge, typically at bankfull flow.

Dimensions are measured at one or more stable reference reach and replicated when constructing a new channel. The analog approach is closely associated with the Rosgen method (Rosgen, 1994; Rosgen and Silvey, 1996, 1998), and many existing design manuals and guidelines primarily follow this methodology for naturalized channel creation (e.g., TRANS, 2001; Flosi et al., 2002; KST, 2002; Doll et al., 2003). The Rosgen method is helpful for understanding the reference and project reaches, organizing visual geomorphic observations and establishing one estimate of stable bankfull channel dimensions and channel pattern, yet is not recommended as a stand-alone project design tool. This method is ideally combined with empirical and analytical methods to arrive at a stable channel configuration over a range of flows. The *Generic Quality Assurance Project Plan for Stream Morphology* (Sweeney and Simpson, 2003) that is used for New Hampshire projects includes a brief description of the reference reach approach and quality assurance guidance for selecting a reference reach. Harrelson et al. (1994) present a useful summary of common measurements performed during the analog approach to naturalized channel design and bank stabilization projects.

9.3.2 The Reference Reach Approach

Channel classification based on observations and measurement of channel geometry is central to the reference reach approach. There are many ways to classify river channels (see review by Niezgoda and Johnson, 2005), and utilization of several different systems is recommended to arrive at the type of local reference reach, and thus stable dimensions at the project reach. Widely used classification systems are based on stream order (Strahler, 1952), watershed position (Schumm, 1977 - Figure 9-4; Montgomery and Buffington, 1993 - Figure 9-5), and the combination of entrenchment ratio, width to depth ratio, sinuosity, slope, and dominant bed material (Rosgen and Silvey, 1996 - Figure 9-6). The *Field Guide for Stream Classification* (Rosgen and Silvey, 1998) is a useful visual reference for understanding different channel types. Utilization of each of these classification systems is recommended to establish a complete picture of the channel type, rather than strictly relying on the observations and naming conventions of a single channel classification system. Channel classification should help determine the reference and project channel form (i.e., profile, cross

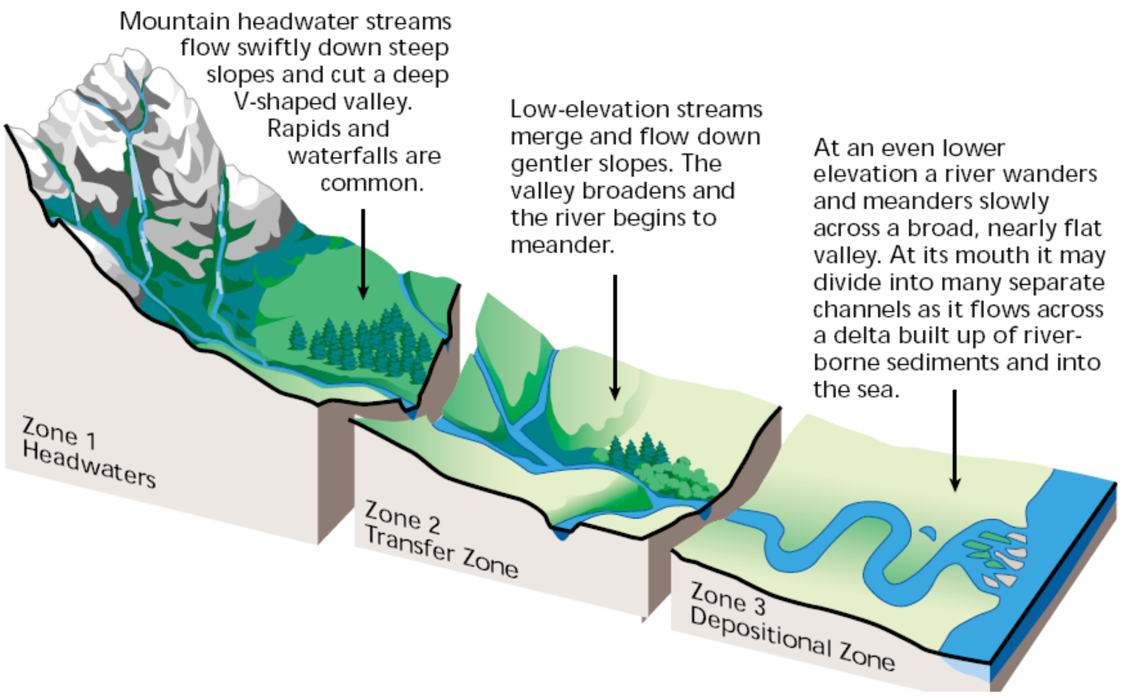


Figure 9-4: Longitudinal zones of a river corridor (Source: Schumm, 1977; FISRWG, 1998).

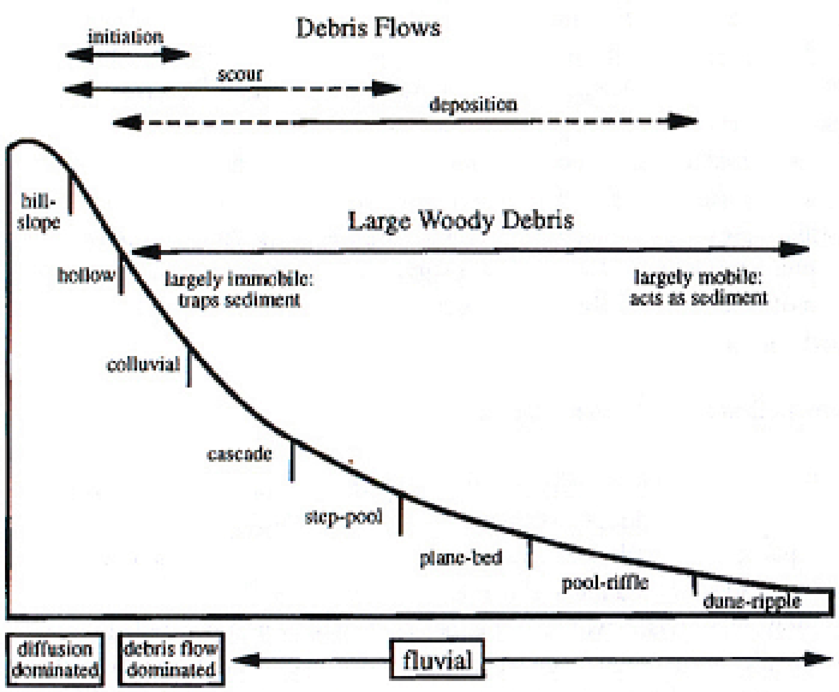


Figure 9-5: Montgomery and Buffington channel classification system primarily based on longitudinal watershed position (Source: Montgomery and Buffington, 1997).

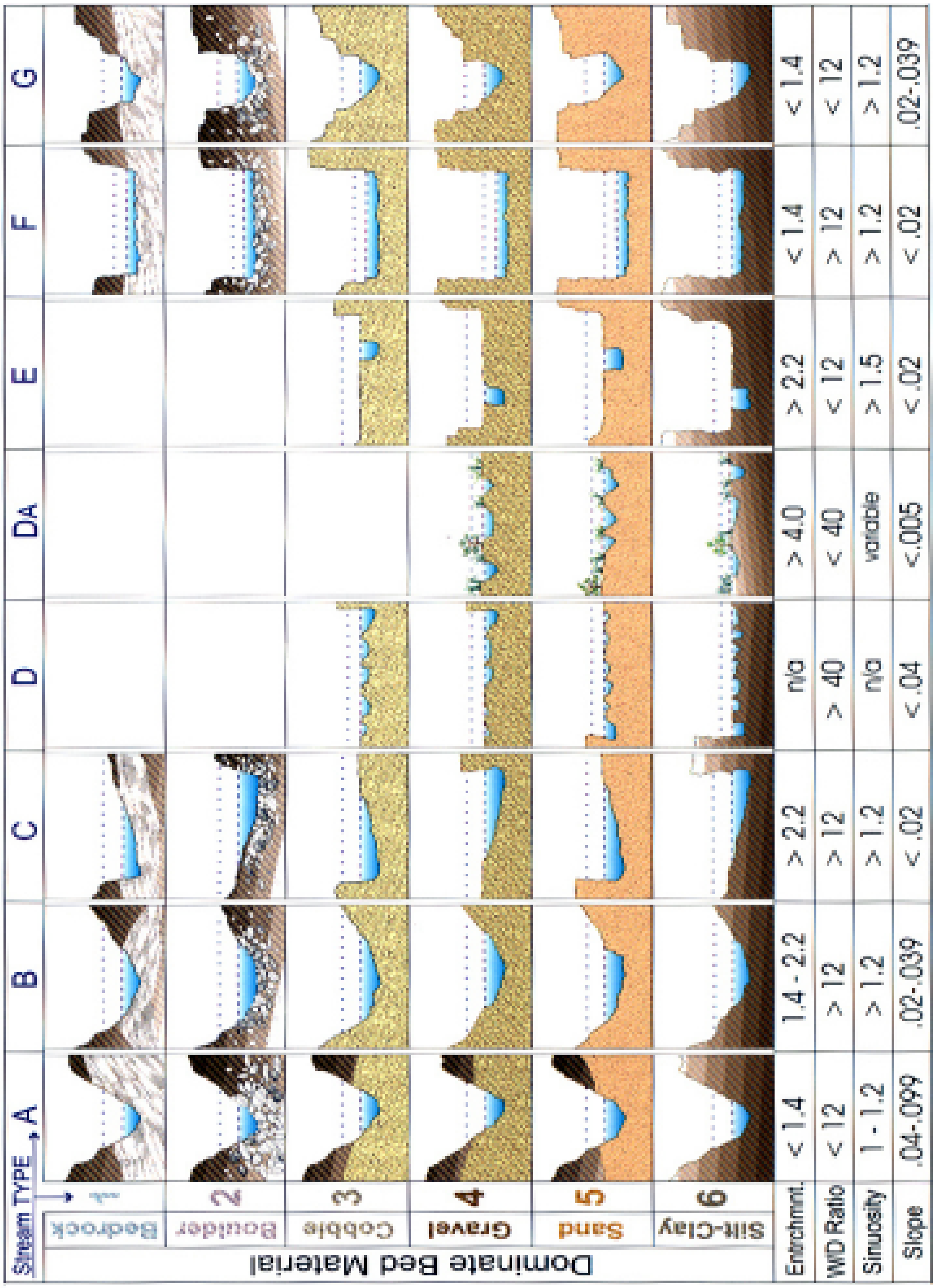


Figure 9-6: Rosgen channel classification system based on slope, sinuosity, width to depth ratio, entrenchment ratio, and dominant bed material (Source: Rosgen, 1994; Rosgen and Silvey, 1996).

section, and planform), and even offer insight on the processes that are likely to dominate the given channel type.

Determining the stage of channel evolution (Figure 9-7) (Schumm et al., 1984; Simon, 1989) is a particularly useful form of classification for understanding channel stability, while considering the natural sequence of reach formation and impacts due to human disturbance (Doll et al., 2003; Brierley and Fryirs, 2005). Knowledge of the channel evolution stage of both the project and reference reaches leads to more appropriate design. Channel evolution also provides information of the likely future channel form and stability. For example, based on the stage of evolution it may be possible to know if a channel is expected to tend towards degradation (Class III), widening (Class IV), aggradation (Class V), or equilibrium (Classes I and VI) following modification (FISRWG, 1998). Channel evolution stage adds a temporal component to projects that spans the time frame of local adjustment following a storm to the long-term river valley formation.

Note that the presence of natural bed armoring, where finer particles are selectively removed from the river bed leaving coarse material to limit vertical adjustment, is a common scenario in rivers in the northeast US that is not considered in most channel evolution models. Widening is much more likely than degradation for armored bed channels as they evolve (see discussion in Chapter 6.0). Identification of bed armoring allows for a more accurate determination of current and future channel stability.

9.3.3 Limitations and Applicability of the Analog Approach

The observation-based design is an appealing aspect of analog methods to both project designers and stakeholders. If an appropriate stable reference reach is present, this relatively efficient approach can lead to effective design. The analog approach to designing river channel and bank stabilization projects does have limitations that include:

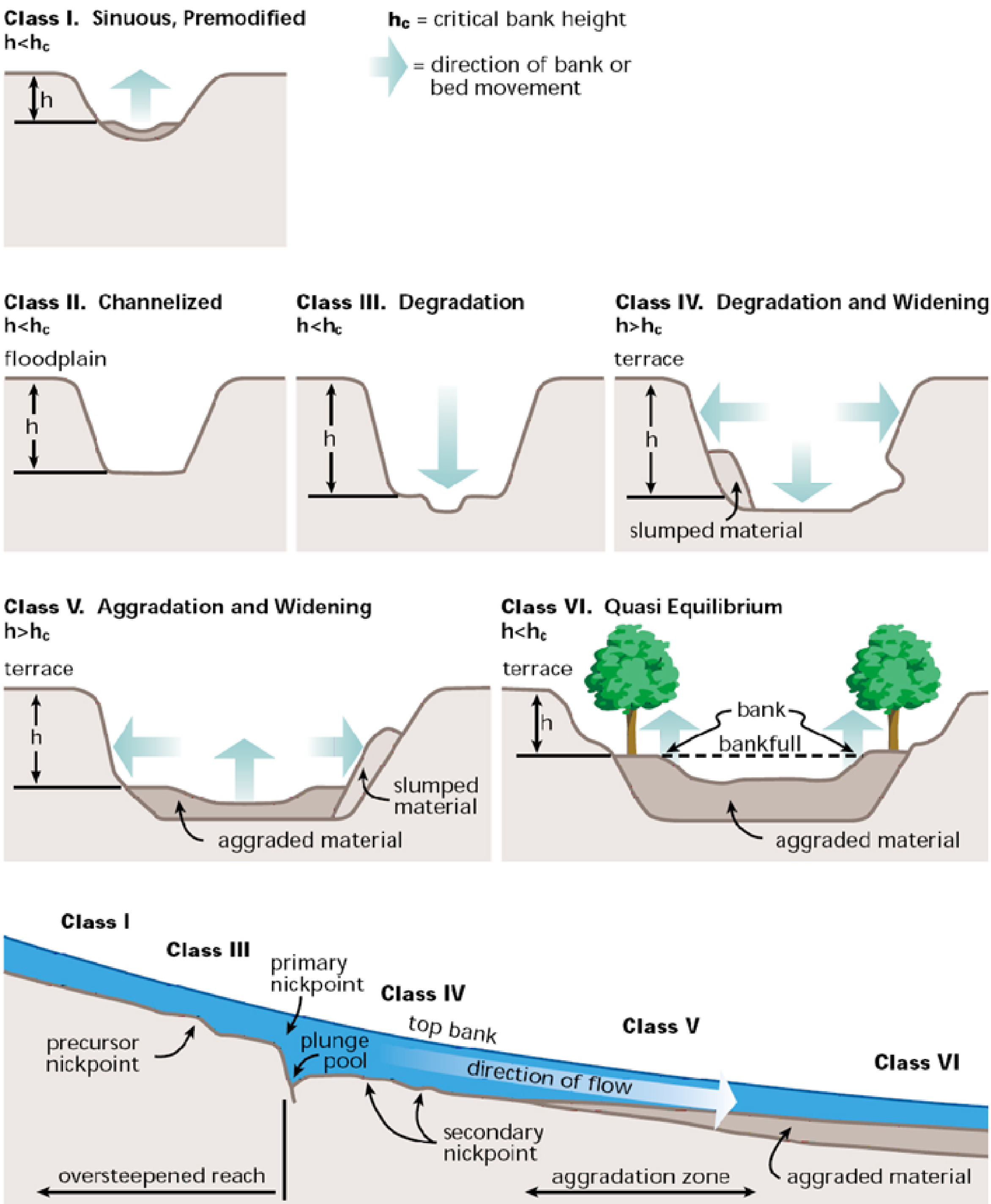


Figure 9-7: A schematic of the Simon incised channel evolution model (Source: Simon, 1989; FISRWG, 1998).

- Reference reaches are often difficult to find in disturbed systems leading to guesswork in the fundamental component of the design approach;
- Reliance on a single design flow, typically the bankfull discharge which can be difficult to identify, limits designs and increases the chances of project failure;
- The determination of dominant particle size is not always straight forward and complicates channel classification;
- Channel form (i.e., profile, cross section, and planform) alone does not always serve as a good predictor of system processes such as disturbance, response and sediment transport (Simon et al., 2005); and
- Reference reach data have to be adjusted for watershed scale.

As with the empirical, the analog approach is a useful method to be used with other computational tool. Specifically, hydraulic modeling is recommended with the analog approach to expand the understanding of the physical processes and anticipated response to project implementation that is not possible from analog methods alone. The combination of analog and analytical computational tools is referred to as "the geomorphic engineering approach" (Soar and Thorne, 2001), and is an effective design strategy for moderate and comprehensive projects.

9.4 Analytical Techniques

9.4.1 Introduction

Analytical, or physical-based, techniques have played a key role in both historic and recent engineering methods of naturalized river channel design and bank stabilization. Common analytical techniques include basic calculations using the Manning's and continuity equations, hydraulic modeling, and channel stability and sediment transport analysis.

9.4.2 Basic Hydraulics

The fundamentals of hydraulics include simple physical-based analytical techniques used to relate water velocity, discharge, and dimensions of open channels (Chanson, 2004). The continuity equation Q=VA indicates that discharge (Q, cfs) is equal to the product of mean water velocity (V, fps) and cross sectional area (A, sq ft). Without inflow, outflow, or changes in storage, discharge is constant between cross sections ($Q_1=V_1A_1=V_2A_2=Q_2$). This relationship is widely used when considering changes in water velocity, and thus sediment transport capacity, following changes in channel dimensions. For a given discharge, increases in cross sectional area lead to a decrease in mean water velocity, while decreases in cross sectional area lead to increased mean velocity.

Assuming uniform flow, or simple flow parallel to the river bed where the magnitude and direction of velocity is the same at every point, mean water velocity (V, fps) is calculated using Manning's equation $V=(1.49/N)R^{2/3}S^{1/2}$. N is the Manning's roughness coefficient and is a product of the bed particle size, type of debris present, and condition of the channel and can be determined with guidance from many existing manuals and texts that address open channel flow (FISRWG, 1998; USACOE, 2005; Arcement and Schneider, 2006) and at several Internet sites (http://www.utdallas.edu/~brikowi/Teaching/Applied_Modeling/SurfaceWater/LectureNotes/Manning_Roughness/ and http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/). R (ft) is the hydraulic radius that is equal to the cross sectional flow area (sq ft) divided by the wetted perimeter of the channel (ft). S is the channel slope (ft/ft). Mean discharge (Q, cfs), assuming uniform flow, can be determined by combining the Manning's and continuity equations $Q = A(1.49/N)R^{2/3}S^{1/2}$. Following field measurements of channel dimensions based on low, bankfull, and high flow indicators, one estimate of design flows is obtained.

9.4.3 Hydraulic Modeling

Hydraulic modeling is commonly employed to represent the more realistic scenario of non-uniform flow, where flow paths are locally variable due to contractions and expansions and small-scale features. Non-uniform water velocity is determined by flow energy according to the Bernoulli equation $E=Y+V^2/2g$. The depth (Y) is the potential energy component and $V^2/2g$ is the kinetic energy component where V is the water velocity and g is the acceleration of gravity constant. The energy is minimal at critical flow conditions, where critical depth and velocity occur. There are two important states of gradual varied flow – subcritical and supercritical. Subcritical flow occurs when the depth is larger than the critical depth and flow is slow and tranquil (Chanson, 2004). Under subcritical flow, water depth will decrease if the river bed is raised and will increase if the bed is lowered. Supercritical flow, on the other hand, occurs when the water depth is less than the critical depth and flow is fast and torrential. (Chanson, 2004). Under supercritical flow, water depth will increase if the river bed is raised, and depth will decrease if the bed is lowered.

Hydraulic modeling is used to compute water surface profiles and associated variables at cross sections in the project river. The most widely used and recommended hydraulics model for naturalized river channel design and bank stabilization projects is HEC-RAS (USACOE, 2005). This one-dimensional simulation of gradually varied flow can be run in both steady (i.e., flow is constant with time) and unsteady modes. Steady flow is used when the peak of different design flows are used to simulate hydrology and is recommended for moderate projects. Unsteady flows are used for more involved comprehensive projects where a full input hydrograph is generated and hydraulic conditions are analyzed over the course of a storm in addition to at the peak flow. HEC-RAS can accommodate a full dendritic network of channels or a single river reach. Water surface profiles can be determined for subcritical, supercritical, and mixed-flow conditions. The basic computational procedure of HEC-RAS is solution of the one-dimensional Bernoulli equation. Energy losses are evaluated by the Manning's equation. The momentum equation (fundamentally the product of water mass and velocity) is used in limited situations where the water surface profile is rapidly varied, such as at culverts, bridges, dams, and confluences.

Hydraulic modeling with HEC-RAS typically includes the following steps:

- Determining peak flow rates or hydrographs for the range of design flows;
- Setting up system geometry based on recent or previous survey information, or approximated cross sectional geometry obtained from topographic maps and field measurements of channel dimensions;
- Setting appropriate boundary conditions; and
- Running several different analysis plans to investigate existing conditions and recommended alternatives.

Additional information on the details of using HEC-RAS can be obtained from the user's manual and hydraulic reference that come with the public-domain software that can be obtained from the Internet (http://www.hec.usace.army.mil/software/hec-ras/), second-party guidance documents and texts, and professional courses. There is an art to HEC-RAS modeling that takes time and experience to develop.

Standard HEC-RAS outputs include discharge, channel thalweg elevation, water surface elevation, critical water surface elevation, energy grade line elevation, energy grade slope, water velocity, cross sectional flow area, top width of flow, and the Froude number. In addition, a wide range of other hydraulic variables are calculated at each cross section.

The results of HEC-RAS hydraulic modeling are useful for completing a range of tasks associated with river channel design and bank stabilization projects. Investigating changes in water surface elevation and flow characteristics proposed after project implementation; iteratively adjusting channel dimensions to reach desired flow characteristics; determining the elevation to place structural components; and investigating a local project in the context of hydraulics of a larger reach, river, or watershed are some of the many common applications.

9.4.4 Channel Stability and Sediment Transport Analysis

9.4.4.1 Dynamic Equilibrium

A fundamental goal of most naturalized river channel design and bank stabilization projects is to increase channel stability. All rivers erode and deposit sediments in a natural dynamic equilibrium; however, departure from this state leads to channel instabilities where excessive amounts of sediment erosion and deposition can take place over short periods of time. Channel stability is a product of the balance between water and sediment (Figure 9-8), where the product of flow discharge and channel slope is proportional to the product of sediment discharge and the median particle size (Lane, 1955). Lane's scale is a useful conceptual tool to understand the root causes of channel degradation and aggradation, and how to slow the on-going process that is destabilizing the channel.

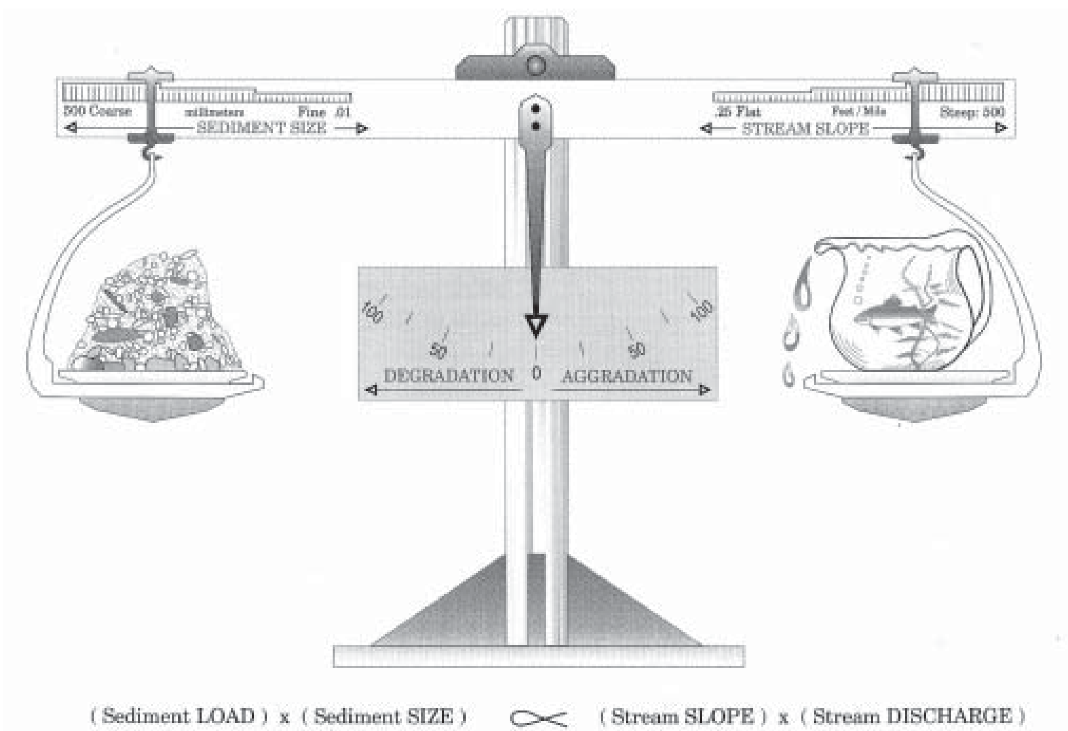


Figure 9-8: The dynamic equilibrium between sediment and water in river channels (Source: Lane, 1955; Rosgen and Silvey, 1996).

9.4.4.2 Threshold Velocity and Critical Shear Stress (Incipient Motion)

The ability of flowing water to dislodge and transport individual sediment particles is a function of the ratio between the hydraulic shear stress and the particle's resistance to motion. Shear stress is directly related to water velocity. Channel stability and the likelihood of erosion or deposition can be determined by calculating critical shear stress – the minimum stress required to initiate motion of a particle of a given size, or threshold velocity – the minimum water velocity required to move a particle of a given size. Erosion is likely to occur at a cross section if the local shear stress (or mean water velocity) is larger than the critical shear stress (or threshold velocity) and deposition is anticipated at a cross section if the local shear stress (or mean water velocity) is smaller than critical (or threshold) levels. Calculated estimates of critical shear stress and threshold velocity exist for both different sized soil particles and materials used in naturalized channel design and bank stabilization projects (Table 9-2). Direct shear stress calculations can get complicated and thus are reserved for moderate and comprehensive projects where computer hydraulic modeling is performed. Approximating channel stability based on threshold velocity calculations is ample for most routine projects and some moderate projects.

There are numerous ways to estimate threshold velocity for comparison to mean velocity as determined from Manning's equation or an existing empirical relationship. Particle size distribution is required to use the many existing simple relationships (Table 9-3A) or charts (Appendix F) to calculate threshold velocity. As most of these relationships were derived from experiments in flumes and only approximate conditions in natural river channels, it is best to calculate several estimates and compare results. Note that the basic equations are empirically derived and thus units do not follow typical calculation rules. Be aware that some diagrams portray critical velocity (or shear stress) in dimensionless forms, which is commonly noted by an asterisk subscript.

Simple relationships also exist for estimating critical shear stress that are a function of the particle size distribution (Table 9-3B) for comparison to shear stress calculations at a cross

Table 9-2: Permissible shear stress and threshold velocity for different soil particle sizes and various materials used in naturalized channel design and bank stabilization (Source: Fischenich, 2001). Note that RECPs represents rolled erosion control products.

Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)	Permissible Velocity (ft/sec)	Citation(s)
Soils	Fine colloidal sand	0.02 - 0.03	1.5	A
	Sandy loam (noncolloidal)	0.03 - 0.04	1.75	A
	Alluvial silt (noncolloidal)	0.045 - 0.05	2	A
	Silty loam (noncolloidal)	0.045 - 0.05	1.75 – 2.25	A
	Firm loam	0.075	2.5	A
	Fine gravels	0.075	2.5	A
	Stiff clay	0.26	3 – 4.5	A, F
	Alluvial silt (colloidal)	0.26	3.75	A
	Graded loam to cobbles	0.38	3.75	A
	Graded silts to cobbles	0.43	4	A
	Shales and hardpan	0.67	6	A
Gravel/Cobble	1-in.	0.33	2.5 – 5	A
	2-in.	0.67	3 – 6	A
	6-in.	2.0	4 – 7.5	A
	12-in.	4.0	5.5 – 12	A
Vegetation	Class A turf	3.7	6 – 8	E, N
	Class B turf	2.1	4 - 7	E, N
	Class C turf	1.0	3.5	E, N
	Long native grasses	1.2 – 1.7	4 – 6	G, H, L, N
	Short native and bunch grass	0.7 - 0.95	3 – 4	G, H, L, N
	Reed plantings	0.1-0.6	N/A	E, N
	Hardwood tree plantings	0.41-2.5	N/A	E, N
Temporary Degradable RECPs	Jute net	0.45	1 – 2.5	E, H, M
	Straw with net	1.5 – 1.65	1 – 3	E, H, M
	Coconut fiber with net	2.25	3 – 4	E, M
	Fiberglass roving	2.00	2.5 – 7	E, H, M
Non-Degradable RECPs	Unvegetated	3.00	5 – 7	E, G, M
	Partially established	4.0-6.0	7.5 – 15	E, G, M
	Fully vegetated	8.00	8 – 21	F, L, M
Riprap	6 – in. d_{50}	2.5	5 – 10	H
	9 – in. d_{50}	3.8	7 – 11	H
	12 – in. d_{50}	5.1	10 – 13	H
	18 – in. d_{50}	7.6	12 – 16	H
	24 – in. d_{50}	10.1	14 – 18	E
Soil Bioengineering	Wattles	0.2 – 1.0	3	C, I, J, N
	Reed fascine	0.6-1.25	5	E
	Coir roll	3 - 5	8	E, M, N
	Vegetated coir mat	4 - 8	9.5	E, M, N
	Live brush mattress (initial)	0.4 – 4.1	4	B, E, I
	Live brush mattress (grown)	3.90-8.2	12	B, C, E, I, N
	Brush layering (initial/grown)	0.4 – 6.25	12	E, I, N
	Live fascine	1.25-3.10	6 – 8	C, E, I, J
	Live willow stakes	2.10-3.10	3 – 10	E, N, O
Hard Surfacing	Gabions	10	14 – 19	D
	Concrete	12.5	>18	H

[1] Ranges of values generally reflect multiple sources of data or different testing conditions.

A. Chang, H.H. (1988).
B. Florineth. (1982)
C. Gerstgraser, C. (1998).
D. Goff, K. (1999).
E. Gray, D.H., and Sotir, R.B. (1996).
F. Julien, P.Y. (1995).
G. Kouwen, N.; Li, R. M.; and Simons, D.B., (1980).
H. Norman, J. N. (1975).
I. Schiechtl, H. M. and R. Stern. (1996).
J. Schoklitsch, A. (1937).
K. Sprague, C.J. (1999).
L. Temple, D.M. (1980).
M. TXDOT (1999)
N. Data from Author (2001)
O. USACE (1997).

Table 9-3: Equations for determining threshold velocity (A) and critical shear stress (B).

(A)

V_s (fps)	Reference	Notes
$V_s=2.6356(D_{75})^{0.306}$	(SCS)	Applicable to sand
$V_s=1.4653(D_{75})^{0.38}$	(SCS)	Applicable to gravel
$V_s=143(d)^{1/3}(D_{75})^{2/3}$	(Neill, Corps)	
$V_s=11.52(Y)^{1/6}(D_{50})^{1/3}$	(Neill, HEC-18)	
$V_s=0.5(D_{50})^{0.5}$	(Mavis & Laushey)	

(B)

τ_c (lbs/ft^2)	Reference	Notes
$\tau_c=5(D_{50})$	(SCS)	
$\tau_c=4.1(D_{50})$	(USACOE)	
$\tau_c=6.18(D_{50})$	(Shields)	

definitions

V_s = threshold velocity (fps)

D_{75} = 75th percentile particle size (ft)

D_{50} = median particle size (ft)

Y = water depth (ft)

τ_c = critical shear stress (lbs/ft^2)

section ($\tau = \gamma RS$, lb per sq ft where γ is the density of water (62.4 lb per cu ft), R is the hydraulic radius, and S is the slope of the energy grade line). Using shear stress to approximate the level of channel stability is a superior method compared to relying on threshold velocity relationships, and thus is recommended for most moderate and comprehensive project. The more involved shear stress calculations at each cross section are common output of hydraulic models so this approach requires only the measuring of the particle size distribution at locations of interest and making basic calculations of critical shear stress or reliance on previously determined estimates of critical shear stress for a given particle size (Figure 9-9).

9.4.4.3 River Bed Armoring

Natural bed armoring, a layer of large particles on the bed surface that limits the removal of underlying small size particles due to sheltering from applied shear stresses, is an important consideration when investigating channel stability. The armor layer is typically only one to three particles thick, and forms initially along the thalweg before spreading laterally. The armor layer can be broken by large flood flows that exceed those that dominated during its

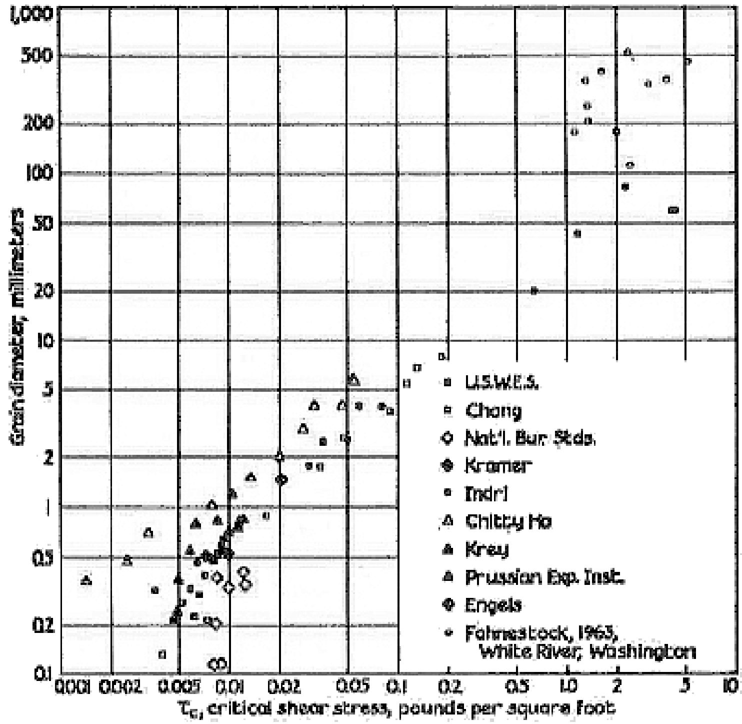


Figure 9-9: Critical shear stress versus particle grain size diameter (Source: Leopold et al., 1964).

formation. The size of stable sediments required to form an armored bed is typically in the range of D_{75} to D_{90}. No armor will form if these sediments are unstable due to the current flow regime. Armoring can limit bed degradation and lead to excess widening due to more erodable banks (see Figure 6-13).

9.4.4.4 Stable Slope Analysis

Stable slope analysis is a useful tool to guide the understanding of channel stability (see Section 8.3.2). River beds with active sediment transport will adjust their gradient, eventually reaching an equilibrium condition where the bed slope is proportional to the sediment size and channel forming discharge. When the sediment size is known, sediment transport equations can be used to solve for the expected equilibrium slope (see Table 8-3 and Appendix E). Channel slopes that are steeper than the equilibrium slope suggest that erosion is likely, while shallower slopes indicate deposition.

9.4.4.5 Stable Channel Dimensions with HEC-RAS

Stable channel dimensions can be estimated in HEC-RAS using the Copeland, Blench Regime, or Tractive Force methods. Refer to the HEC-RAS Hydraulics Reference Manual for additional details on theory and application. The output for each of these algorithms is channel width, depth, and slope. The definition of stability is a function of which method is used. For Copeland's (1994) method, stability is achieved when sediment inflow equals sediment outflow. Output from this model includes stability curves of width and depth versus slope, including indications of when aggradation and degradation may occur. In addition, the width and depth associated with the minimum stream power solution, or the minimum slope that will transport the incoming sediment, is computed. The Copeland method is primarily used for sand bed channels.

Regime methods are empirically-based and stability is present when no net annual erosion or deposition occurs. The Blench Regime method (Blench, 1970) used in HEC-RAS is appropriate for sand bed channels. If the channel can be approximated by this and other suggested application criteria, this is a quick way to get stable channel dimension estimates.

Tractive force methods consider a channel stable when there is no net movement of particles on the bed. Critical shear stress is used to assess if the channel is prone to degradation or aggradation, or is in equilibrium. Methods by both Lane (1953) and Shields (Shields, 1936) for determining the initiation of motion, in addition to a user entered critical value are available. The tractive force approach to estimating stable channel dimensions is applicable to channels with substrates that are more coarse than sand.

9.4.4.6 Sediment Transport Analysis in HEC-RAS

The potential sediment transport capacity is calculated based on hydraulics and the particle size distribution for a given reach. The primary outputs of the analysis are a sediment rating curve, or sediment capacity (tons/day) versus flow (cfs) at a cross section, and a sediment profile, or sediment capacity (tons/day) versus main channel distance (ft). The rating curve is useful for understanding the capacity at a given cross section, while the rating curve represents the continuity of sediment transport. If sediment transport capacity drops in successive reaches deposition is expected, whereas if transport increases erosion is expected.

There are a wide range of sediment transport functions that have a major influence on results, and selecting the appropriate method to determine sediment transport capacity is one of the central challenges with the analysis. A review of the many sediment transport equations is beyond the scope of this guidelines document, and one can refer to the HEC-RAS Hydraulics Reference Manual for a summary of theory and application notes of several of the more common formulae. The most common methods used are those by Meyer-Peter Müeller and Yang. The Meyer-Peter Müeller equation is valid for sands and gravels, and transport rate is determined from the difference between the mean and critical shear stresses. Yang's method is applicable for silts, sands, and fine gravels, and transport rate is primarily a function of stream power.

Although there is an extensive body of research and many application methods on sediment transport analysis, the typical wide range of results originating from different methods suggests that there currently is no clear single way to approximate sediment transport. A comparative approach is recommended where several methods that are applicable to the project site are used and findings are checked for consistency. In addition, the sediment transport scenario should be checked with respect to the geomorphic analysis to see if findings make physical sense. Finally, and ideally, verification via field measurements in the project watershed or region is useful for strengthening modeling results.

9.4.5 Limitations and Applicability of the Analytical Approach

The ability to model designs with both spatial and temporal dynamics is a primary advantage of using analytical techniques for naturalized river channel design and bank stabilization projects that is not available via other computation methods. A variety of useful computer programs are available through both public domain and private software distributors to readily perform a variety of computations. Once models are set up, existing conditions and a range of alternatives can typically be run over short periods of time.

There are some limitations to analytical methods that include:

- Even with guidance materials, some up front research and experience is necessary to accurately select and use each variable, equation, and model parameter;
- Equations and numerical analytical tools can appear abstract to the public, and thus they are often not as readily digestible by project stakeholders as compared to more visual approaches;
- Setting up and debugging large computer models takes time, and thus can increase project costs; and
- Fundamentally, there are insufficient physical equations to generate an analytical solution when modeling a natural river channel that can have up to nine degrees of freedom (variables) (Hey and Thorne, 1986), and thus empirical or analog methods are also needed. The independent variables are usually watershed area, dominant discharge, and sediment load. The dependent variables are channel width, depth, slope, sinuosity, substrate, and bank slope.

CHAPTER 10.0: COMMON CHANNEL AND BANK PRACTICES

10.1 Introduction

Installation of channel and bank practices is necessary when the 'do nothing' or passive approaches to naturalized river channel design and bank stabilization projects are not enough to establish suitably stable boundary conditions based on site constraints, improve aquatic habitat and meet other goals. A variety of practices using both hard and soft materials can be used to stabilize the bed (i.e., establish grade control), stabilize banks, enhance habitat, and improve riparian vegetation. Soft materials such as natural vegetation and fiber rolls and mats are preferable from a habitat point of view, but are not always appropriate due to site characteristics and constraints requiring a more rigid design. In these situations, a combination of hard and soft materials is the best approach to achieve the desired channel and bank stability, and maintain some natural habitat features of the river.

Channel and bank practices have been used for decades to improve river conditions and thus existing manuals offer a lot of useful information on application details. Table 10-1 organizes common practices by their application, and lists the appropriate references for design information. Some manuals (e.g., FISRWG, 1998) primarily offer general guidance on what a particular practice is useful for and where it is most applicable. Other manuals (e.g., MDE, 2000; Eubanks and Meadows, 2002) offer construction guidelines that include uses and limitations, material specifications, approximate costs, installation guidelines, and detailed schematics. Other manuals (e.g., NRCS, 2005) provide additional theory and detailed design guidance. Note that all of the references that are available for public use are assembled in the accompanying electronic library for quick access while using this guidelines document.

Choosing the appropriate practices primarily is a function of using materials that have threshold velocities that are suitable for the site conditions and their planned location of installation (Fischenich, 2001), accomplish project goals and objectives and allow for the most

Table 10-1: Common channel and bank practices for a given application, and references containing application details. Note that all references are available in the accompanying electronic document library.

Application	Practice	Reference 1	Reference 2	Reference 3	Reference 4	Reference 5	Reference 6	Reference 7	Reference 8
10.2 Grade Control	Channel Shaping	(Cramer et al., 2003)	(Saldi-Caromile et al., 2004)						
	Check Dams	(Flosi et al., 2002)	(MDE, 2000)						
	Cross Vanes (Log or Rock)	(Doll et al., 2003)	(MDE, 2000)	(Rosgen and Silvey, 1996)	(FISRWG, 1998)				
	Drop Structures	(Cramer et al., 2003)	(Saldi-Caromile et al., 2004)	(FISRWG, 1998)					
	Step Pools	(MDE, 2000)							
	Wiers (Vortex, W, log)	(Cramer et al., 2003)	(MDE, 2000)	(Doll et al., 2003)	(Rosgen and Silvey, 1996)	(FISRWG, 1998)	(Flosi et al., 2002)		
10.3 Bank Stabilization	Bank Re-shaping	(Cramer et al., 2003)	(GASWCC, 2000)	(FISRWG, 1998)					
Soft (Bioengineering)	Branch Packing	(Eubanks and Meadows, 2002)	(NRCS, 1996)	(GASWCC, 2000)	(LCSMC, 2002)	(FISRWG, 1998)			
	Brush Layering	(Eubanks and Meadows, 2002)	(MDE, 2000)	(Walter et al., 2005)					
	Brush Mattress	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(GASWCC, 2000)	(LCSMC, 2002)	(Walter et al., 2005)	(FISRWG, 1998)	(Flosi et al., 2002)
	Channel Shaping	(Cramer et al., 2003)							
	Coconut Fiber Rolls	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(Cramer et al., 2003)	(LCSMC, 2002)	(Walter et al., 2005)	(FISRWG, 1998)	
	Dormant Post Planting	(LCSMC, 2002)	(Walter et al., 2005)	(FISRWG, 1998)					
	Erosion Control Fabric	(Eubanks and Meadows, 2002)	(LCSMC, 2002)						
	Hay Bale Breakwater	(Eubanks and Meadows, 2002)							
	Joint Planting	(Eubanks and Meadows, 2002)	(NRCS, 1996)	(GASWCC, 2000)	(FISRWG, 1998)				
	Jute-mat Rolls	(Eubanks and Meadows, 2002)							
	Live Cribwall	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(Cramer et al., 2003)	(GASWCC, 2000)	(Walter et al., 2005)	(FISRWG, 1998)	(Flosi et al., 2002)
	Live Fascine	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(GASWCC, 2000)	(LCSMC, 2002)	(Walter et al., 2005)	(FISRWG, 1998)	
	Live Post	(Eubanks and Meadows, 2002)							
	Live Siltation	(Eubanks and Meadows, 2002)	(LCSMC, 2002)	(Walter et al., 2005)					
	Live Stake	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(GASWCC, 2000)	(LCSMC, 2002)	(Walter et al., 2005)	(Doll et al., 2003)	
	Log Breakwater	(Eubanks and Meadows, 2002)							
	Log Toe	(Cramer et al., 2003)	(Flosi et al., 2002)						
	Plant Mat	(Eubanks and Meadows, 2002)							
	Plant Roll	(Eubanks and Meadows, 2002)							
	Root Wad	(Eubanks and Meadows, 2002)	(MDE, 2000)	(NRCS, 1996)	(LCSMC, 2002)	(Walter et al., 2005)	(Doll et al., 2003)	(Flosi et al., 2002)	
	Engineered Log Jams	(Saldi-Caromile et al., 2004)							
	Rooted Stock	(Eubanks and Meadows, 2002)							
	Snow Fence	(Eubanks and Meadows, 2002)							
	Terraced Crib	(Eubanks and Meadows, 2002)							
	Tree and Log Revetment	(Eubanks and Meadows, 2002)	(NRCS, 1996)	(LCSMC, 2002)	(Walter et al., 2005)	(FISRWG, 1998)	(Flosi et al., 2002)		
	Trench Pack	(Eubanks and Meadows, 2002)							
	Vegetated Geogrid	(Eubanks and Meadows, 2002)	(NRCS, 1996)	(FISRWG, 1998)					
	Woody plantings	(Cramer et al., 2003)							
Hard (Traditional)	Block Revetment	(NRCS, 2005)							
	Boulder Revetment	(NRCS, 1996)	(LCSMC, 2002)	(FISRWG, 1998)					
	Concrete Bulkheads	(NRCS, 1996)							
	Concrete Celular Blocks	(NRCS, 1996)							
	Concrete Jack	(NRCS, 1996)							
	Floodplain Grade Control	(Cramer et al., 2003)							
	J-hook Rock Vane	(Doll et al., 2003)	(MDE, 2000)	(Rosgen and Silvey, 1996)					
	Piling Revetment/Wall	(NRCS, 1996)	(NRCS, 2005)						
	Riprap	(NRCS, 1996)	(MDE, 2000)	(Cramer et al., 2003)	(Fischenich, 2003)	(LCSMC, 2002)	(FISRWG, 1998)	(NRCS, 2005)	
	Rock Gabions	(LCSMC, 2002)	(MDE, 2000)						
	Rock Riffle	(LCSMC, 2002)							
	Single Rock Vane	(Doll et al., 2003)	(Rosgen and Silvey, 1996)						
	Slotted Board Fencing	(NRCS, 1996)							
	Groins (Barbs or Dikes)	(Cramer et al., 2003)	(NRCS, 1996)	(LCSMC, 2002)					
	Stream Jetty	(NRCS, 1996)							
	Wing Deflectors (Rock/log)	(FISRWG, 1998)	(MDE, 2000)	(Flosi et al., 2002)					
Combination	Vegetated Rock Gabions	(NRCS, 1996)	(FISRWG, 1998)						
	Vegetated Rock Walls	(NRCS, 2005)							
	Toe Protection	(FISRWG, 1998)	(MDE, 2000)						
10.4 Habitat Enhancement	Channel/Meander Shaping	(Cramer et al., 2003)	(FISRWG, 1998)						
	Boulders (Erratics/Clusters)	(Doll et al., 2003)	(MDE, 2000)	(Saldi-Caromile et al., 2004)	(FISRWG, 1998)	(Flosi et al., 2002)			
	Debris Jam	(Cramer et al., 2003)							
	Large Woody Debris/Jams	(Doll et al., 2003)	(NRCS, 2005)	(Saldi-Caromile et al., 2004)	(Flosi et al., 2002)				
	Side/Off-Channel Habitats	(Saldi-Caromile et al., 2004)							
	Spawning/Rearing Habitat	(Cramer et al., 2003)	(Saldi-Caromile et al., 2004)						
10.5 Riparian Vegetation	Buffer Management	(Cramer et al., 2003)							
	Floodplain Roughness	(Cramer et al., 2003)							
	Re-vegetation	(Eubanks and Meadows, 2002)	(Saldi-Caromile et al., 2004)	(Walter et al., 2005)	(NRCS, 1996)	(Cramer et al., 2003)	(Doll et al., 2003)	(FISRWG, 1998)	(Flosi et al., 2002)

ecological recovery possible. Application guidance exists for practices (Tables 10-2 and 10-3), and the uniqueness of each site often allows, if not requires, different combinations of practices in different locations. The following general questions can help with the appropriate selection of practices.

- Could the problem be addressed with a 'no action' or passive approach, or is an installed practice required?
- Will the practice be stable in the near future given the estimated water velocities on the bed; low, mid and upper bank; and adjacent buffer during overbank floods?
- Is the practice over-sized relative to naturally occurring habitat features in the project reach, which could inadvertently degrade habitat during low flows?
- What is the expected lifetime of the practice and is that ample for its objective?
- Is the practice treating the source or response of a problem, and is that appropriate given the lifetime of the project?
- What are the ecological benefits and risks associated with the practice?
- Will the practice result in unintended effects at the site, along the reach, or on nearby properties?

10.2 Grade Control

10.2.1 Introduction

Grade control structures are used to stabilize the elevation of the river bed. Vertical channel degradation, or incision, can occur due to the upstream migration of a nick point during channel evolution (Schumm et al., 1984; FISRWG, 1998). This incision process can be accelerated by adjustment of the balance between sediment and water in a river channel (Lane, 1955), and disturbance such as channelization (Simon, 1989; Doll et al., 2003).

Table 10-2: Functions of common channel and bank practices (Source: MDE, 2000).

RESTORATION/ STABILIZATION PRACTICE	FUNCTIONAL APPLICATIONS					
	armor & protect surface	enhance mass stability	propagate vegetative growth	filter sediment	provide instream habitat	provide riparian habitat
Brush Layering	●	●	●	●	❍	◗
Brush Mattresses	●	❍	◗	●	❍	◗
Fascines	◗	❍	◗	●	❍	◗
Live Crib Walls	◗	●	●	❍	◗	❍
Live Stakes	◗	◗	●	◗	❍	◗
Natural Fiber Rolls	◗	❍	●	◗	❍	◗
Deflectors	❍	❍	❍	❍	◗	❍
Gabions	●	◗	❍	❍	❍	❍
Root Wads	◗	◗	◗	◗	●	◗
Riprap, dumped	●	❍	❍	◗	❍	❍
Riprap, imbricated	●	●	❍	◗	❍	❍
Boulder Placement	❍	❍	❍	❍	◗	❍
Log Weirs	❍	❍	❍	◗	◗	❍
Stone Dikes	❍	❍	❍	●	❍	❍
Rock Vanes	●	◗	❍	❍	◗	❍
Log Vanes	●	◗	❍	❍	◗	❍
J-Hooks	●	◗	❍	❍	●	❍
Vortex Rock Weirs	◗	❍	❍	❍	◗	❍
"W" Rock Weirs	●	◗	❍	❍	◗	❍

Key:

● - the approach is well suited for this functional application (primary benefit)
◗ - the approach is moderately well suited for this functional application (frequent secondary benefit)
❍ - the approach is not well suited/rarely used for this functional application (possible incidental benefit)

Table 10-2 (continued).

RESTORATION/ STABILIZATION PRACTICE	FUNCTIONAL APPLICATIONS				
	provide organic material	protect bank toe	redirect flow	create flow diversity	stabilize bed
Brush Layering	◗	❍	❍	❍	❍
Brush Mattresses	❍	❍	❍	❍	❍
Fascines	❍	❍	❍	❍	❍
Live Crib Walls	●	◗	❍	❍	❍
Live Stakes	◗	❍	❍	❍	❍
Natural Fiber Rolls	◗	❍	❍	❍	❍
Deflectors	❍	◗	●	●	❍
Gabions	❍	●	❍	❍	❍
Root Wads	●	◗	●	◗	❍
Riprap, dumped	❍	●	❍	❍	❍
Riprap, imbricated	❍	●	❍	❍	❍
Boulder Placement	❍	❍	◗	●	❍
Log Weirs	◗	❍	●	●	❍
Stone Dikes	❍	❍	◗	◗	◗
Rock Vanes	❍	●	●	●	❍
Log Vanes	❍	●	●	●	❍
J-Hooks	❍	●	●	●	❍
Vortex Rock Weirs	❍	●	●	●	●
"W" Rock Weirs	❍	●	●	●	●

Key:

● - the approach is well suited for this functional application (primary benefit)
◗ - the approach is moderately well suited for this functional application (frequent secondary benefit)
❍ - the approach is not well suited/rarely used for this functional application (possible incidental benefit)

Table 10-3: Site conditions suitable for common channel and bank practices (Source: MDE, 2000).

RESTORATION/ STABILIZATION PRACTICE	FUNCTIONAL APPLICATIONS					
	high design velocity	slow flow or pooled reaches	flashy flows	limited backwater effects	silt or fine sand bed	high bedload transport
Brush Layering	◗	●	◗	●	●	●
Brush Mattresses	◗	●	◗	●	●	●
Fascines	◗	●	◗	●	●	●
Live Crib Walls	◗	❍	◗	●	●	◗
Live Stakes	◗	●	◗	●	●	●
Natural Fiber Rolls	❍	●	❍	●	●	●
Deflectors	●	◗	●	◗	❍	◗
Gabions	◗	●	◗	●	◗	●
Root Wads	◗	●	◗	◗	●	◗
Riprap, dumped	●	●	●	●	◗	●
Riprap, imbricated	●	●	●	●	◗	●
Boulder Placement	●	❍	◗	●	❍	◗
Log Weirs	●	❍	❍	◗	❍	❍
Stone Dikes	◗	◗	●	◗	◗	◗
Rock Vanes	●	◗	◗	●	❍	●
Log Vanes	●	◗	◗	●	◗	●
J-Hooks	●	◗	◗	◗	◗	◗
Vortex Rock Weirs	●	❍	◗	◗	❍	◗
"W" Rock Weirs	●	❍	●	◗	❍	●

Key:

● - the approach can be used effectively in (is well suited to) reaches with this constraint
◗ - with supporting measures, the approach is not severely limited by this constraint (use cautiously)
❍ - the approach should not be used in reaches with this constraint

Table 10-3 (continued).

RESTORATION/ STABILIZATION PRACTICE	FUNCTIONAL APPLICATIONS				
	bedrock	lateral channel adjustments	highly erodible banks	rigid/fixed banks	steep bank grade
Brush Layering	❍	◗	◗	◗	❍
Brush Mattresses	❍	◗	◗	◗	❍
Fascines	❍	◗	◗	◗	❍
Live Crib Walls	❍	●	◗	●	●
Live Stakes	❍	◗	◗	◗	❍
Natural Fiber Rolls	❍	◗	◗	◗	❍
Deflectors	◗	❍	❍	◗	●
Gabions	●	●	●	●	◗
Root Wads	❍	●	◗	◗	◗
Riprap, dumped	◗	●	●	●	❍
Riprap, imbricated	◗	●	●	●	●
Boulder Placement	❍	●	◗	●	●
Log Weirs	❍	◗	●	●	●
Stone Dikes	●	◗	◗	◗	●
Rock Vanes	❍	●	●	●	●
Log Vanes	❍	●	●	●	●
J-Hooks	❍	●	●	●	●
Vortex Rock Weirs	◗	●	◗	●	●
"W" Rock Weirs	❍	●	●	◗	●

Key:

● - the approach can be used effectively in and is well suited to reaches with this constraint
◗ - with supporting measures, the approach is not severely limited by this constraint
❍ - the approach should not be used in reaches with this constraint

Selection of grade control structures is closely linked to the equilibrium bed slope (see Section 8.3.2) bed particle size, the existing bed stability, and the severity of the system conditions. In addition, it is helpful to know the current stage of channel evolution (see Figure 9-7), and if degradation, aggradation or widening are taking place due to changes in sediment transport (see Figure 6-13).

10.2.2 Common Grade Control Practices

Weirs, drop structures, cross vanes, and check dams are typically used for grade control. On smaller rivers these practices essentially create step-pools, while on larger rivers they result in the creation of a local scour hole. In both cases, successful installation creates a vertical control that stops additional degradation of the bed. In addition to structural elements, channel shaping is used on occasion to adjust channel form to stabilize the river bed.

Grade control structures on smaller rivers can be made of logs or large boulders, while large boulders are almost exclusively used on larger rivers. Certain structures such as V- (medium-sized rivers) and W-weirs (large rivers) direct flow away from the banks as well. Check dams and step-pool creation are grade control practices that are typically more applicable for medium to small rivers.

Important design considerations for grade control structures include the bottom and top installation elevations of the practice (top at the outside of the channel at bankfull level and bottom around the middle of the channel near the channel invert), how the structure is tied into the bed and banks (tight fit, 20-30 degrees upstream), local hydraulics that will exist over a range of flows around the structure (scour pool and plunging flow), and the anticipated longevity of the installation. Where bed or banks are composed of erodable fine materials such as sands and silts, undermining and dislocation is possible. Be sure that the material under the river bed can support heavy materials, and machinery used to transport them into place, before beginning installation. Information on previous projects is a good source of information on what has and has not worked.

A common pitfall of grade control structures is creating fish blocks during low and moderate flows if structures are over-built. Careful attention to the material size and vertical location of installation relative to different flows can avoid this common habitat impairment. When unsure about the applicability or construction details of a practice, walk the river channel and try to observe and photograph natural features that the practice is trying to mimic. When doing so, keep in mind that some natural features can fragment aquatic habitat.

10.3 Bank Stabilization

10.3.1 Introduction

River banks become unstable and erode due to general bank scour, undercutting, or localized scour (GASWCC, 2000). General bank scour is the widespread erosion of streambanks caused by excessive mean water velocity impinging on the bank. Undercutting, or removal of the submerged low bank (i.e., the toe), is one of the most common modes of river bank failure. Some level of undercutting occurs on the outside of most meander bends, and when excessive usually leads to subsequent collapse of the mid and upper bank. A challenge when contemplating the extent of bank stabilization projects is separating out locations that are undergoing normal levels of scour for the system versus excessive undercutting erosion. Field observations are used to identify localized scour where only isolated sections of eroding banks occur in otherwise stable reaches. Common signs of excessive erosion include large bank areas that do not have vegetation and appear to be sliding or caving in, and slumping vegetation at the top of bank. Bank erosion can also originate from landslides adjacent to the river channel, or an avulsion where the river rapidly changes its flow path via erosion of a new channel.

Another important mode of river bank erosion in the northeast United States is destabilization due to annual or more frequent freeze-thaw cycles, and physical abrasion due to ice rafting during spring ice out (Watson et al., 1999). Ice often leads to increased flow depths, and excessive scour of the low bank in channels with deformable banks (Ettema, 2002). Designs must consider the range of forces acting on the bank due to winter ice, especially in locations such as large meanders, natural contractions, or bridge crossings where ice jams tend to occur. Ice can lead to substantial changes to a river channel, especially when there is a large flood while the river is still covered by ice. Large amounts of material can be removed from the banks, and channel depth and thalweg location often change. Whether the channel changes due to winter ice are temporary or permanent, a variation in the hydraulic forces acting on the low bank and channel bed take place and should be considered when selecting practices for naturalized channel design and bank stabilization projects.

There are many factors that influence bank erodability. The Bank Erodability Hazard Index (BEHI) (Rosgen and Silvey, 1996) ranks bank stability based on (1) the ratio of bank height to bankfull height, (2) the ratio of vegetative-rooting depth to bank height, (3) the density of roots, (4) the streambank angle and (5) the vegetative bank protection. Coupled with the bank particle size and cohesiveness, these factors, along with the localized hydrology around the bank (i.e., seeps, evapotranspiration, canopy interception) dictate the stability of a bank (Simon and Collison, 2002). The BEHI has been adapted for use in Vermont and this analysis is useful for assessing banks in New England (See Appendix N in VTANR, 2004).

Diverting the flow of water away from the river bank and improving bank resistance are the two objectives of most bank stabilization applications. There is a large existing database of practices that use both soft natural materials (i.e., bioengineering techniques) and hard non-degradable materials (i.e., traditional engineering techniques). Typically, a combination of soft and hard practices is used to divert flow and improve mechanical resistance to bank erosion. The main design task for bank stabilization is selection of the appropriate practice (Figure 10-1), and proper installation.

Beyond installation of bioengineering and traditional practices, bank shaping is needed for most structural applications, where horizontal to vertical slopes of 3:1 or shallower are

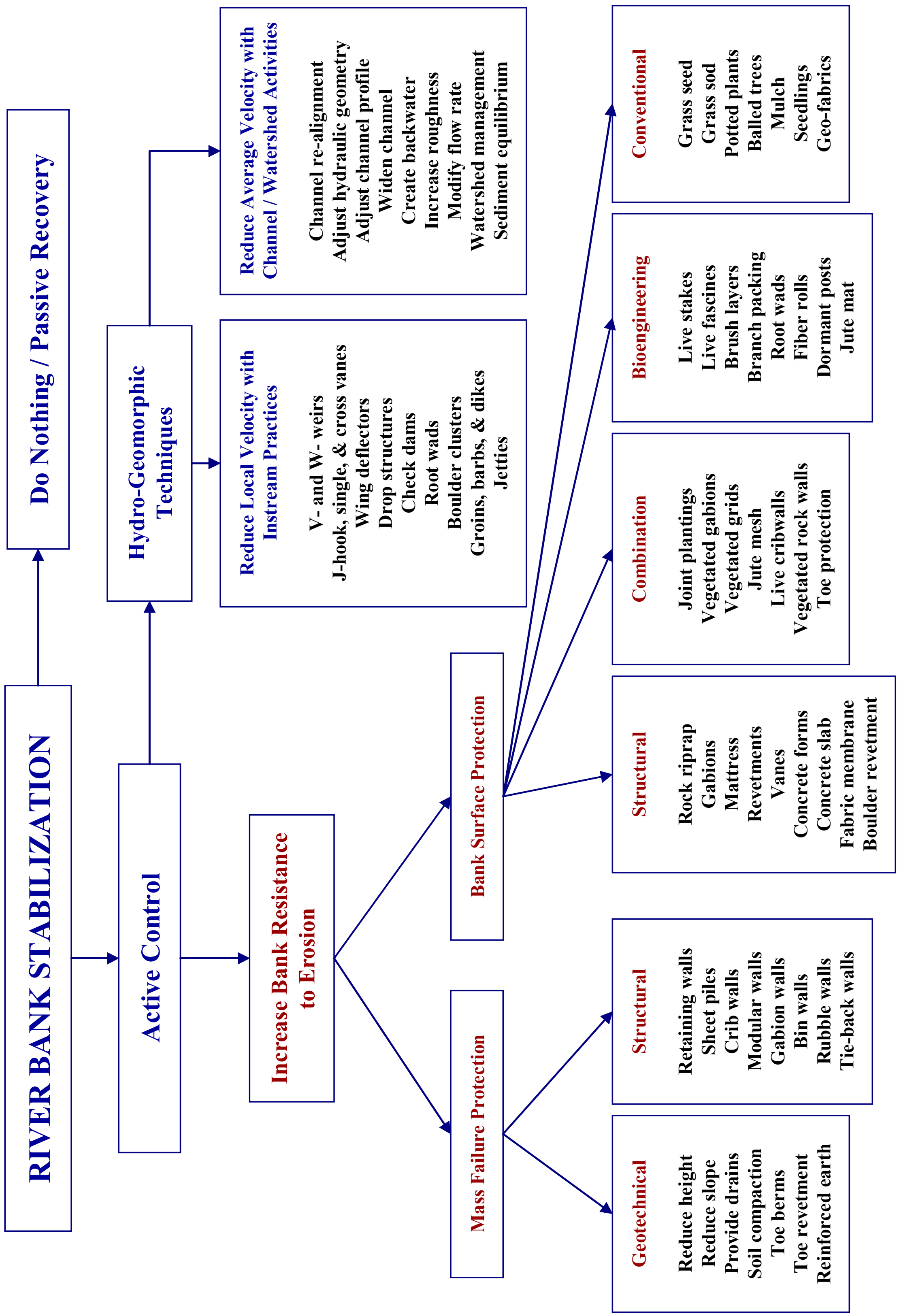


Figure 10-1: General procedure for selecting a type of bank stabilization practice.

preferable (GASWCC, 2000), with a 1:1 maximum bank slope particularly for more erodable soils. The bank angle is a function of the particle sizes and their cohesiveness (see Table 8-4).

General design considerations for bank stabilization projects have been laid out in existing manuals (LCSMC, 2002), and, as with grade control, each site is unique and thus selected practices are based on individual site conditions, constraints, and project objectives.

10.3.2 Soft (Bioengineering) Bank Stabilization Practices

River bank stabilization using natural vegetative materials such as coconut fiber rolls and live staking are desired for their habitat benefits over harder practices such as riprap (Fischenich, 2003). Habitat benefits of bioengineering that are not present with riprap include rehabilitation of bank and riparian vegetation, promotion of important habitat features such as undercut banks and low overhanging vegetation, and importation of detritus and large woody debris into the river channel (Schmetterling et al., 2001). The use of bioengineering practices for bank stabilization has become widespread. Several existing manuals (e.g., Eubanks and Meadows, 2002; LCSMC, 2002) solely address these natural material-based techniques, and manuals exist to guide re-vegetation techniques as well (e.g., Walter et al., 2005).

Lower material stability thresholds (see Table 9-2) (Fischenich, 2001), fragile post-construction periods until vegetation is established, and reduced life span in rivers prone to scour, are central challenges associated with bioengineering applications. Although bioengineering practices are preferable, lower stability thresholds often preclude application on the submerged low bank, and at times even the mid bank. The range and duration of submergence levels are important design considerations for bank stabilization projects when working on large rivers or water bodies with fluctuating flow levels. Cabling materials in place is possible, but a less desirable option that can result in dislocation of materials during large floods and leaving metal wires, rebar, and baskets in the river channel (see Flosi et al., 2002 for application notes). For high energy systems such as those with steep or moderate slopes that are channelized, mostly disconnected from their floodplains, or in active adjustment where natural materials would be dislodged from the lower bank, combination practices (e.g., Cramer et al., 2003) are recommended where the low bank is reinforced with a hard material while the middle and upper bank are stabilized using bioengineering practices. These combined approaches allow structural fixes that are more likely to achieve local channel stability, and include some of the habitat benefits of bioengineering techniques.

Due to the reliance on established vegetation to stabilize river banks, bioengineering applications are vulnerable to failure immediately following construction should a drought or large flood take place. For large scale bioengineering applications, resources should be set aside to water young plantings and to replace materials that die or are dislodged during flood events. Vegetated geogrids and jute mats (Eubanks and Meadows, 2002) help increase the durability of bioengineering projects immediately after installation. In addition, continued maintenance is needed to remove weeds of and deter competing plants until the plantings are large enough to survive. In addition, plantings must be protected from animal damage. Saplings should have metal or thick plastic guards on their base to ward off beaver, and herbaceous plantings may need to be fenced to keep deer, skunk, and other animals away.

The life span on bioengineering materials is typically much shorter than practices made from rock, unless full re-vegetation is accomplished before the bank can fail again. This implies that some level of passive recovery is expected once a bioengineering application is installed. Passive recovery can include the growth of roots in the bank, the capture and re-vegetation of fine sediments, and the migration of flow paths toward the center of the channel. In other words, bioengineering approaches function best when the primary stressor has been removed from the system and an assisted natural recovery is desired. Bioengineering approaches often fail when applied on a very small scale to patch the channel response to a remaining problem. In this case, funds are likely better spent to address the ultimate source of the problem.

10.3.3 Hard (Traditional) Bank Stabilization Practices

Traditional bank stabilization practices primarily composed of rock have been used extensively to manage rivers typically following floods and large erosion events, and in the vicinity of infrastructure. Riprap, angular rock, is the most common traditional practice used to stabilize a bank and limit lateral channel movement. Applications of riprap for bank stabilization typically include laying down a filter layer to contain the bank material and then placing the appropriate size stone on top for stabilization. Existing manuals and papers (e.g., NRCS, 1996; Fischenich, 2001, 2003) offer guidance on appropriate stone size for site conditions (see Table 9-2). Grading is often performed prior to riprap applications to reduce the angle of the bank relative to the water surface. Revetments made of shapes such as blocks and jacks that are cast from concrete function in the same way as riprap to increase the resistance to erosion on the river bank.

Riprap is well-known for both its utility where quick application is needed to stabilize a bank, and for impairing aquatic habitat once installed. There are several ways to improve the poor habitat value of a riprap application (Fischenich, 2003):

- Apply rock cautiously to maintain as many mature trees and shrubs as possible;
- Install joint plantings throughout the crevices of the riprap;
- Use few large boulders on the low bank to increase the size of interstitial spaces useful for fish cover;
- Add structure to the installation such as spur dikes (perpendicular to flow) and ridges (or groins) on the riprap; and
- Where appropriate, filling interstitial spaces with gravel to create salmonid spawning habitat.

Gabions, or rock filled baskets, are also used to increase bank strength where either a short section of bank is in need of stabilization or a stackable structural practice is desired. Important application details are similar to riprap, with the added concern of the longevity of the basket material. Gabion baskets are typically placed on the low and mid bank and thus the basket material can deteriorate due to submergence, at which point dislodged materials can lead to public safety hazards along the river's edge. Gabion applications typically include joint plantings.

Many traditional practices are extensions of riprap applications that also function to increase bank resistance. Large-boulder revetments placed on the bank are a current common hard practice used to stabilize a bank, where individual large boulders are spaced along an eroding bank with small gaps in between the adjacent boulder. The interstitial gaps are created primarily to provide pockets of refuge for juvenile fish.

Riprap and other hard practices that increase bank resistance often create erosion problems at nearby downstream locations. The reason for this problem is that practices that increase bank resistance essentially reflect the river's energy, or the force that causes erosion, downstream. For channels where the banks are more erodable than the bed, such as a riffle-pool river with sandy banks and a cobble bed, bank erosion often occurs immediately downstream of a riprap application, requiring another management action be taken. The pattern of riprap installation followed by additional downstream erosion followed by another riprap application often repeats itself many times and is called "chasing the river" (Figure 10-2). Increasing bank resistance in a river with a sandy or silty bed can lead to increased channel degradation as energy is reflected from the bank that can generate velocities to move the smaller bed particles. As the collective length of riprap increases on the banks of a river, more and more riprap is needed to "chase the river." The only way to break out of this costly

Figure 10-2: "Chasing the river" photograph where attempts to stop bank erosion with riprap lead to more erosion downstream on the Nooksack River, WA (Source: Field Geology Services).

management cycle is to begin to address the source of the problem and to take corrective actions to reduce the rivers energy such as re-connect floodplains and eliminating conflicts by giving the river the room to move.

Single rock vanes, J-hook vanes, and wing deflectors are practices that are typically used to deflect flow away from an eroding bank, create downstream scour holes for refuge, and diversify local hydraulics. Important application details include the rock size, proper elevation to set the structures (bankfull at the bank and at the channel invert 1/4 to 1/3 of the way across bankfull channel), angle relative to flow (20-30 degrees), and structure shape. A J-hook locates the scour pool towards the middle of the channel cross section while the scour pool associated with a single rock vane is closer to the bank.

Various types of wall/piling systems and slotted board fencing can be used to prevent lateral channel migration where space is limited for a sloping bank. These practices essentially eliminate the river bank and the connection between river and floodplain, and are only suggested as a last option when the source of the problem cannot be fixed and unavoidable conflicts must be resolved. An example of where a piling system may be recommended is when very tall (i.e., ~100 ft) sandy banks of large rivers erode and threaten nearby infrastructure that cannot be moved. It is difficult to re-direct the flow of a large river during flood events, so the project must primarily relay on increasing the resistance of the bank to erosion. Large slumping sandy banks lack stable surfaces to anchor materials or install plantings so pilings and walls can be used to create terraces on the low to mid bank, and then some plantings can be attempted on the mid to upper bank.

An important application consideration for all practices where large rock is being used is the ability of the river bed and banks to support heavy materials. If the potential exists for underlying silt and clay, such as those associated with post-glacial lacustrine deposits, some geotechnical testing may be required to confirm materials will not sink into the river bed. It is always preferable to construct projects from the river bank to avoid the many negative impacts of having construction equipment in the channel. If the only option is to construct a project from within the channel, geotechnical testing will also confirm if construction vehicles can safely enter the river channel.

10.4 Habitat Elements

10.4.1 Introduction

Localized habitat enhancement uses practices to expand existing aquatic habitat features that are deficient in the river channel. Habitat enhancement is most frequently used for improving fisheries. Installation of habitat features alone typically does not address the source of a problem, yet improves the current state of the rive channel as it responds to stressors. The introduction of habitat features is common in small and medium rivers, and existing manuals (e.g., Saldi-Caromile et al., 2004) can be used to guide feature selection and application.

10.4.2 Habitat Enhancement Practices

Large woody debris and debris jams are important habitat features that provide shelter and a food source for some aquatic organisms. In addition, coarse woody material is important to channel and bank stability. In small rivers, large trees can create step-pool networks that control grade and stabilize banks via adding roughness to the channel boundaries. Trees and jams contribute to grade control and bank stabilization in larger rivers as well. Installation of large woody debris and jams is useful when natural woody riparian vegetation is limited. The main challenge with the installation of large wood is preventing it from washing away during moderate and high flows. Materials are typically tied into the banks and/or cabled into the bed or banks. Keep in mind that the processing and downstream transfer of large wood is natural in a river channel, although not desired if there is a lack of wood input.

Individual and clusters of instream boulders are typical habitat features in many river channel types. The large rocks diversify local hydraulics and create holding locations for fish and insects. Large material, diameter of 2 to 5 feet (MDE, 2000), is recommended for boulder applications. Instream boulders are typically applied in conjunction with other practices. Other features that can be installed to enhance local habitat include lunker structures to mimic undercut banks, clean gravels for spawning, and side- and off-channel for refuge areas.

As with all other types of practices, installed habitat elements should be consistent with naturally occurring habitats in healthy portions of the project river, or healthy reference sites in nearby rivers in the watershed.

10.5 Vegetated Riparian Buffers

A wide naturally vegetated and undisturbed riparian buffer improves bank and channel stability, protects water quality, and supports a healthy aquatic ecosystems. Buffer protection and re-vegetation are typical components of moderate and comprehensive naturalized river channel design and bank stabilization projects. Riparian practices can be difficult to apply as river corridors often contain human infrastructure such as roadways, utilities, and structures. Inclusion of buffer practices to improve the amount and type of vegetation in conjunction with bank and channel work increases the chances of a successful project. The protection and re-introduction of buffer vegetation is an important practice to consider with every project or management activity.

Naturally vegetated buffers and extended floodplains reduce peak river flows by absorbing and slowing portions of incident stormwater runoff that must travel through hydraulically rough areas on the way to a river channel. The long, slow flow path common in vegetated buffers also allows for sediment, nutrient, and pollutant removal to safeguard water quality (Perry et al., 1999; Dabney et al., 2006). Bank stability generally increases with riparian vegetation due to hydrologic (i.e., interception and evapotranspiration) and mechanical (i.e., soil compression increases with root tensile strength) effects (Simon and Collison, 2002). A lack of a buffer can lead to bank erosion and even channel degradation. If excessive down-cutting takes place, the channel can no longer access its floodplain. At this point, all of the energy associated with runoff events is confined to the river channel, channel adjustment often intensifies, and the threat to human investments dramatically increases.

Naturally vegetated and undisturbed riparian buffers are important for aquatic habitat. Beyond the reduction of flood flows and the protection of water quality, buffers help maintain physical habitat (Wang et al., 1997; Sweeney et al., 2004). Large woody debris and coarse particulate organic matter are essential for many different aquatic organisms and are introduced to the channel from the buffer. In fact, large trees that fall into small, steep headwater channels are critical for setting up the step-pool patterns often present in this location. Direct associations have been shown between shredding macroinvertebrates and the riparian plant communities growing in their immediate upstream surroundings (Cummins et al., 1989). Fish also depend on vegetated buffers for cover, with the overhanging vegetation near the water surface and the overhead tree canopy providing shelter. Some of the insects that salmonids consume either live in or use buffer vegetation for part of their life cycle. Buffers thus also play an important role in the aquatic food chain in rivers.

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CHAPTER 11.0: IMPLEMENTATION

11.1 Introduction

The implementation process for naturalized channel design and bank stabilization varies for routine, moderate, and comprehensive projects. Implementation includes funding, regulatory permitting, and land rights, which are all essential for moving a project beyond design towards construction. These time-consuming tasks must be initiated at the very beginning of project planning to improve the chances of implementation as scheduled by the project team.

11.2 Regulatory Permits and Reviews

11.2.1 Introduction

Several state and federal agencies regulate activities that affect water resources in New Hampshire (Figure 11-1). The series of regulatory programs that expanded since the 1970s is intended to protect water resources including river channels, banks, wetlands, tidal waters, and adjacent lands. Permits specifically have thresholds of applicability that attempt to protect water quality, minimize erosion and sediment deposition, conserve fish and wildlife habitat, minimize flooding, protect endangered species, protect potable water supplies, and maintain instream flows.

The specific activities that are regulated vary from one agency to another, as does the permitting threshold that determines if an activity is either exempt or requires a permit. Regulated activities in rivers or wetlands include discharges, excavation, construction of culverts, bridges, dams or dikes, bank disturbance, dredging, and filling. Some activities on lands adjacent to surface waters are also regulated, such as earth moving, applying fertilizer, cutting vegetation, wells, and septic systems.

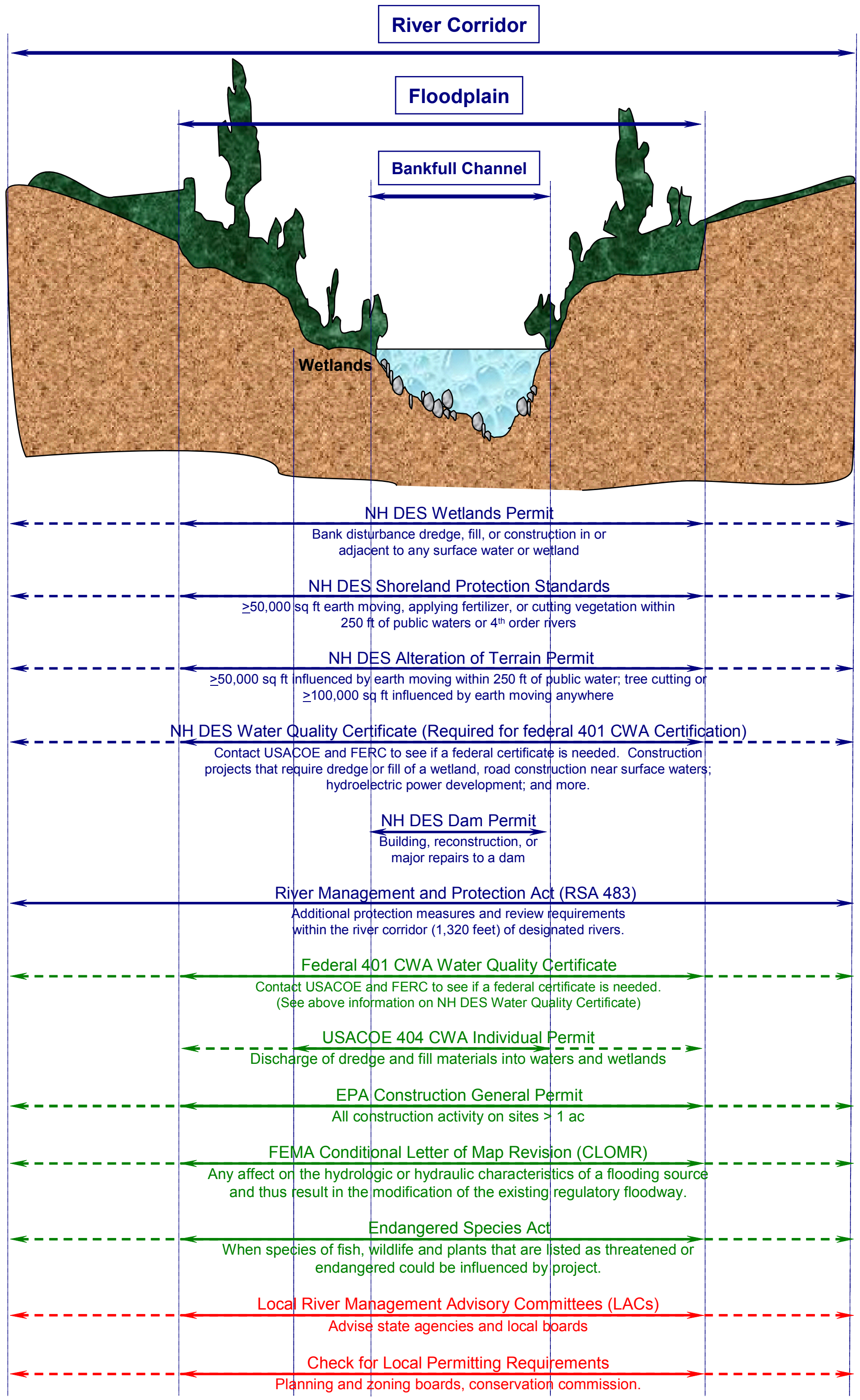

Figure 11-1: Common state (blue), federal (green), and local (red) permit requirements for naturalized channel design and bank stabilization projects in New Hampshire (After OMNR, 2001). Solid arrows indicate permits typically applicable in the location, while dashed lines represent locations where permits could be required. In New Hampshire, the river corridor is generally considered to be 1,320 feet wide, as defined for designated rivers in the Rivers Management and Protection Act (RSA 483).

The process of preparing, submitting, and processing regulatory permits can be very time consuming and expensive. It is a complex task because of overlapping jurisdictions, detailed application requirements, and limited agency staff to assist with the procedure. Although the regulatory process can be complicated, New Hampshire Department of Environmental Services (DES) staff is available to assist with the planning and permitting of complex naturalized channel design and bank river stabilization projects. Technical staff is actively involved in project planning around the state and participate in many professional committees and task force groups to stay current on natural channel design and bio-engineered bank stabilization techniques. Pre-application meetings with DES staff are welcomed and strongly encouraged. The general permitting process includes the following steps:

- Identify project goals and objectives;
- Identify proposed activities;
- Gather data, map wetlands;
- Evaluate alternatives;
- Define potential regulatory permits;
- Identify regulated activities;
- Conduct pre-application meeting;
- Assess methods to avoid regulated activities;
- Minimize resource impacts;
- Develop mitigation plan for unavoidable impacts;
- Prepare permit application package;
- Respond to review comments;
- Public notice;
- Public hearing (if needed); and
- Decision.

11.2.2 Pre-application Meetings

State and federal permits, and occasionally local permits, have specific criteria for regulatory eligibility, exclusions, and application data. Regulations and their criteria periodically change and need to be reviewed for each new project.

Applicants for proposed projects that affect New Hampshire wetlands, shorelands, floodplains, and public waters are advised to schedule a pre-application meeting with appropriate agencies. The purpose of this meeting is to explore current regulations, define the project goals and activities, assess the project's regulated activities, and confirm regulatory permit data needs. The meeting should identify potential regulatory issues and adverse impacts, alternatives that need to be evaluated, and mitigation. Many permitting data requirements are regularly collected as part of the design.

11.2.3 Federal Permit Summary

Federal legislation has created numerous regulatory programs concerning water resources, including "Waters of United States" that are required for projects in New Hampshire (see Figure 11-1). The main programs are authorized by the Clean Water Act (CWA) (1972) and subsequent US EPA (EPA) and US Army Corps of Engineers (USACOE) regulations. The CWA delegates permitting to the USACOE.

The main programs are authorized by the Clean Water Act (CWA) of 1972 and subsequent US Environmental Protection Agency (EPA) regulations, some of which delegate enforcement to the US Army Corps of Engineers (USACOE). The key federal regulatory programs include:

- CWA (Section 404, USACOE);
- CWA (Section 401, Water Quality Certifications, DES);
- Rivers and Harbors Act of 1899 (Section 10);
- National Environmental Policy Act (NEPA);

- Marine Protection, Research, and Sanctuaries Act (MPRSA) (Section 103);
- Endangered Species Act - US Fish and Wildlife Service (FWS), EPA, National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA);
- National Historic Preservation Act (Section 106);
- Federal Energy Regulatory Commission (FERC) Licenses;
- Federal Emergency Management Agency (FEMA), National Flood Insurance Program; and
- Wild and Scenic Rivers Act.

The Section 404 permit affects most projects and is a key to successful permitting. The program is administered by the USACOE, in cooperation with EPA, NMFS, FWS, and state agencies.

Three categories of regulated activities are defined by the New Hampshire Programmatic General Permit (PGP).

Minimum: Activities of minimal environmental impact that do not require USACOE regulatory review and are classified as non-reporting, yet projects must still comply with conditions contained in the PGP. In New Hampshire, a project is called minimum and does not require USACOE notification if less than 3,000 square feet of fill or dredge are taking place.

Minor: Activities likely to be of minimal environmental impact but that have the potential to have adverse effects. Project specific review and authorization from the USACOE in writing is required. All activities involving dams, dikes, water withdrawals and diversions are classified as minor. Minor projects apply to activities with more than 3,000 square feet of fill or dredge that affect less than three acres.

Major: Activities that have the potential to cause adverse environmental impacts or are too big for the minor category require project-specific review, are available for public review and comment, and may require preparation of an Environmental Impact Statement. Major permits are required for projects over three acres or when requested by the USACOE.

Permits typically stipulate seasonal limits of when regulated activities are allowed; usually July 1 to September 30th. The USACOE may confer with other federal agencies, including FWS, EPA, NOAA, NMFS, FERC, and the State Historic Preservation Officer.

11.2.4 New Hampshire Permits and Reviews

DES has several regulatory programs that apply to naturalized channel design and bank stabilization projects (see Figure 11-1). The *Guidebook for Environmental Permits in New Hampshire* is available on the Internet (http://www.des.state.nh.us/PermitGuide/) and contains useful information to get started with project permitting. Contact DES for permitting guidance on all projects.

New Hampshire permitting requirements for naturalized channel design and bank stabilization projects include:

- DES Wetlands Permit;
- DES Shoreland Protection Standards;
- DES Alteration of Terrain Permit;
- DES Water Quality Certificate;
- DES Dam Permit; and
- New Hampshire Rivers Management and Protection Act (RSA 483).

Most naturalized channel design and bank stabilization projects require a state wetlands permit because projects take place in or adjacent to any surface water or wetland. RSA 482-A authorizes DES to protect the state's wetlands and surface waters by requiring a permit for dredge or fill or construction of structures in wetlands or other waters of the state (http://www.gencourt.state.nh.us/rsa/html/NHTOC/NHTOC-L-482-A). The permit generally applies to any activities (e.g., bank stabilization, installation of structures in the channel, dredging, fill placement, and culvert installation) that take place below the natural mean high water level of any public waters. Useful information on wetland permitting can be found on the Internet site of the DES Wetlands Bureau (http://www.des.state.nh.us/wetlands/).

The state Comprehensive Shoreland Protection Act (CSPA) (RSA 483-B) (http://www.gencourt.state.nh.us/rsa/html/nhtoc/nhtoc-l-483-b) regulates activities in areas adjacent to river channels and wetlands. The CSPA applies to all land within 250' of waters listed in the *Official List of Public Waters* and fourth order and larger streams (except the Saco and Pemigewasset Rivers). Projects and activities located in the protected shoreland are subject to Minimum Shoreland Protection Standards as set forth in the CSPA. Regulated activities include earth moving or excavation of areas over 50,000 square feet, cutting vegetation, and certain building modifications. Useful information on the applicability of the minimum shoreland standards to a project can be found on the Internet (http://www.des.state.nh.us/cspa/).

An Alteration of Terrain (or Site Specific) Permit regulates construction, earth moving or other substantial alteration of the characteristics of the terrain when a contiguous area of 100,000 square feet or more will be disturbed. The jurisdictional area of disturbance is lowered to 50,000 square feet of earth moving when it is within 250 ft of public water, or the state shoreland. The permit is issued by the DES Water Division under the Water Pollution and Waste Disposal Act (RSA 485-A) (http://www.gencourt.state.nh.us/rsa/html/NHTOC/NHTOC-L-485-a). Useful information on the Alteration of Terrain Permit can be found on the Internet (http://www.des.state.nh.us/SiteSpecific/).

A Section 401 CWA Water Quality Certificate is needed from the state for any project where a federal permit is being sought to conduct any activity that may result in a discharge of material into navigable waters. The purpose of the state permit is to provide the federal permitting agency (i.e., USACOE and FERC) with a certification from the state agency where the discharge originates (i.e., DES) that the discharge will meet state surface water quality standards. The permit is issued by the DES Watershed Management Bureau under the Water Pollution and Waste Disposal Act (RSA 485-A) (http://www.gencourt.state.nh.us/rsa/html/NHTOC/NHTOC-L-485-a). Surface waters include, but are not limited to rivers, lakes, ponds, and wetlands. Useful information on the Section 401 Water Quality Certificate can be found on the Internet (http://www.des.state.nh.us/WMB/Section401/).

DES, through its Dam Bureau (http://www.des.state.nh.us/dam/), regulates the repair, reconstruction, maintenance, and operation of existing dams, and reviews design plans and issues decisions for the construction, operation, and maintenance of new dams. Any project involving a jurisdictional dam is regulated under the Dams, Mills, and Flowage Act (RSA 482) (http://www.gencourt.state.nh.us/rsa/html/NHTOC/NHTOC-L-482). Jurisdictional dams in New Hampshire are defined as any artificial barrier, including appurtenant works, which impounds or diverts water, and which has a height of 4 feet or more, or a storage capacity of 2 acre-feet or more, or is located at the outlet of a great pond. A roadway culvert shall not be considered a dam if its invert is at the natural bed of the water course, it has adequate discharge capacity, and it does not impound water under normal circumstances.

Though it is not an additional permit, designated rivers under the New Hampshire Rivers Management and Protection Act (RSA 483) require additional review and have some additional protection measures (http://www.gencourt.state.nh.us/rsa/html/NHTOC/NHTOC-L-483). A designated river is one that is "managed and protected for its outstanding natural and cultural resources (http://www.des.state.nh.us/rivers/desigriv/)" (Appendix G). Reviews are required for activities in the river corridor, which RSA 483 defines as "the land area located within a distance of 1,320 feet of the normal high water mark or to the landward extent of the 100 year floodplain as designated by the Federal Emergency Management Agency, whichever distance is larger." Useful information on RSA 483 can be found at the DES RMPP Internet site (http://www.des.state.nh.us/rivers).

RSA 483 also established local river management advisory committees (LACs), which are citizens appointed to help create river corridor management plans for designated rivers. LACs also participate in other activities to protect and improve the resource, such as the review of proposed projects on designated rivers. LACs report to state agencies and local boards.

Local conservation commissions and planning and zoning boards may also play a role in permit review. Based on the reports from LACs and their own project review, a decision is made on the level of support of the project. Local boards often request information on how the project will influence the local resource and area both during implementation and once complete.

11.3 Funding

11.3.1 Introduction

Financial assistance for naturalized channel design and bank stabilization projects is available from many government and private sources (Table 11-1). Routine projects are often funded by the affected property owner, particularly for bank stabilization and planting. Moderate and comprehensive projects encompass a larger geographical area often involving multiple land-owners, infrastructure elements, and reaches. As the level of complexity increases with project design and implementation, there is a parallel rise in project cost.

The majority of funding sources are typically awarded to state agencies, non-profit organizations, and municipalities. It is therefore advantageous for individual land-owners to bring potential naturalized river channel design and bank stabilization projects to the attention of local, regional, and state resource organizations and agencies when financial limitations are anticipated. The partnerships formed with local watershed associations, state agencies, municipalities, and other non-profit organizations generate diversified funding options, access to technical support, and eligibility to receive grant funding from various sources. In addition

Table 11-1: Common sources of funding for naturalized channel design and bank stabilization projects in New Hampshire.

Federal Agencies	State	Non-profit Organizations	Municipal	Private
EPA	DES – 319 Grants	Trout Unlimited	CIP	Land-owners
NOAA – Anadromous Fish Programs	NHDOT	The Nature Conservancy	Conservation Funds	Abutters
NOAA – Community Based Restoration	NH Fish & Game	American Rivers	DPW	Foundations
NRCS	State Conservation Committee	Watershed Organizations		Upper CT River MEF
FWS	NH Estuaries Program	Academic Institutions		NH CWRP
FS	NH Coastal Program	Ducks Unlimited		
DOT		GOM Habitat Restoration Program		
USACOE (large federal projects)				
Military Training (Army Reserve, Guard)				

Abbreviations: EPA = U.S. Environmental Protection Agency; NOAA = National Oceanic and Atmospheric Administration; NRCS = U.S. Natural Resources Conservation Service; FWS = U.S. Fish and Wildlife Service; FS = U.S. Forest Service; DOT = U.S. Department of Transportation; USACOE = U.S. Army Corps of Engineers; NHDOT = NH Department of Transportation; DES = NH Department of Environmental Services; GOM = Gulf of Maine; CIP = Conservation Improvement Program; DPW = Department of Public Works; MEF = Mitigation and Enhancement Fund; and CWRP = Corporate Wetland Restoration Partnership.

to the funding options that the partnerships create, the project goals can often fulfill elements within watershed management plans, corridor management plans, and other resource based conservation or restoration efforts thereby leveraging matching funds and project management support that would normally be unavailable to the individual land owner.

11.3.2 Fund Raising

Raising ample funds for moderate and comprehensive projects that require multiple funding sources and matching requirements can be a daunting task for the individual land-owner seeking to implement naturalized river channel design and bank stabilization. Forging partnerships with local watershed organizations, non-profit organizations, municipalities, and state agencies will provide the local support, technical assistance, and guidance required for securing the appropriate funding sources available for project implementation.

Funding applications require a clear connection between the project goals and those of the funding institutions. Financial grants are often conditional upon raising matching funds, and some project elements such as utilities and land rights may not be eligible for grants. The funding sources listed above (see Table 11-1) have varying grant cycles and requirements for applicants to fulfill. It is highly advisable to speak with representatives from potential funding sources prior to submitting a grant application to ensure project eligibility and to request guidance with the grant application process.

Competitive grant programs typically develop contracts and/or grant agreements between the grant provider and the project implementer. A project schedule is developed based upon tasks and deliverables with measures of environmental success integrated throughout the implementation phases of the project. Projects receiving funding must have a high probability of leading to successfully completed projects that meet the conservation or restoration goals established by the grant provider and the project implementer.

Grant applications generally require a preliminary study to define the project problem, goals, alternatives, and feasibility of implementation options. This initial document needs to identify project issues, project benefits, and potential adverse impacts. This information is readily available following project classification as routine, moderate or comprehensive, and following the initial assessment. Project cost estimates are required as part of the final grant application process. Receipt of financial grants requires that an efficient accounting system be in place, which is another reason for developing partnerships with watershed organizations, municipalities, and other non-profit organizations that routinely manage budgets and process invoices. Additional responsibilities that can be required as a grant recipient include competitive contractor selection via bids, preparation of environmental permits, and post-construction performance monitoring.

Construction projects can be expensive and involve unanticipated conditions, design changes, and weather-related delays and costs such as floods. Experienced project budget development and careful financial management is necessary to track expenses, matching sources (in-kind and cash), as well as maintaining a contingency or reserve fund whenever possible.

There are several naturalized channel design and bank stabilization projects in New Hampshire that originated with individual land-owner concerns that eventually matured into multi-source funded projects. The partnerships developed from these initial inquiries led to the acquisition of funding, professional design, construction supervision, and ultimately the implementation of successful projects that achieved self-sustaining stable channels that are preferred over the typical patch fixes often undertaken by individual land-owners on their own.

11.4 Land Rights and Access

Naturalized channel design and bank stabilization projects may involve both private and public properties, plus public waters of the state and navigable waters of United States. In all cases, access must be granted to the project site from the land owner. Gaining legal access may include temporary permission to work on property, temporary construction easements, permanent easements, and land acquisition. The right to inundate land may be required on projects that raise water levels or divert water to areas that would not normally be inundated. Naturalized channel design and bank stabilization projects that partially or fully drain impoundments need to research and address water use rights. All property and water rights need to be carefully documented, often requiring the services of a licensed land surveyor and a lawyer that specializes in property rights.

For routine or smaller moderate projects land access may be confirmed with a simple letter agreement that defines the area involved, allowable activities, project duration, completion dates, and proposed site conditions. Photograph the site just prior to initiating work to document the pre-project conditions for land-owners and abutters. For comprehensive projects, it is advisable to have formally surveyed easement maps and legal documents describing the terms of agreement for land access.

Access should include a route to reach the project site from a public road, storage areas for materials and equipment, clearing rights, grading rights, sanitary facilities, and electrical power lines as needed. Long-term considerations include project site ownership, public access after implementation, signage, fences, and maintenance.

11.5 Construction Phase

11.5.1 Introduction

Most naturalized channel design and bank stabilization projects require some kind of construction work along the bed, banks, or shoreline area of a watercourse or wetland. Even small construction projects can be surprisingly difficult when working with water in environmentally sensitive areas often prone to flooding and with complicated access.

Construction work may be performed by contractors hired by the project sponsor, by state or federal government agencies, or by the land-owner. The scope of work ranges from basic bank planting programs, to modest in-channel habitat improvements, to larger scale installations or channel relocation. Contractors may be engaged on a time and material, itemized bid, or lump sum fee basis depending on project size or sponsor requirements. Unlike routine "do-it-yourself" projects where basic sketches will do, contractors need detailed construction plans and specifications that usually exceed the level of detail used for permitting plans.

Typical construction issues include:

- Construction access;
- Construction staging areas;
- Construction sequence;
- Limits of site clearing;
- Seasonal construction limits and schedules;
- Construction stake out to mark disturbance limits, fill, and cut elevations;
- Storage areas;
- Utility maintenance and/or relocation;
- Review shop drawings and change orders;
- Water control such as coffer dams;
- Soil erosion control;
- Traffic control;
- Disposal sites;
- Site recovery and planting;
- Quality control on work being performed;
- Conformance with the approved plans;

- Conformance with the regulatory permits;
- Measurement of work and payment; and
- Progress reports.

11.5.2 Construction Administration

Construction administration tasks are related to engaging a contractor and serving as a coordinator between the contractor and project sponsor. Typical construction administration tasks include:

- Advertise for bids;
- Respond to bidder's questions;
- Pre-bid meetings;
- Review contractor bids;
- Review contractor qualifications;
- Help select successful bidder;
- Pre-construction meetings;
- Clarification of contract drawings;
- Review contractor submissions;
- Payment reviews;
- Review shop drawings, materials;
- As-built drawings;
- Progress meetings and reports; and
- Final punch list of outstanding work.

The construction administrator works in careful coordination with the on-site inspector for comprehensive projects, and may perform both functions for routine and moderate projects.

11.5.3 Construction Inspection

Construction work on naturalized channel design and bank stabilization projects should be inspected by an experienced person familiar with the design intent, goals, and contract documents. The inspector provides on-site guidance and quality control but does not guarantee contractor performance. The common tasks of the construction inspector include:

- Observe construction work;
- Record deviations from plans and specifications;
- Inspects materials;
- Records quantities of items and work performed;
- Prepares progress reports;
- Conduct final inspection and report on findings; and
- Consults with construction administrator.

CHAPTER 12.0: EVALUATION AND MANAGEMENT

12.1 Introduction

A project is not complete until some level of post-implementation evaluation is performed to determine the effectiveness, and if specific objectives and over-arching goals have been achieved. Evaluation also indicates if regularly scheduled operation and maintenance is sufficient. If the project is not performing as anticipated adaptive management, or adjustment of the project installation, may be needed.

The amount of recommended evaluation is a function of whether a project is routine, moderate or comprehensive, where monitoring needs are typically larger for more involved projects with biological and water quality improvement goals (Figure 12-1). Evaluation generally includes the assessment of physical channel (stability), biomonitoring, and measurement of basic and priority chemical parameters. Monitoring requirements can also be linked to permitting, especially for long-term monitoring for more complex projects, so the recommendations here must be considered along with required monitoring.

The minimal baseline assessment recommended for all projects includes:

1. Seasonal photo documentation for one year (see Appendix B), with record of extreme flow events to understand any channel adjustment that takes place;
2. Estimate of the physical stability of the channel, banks, and installed practices; and
3. Qualitative report on project outcome.

A single rapid field assessment is also recommended for routine projects. For routine projects with the main goal of increasing channel stability, measurements at monumented cross sections with a tape measure and surveying the channel slope with a hand level are recommended to see how the channel is moving locally. Routine projects with biological or

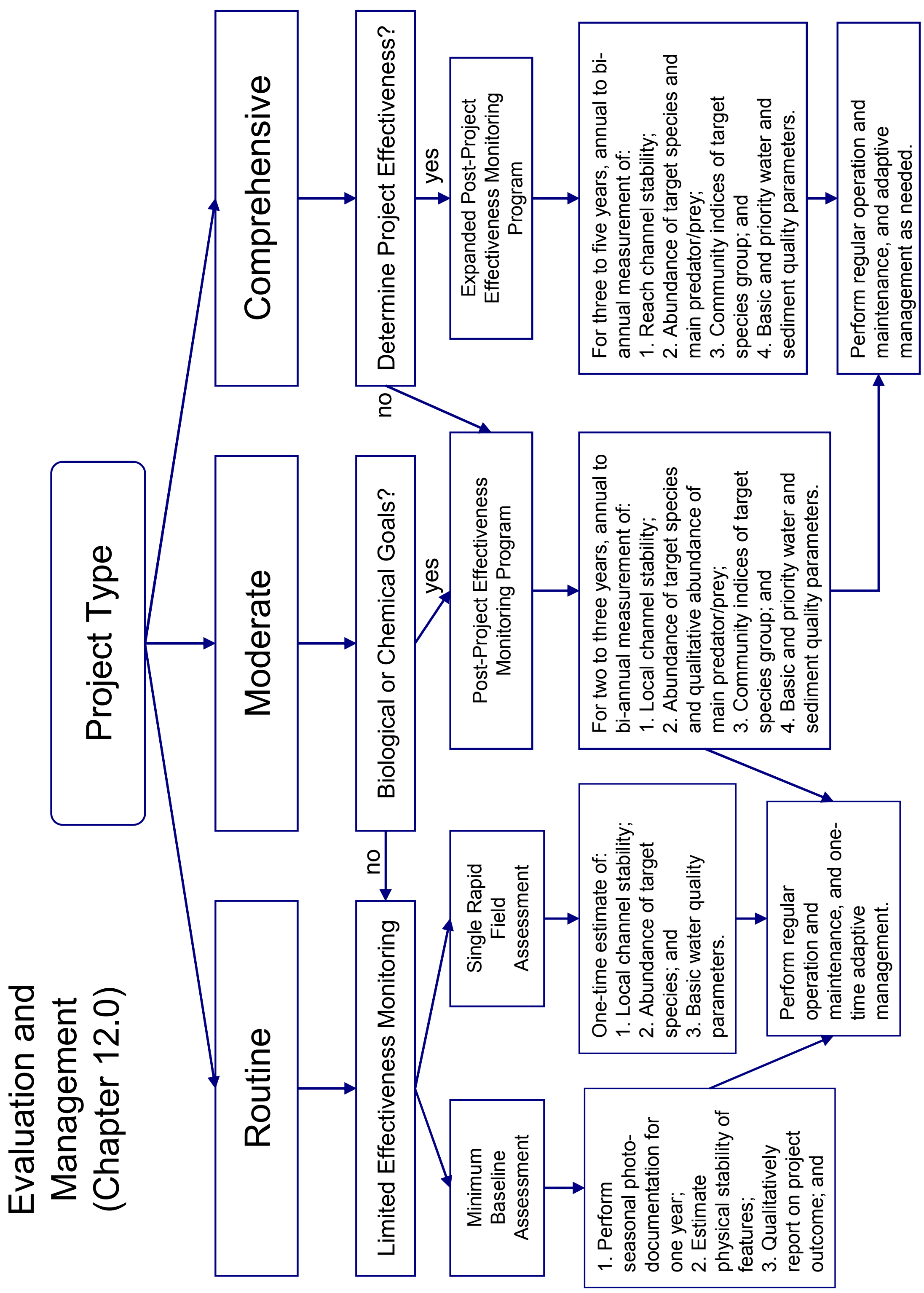

Figure 12-1: Recommendations for evaluation and management for routine, moderate, and comprehensive projects.

water quality goals would include a rapid field determination of population estimates and/or relative abundances of the target species, and measurement of basic water quality parameters. Repeated turbidity monitoring is recommended for any project where the channel or banks are disturbed, such as for channel re-alignment or bank shaping. The post-project evaluation is tailored to the project goals, and the level of effort is low for routine projects since funding for these projects is typically limited. This level of post-project evaluation is also recommended for moderate projects that do not have biological or chemical goals, although the assessment will likely take place at several cross sections since moderate projects are larger in scope.

For moderate projects that have biological or chemical goals, or for comprehensive projects that do not require the rigorous determination of project effectiveness, a post-project monitoring program is recommended to assess local channel stability, population estimates and/or relative abundances of the target species, a qualitative estimate of their main predator and prey, community indices for the target species group, and basic and priority chemical parameters.

Determining the effectiveness of comprehensive projects requires extended monitoring to track system recovery from the initial large disturbance following installation and observe if improvement takes place. Re-surveying the full project reach and other important nearby locations in the system, determining population estimates and/or relative abundances of the target species, identifying main predator/prey relationships, calculating biological indicator metrics in the get species group, and measuring basic and priority chemical parameters for at least three years is recommended. Although typically not practical based on project funding, monitoring for up to ten years increases the odds of determining project effectiveness so extend the duration of monitoring where possible. When considering long-term monitoring, be sure to see if a watershed organization or volunteer group already has a monitoring plan in place in the area so that existing data can be used and future data collections could already be planned.

Regular operation and maintenance is recommended, as needed, for all projects. Such activities include watering plantings, controlling competing vegetation, and cleaning out sediment basins. Ideally, projects should be designed to minimize the need for ongoing maintenance. Many projects will likely need some level of adaptive management, where a wide range of activities are performed to fine-tune or correct installations. Installing additional vegetation, re-connecting components to bed and banks, and spot fixing cross section and profile are all common types of adaptive management performed after implementation of naturalized river channel design and bank stabilization projects. Allocations should be made for a single management activity for routine and less-involved moderated projects, while additional resources should be set aside for more-involved moderate and comprehensive projects since adaptive management needs for these projects tend to be greater.

Should a project that is not accomplishing its anticipated goals and objectives not improve with adaptive management, or additional work is not possible, document the cause of failure to improve future methods. Projects can fail for a variety of reasons including natural events (e.g., a large storm immediately after construction) and human errors (e.g., under sizing the channel). The best way to avoid design problems that lead to project failure is to document the reasons for failure and avoid making the same mistake twice.

12.2 Project Evaluation Methods

12.2.1 Introduction

Project evaluation is important to determine the effectiveness of the current implementation and to improve methodologies for similar future projects, especially those on the same system and in the same region. Regularly allocating time and funds for post-project evaluation, and distributing and archiving evaluation findings, will fine-tune design and implementation methods and increase the rate of successful projects. Funds should be set aside at the beginning of the project based on the anticipated level of evaluation collectively desired by the project team. It is important to initiate a conversation about post-project evaluation with everyone involved in the project early in the planning phase to achieve consensus on the appropriate level of monitoring.

The general recommendations for post-project monitoring presented here (see Figure 12-1) may need to be expanded based on specific project objectives. For example, if the creation of pool habitat is an objective to meet the over-arching goal of improving fish habitat, then monitoring of the density and size of pools is performed in addition to determining channel stability and monitoring fish to determine population estimates and relative abundances. Likewise, if bank stabilization in the vicinity of a bridge is the main project goal then expanded observations of the structural stability of installed bank materials is required. As mentioned above, turbidity should be monitored in all projects where the channel and bank are disturbed and the potential for sediment deliver to the river exists. The project team should establish an evaluation plan during project planning that reflects the goals and objectives of the project, in addition to the general monitoring recommendations presented here.

When conducting post-project evaluations, collect data using methods that are similar to pre-project efforts to facilitate comparisons. Consider the location, timing, and techniques used for previous data collections.

12.2.2 Physical (Stability) Monitoring

Channel stability, particularly in the vicinity of existing human infrastructure, is a common goal of naturalized river channel design and bank stabilization projects, and thus the stability of channel bed, banks, and installed habitat features should be assessed during post-project evaluation. Photo documentation (see Appendix B) and a qualitative description of stability on a seasonal basis for one year are the minimal recommendations for routine projects and moderate projects that do not have biological or chemical goals. Photo documentation should take place during low flows so that more of the channel and bank features are visible. With the ease of photo documentation with a digital camera, it is recommended to extend this coarse level of monitoring whenever the project site is visited. Ideally, annual photos would be taken for five to ten years after construction. Document obvious erosion or deposition areas, any practice dislocation, and critical locations such as areas around infrastructure and points where practices tie into the banks. Identify the condition of the river banks while noting areas where stability is lower than expected and active erosion, sliding, and slumping are taking place. Brown (2000) offers guidance on the qualitative assessment of installed practices that includes recording:

- The length of channel influenced by the structure;
- The percent of the original practice remaining in place;
- The degree of unintended erosion and deposition;
- If the practice is serving its design purpose;
- If the practice improving habitat;
- If the practice is causing unintended harm to habitat;
- The percent of installed vegetative material that is living;
- If the soil in the vegetation area is eroded; and
- If the practice is collectively meeting its design objective.

Survey is recommended for all but the simplest projects and basic moderate projects to identify changes in channel cross section and profile. The recommended minimal assessment for routine projects is to re-visit one or two local monumented cross sections directly at or downstream of the project site to measure changes in cross section and profile using a surveyor's level and stadia rod. This basic level of survey can be performed in short periods of time with minimal equipment, and is useful for on-going monitoring of channel shape and slope.

The extent and frequency of the recommended survey is expanded for more involved moderate projects and for comprehensive projects. For moderate projects with biological and chemical goals and for comprehensive projects that do not require the determination of project effectiveness, bi-annual survey near the project site is recommended for two to three years. The site should be surveyed after a large flood, such as following the spring thaw or an intense rain storm, to determine if channel or bank adjustment occurred. This survey could be performed using a surveyor's level or a total station theodolite, depending on available equipment and if local cross sections were monumented.

When the effectiveness of comprehensive projects is to be determined, the entire project reach should be re-surveyed one to two times per year, for at least three years. This increased survey effort will allow for observation of system recovery following the disturbance associated with project implementation, and if the channel moves towards a more stable equilibrium. The expanded survey will also determine the necessary amount of adaptive management. The expanded survey associated with this most involved project type should be led by the licensed surveyors who did the original survey for the project design, or other surveyors with comparable experience. It is best to do one of the surveys following a large flood to track how the channel handles large disturbances.

Additional survey needs will be needed for moderate or comprehensive projects that attempt to rectify problems with specific components of the channel. For example, a project addressing conveyance issues at a bridge would include determining the local channel slope in the vicinity of the bridge opening. Instream habitat work over a large reach may include locating installed practices to observe if dislocation is occurring. Channel realignment projects would track the thalweg around a re-shaped meander bend to see if channel migration is taking place.

12.2.3 Biological Monitoring

The recommended biological assessment for routine projects is a one-time sampling effort to establish population estimates and/or relative abundances of the target species. This basic level of post-project biological evaluation is also appropriate for moderate projects that lack biological recovery goals. In this situation, estimate the influence on the species that the project is most likely to affect. Biological monitoring is absent or secondary for routine and moderate projects that prioritize channel stability and infrastructure protection rather than biological recovery, and the post-project evaluation would revert to the minimum baseline assessment (see Figure 12-1).

For moderate projects that have biological goals, or for comprehensive projects that do not require a rigorous determination of project effectiveness, increased biomonitoring is recommended. One to two collections of the target species for two to three years after implementation (for a total range of two to six collections), should allow for determining large biological change relative to pre-project collections. In addition to the target species, a qualitative population estimate and/or relative abundance of the main predator and primary prey of the target species should also be determined to understand how much ecological interactions are driving the recovery. Finally, community indices should be calculated for the group in which the target species belongs to.

For comprehensive projects where the determination of project effectiveness is required, biomonitoring is expanded further to increase the likelihood of seeing smaller changes in biological assemblages that are more common following projects. Sampling is recommended one to two times a year for three to five years (total of three to ten collections). Population estimates and/or relative abundances of both the target species and main predator and prey are determined along with community indices. Where possible, determine the dominant biological processes (e.g., photosynthesis/respiration, a predator/prey interaction, recruitment of large woody debris, or the break down of coarse organic material) taking place in the ecosystem.

The post-project biomonitoring recommendations should be expanded to match specific project objectives. For example, monitoring for projects focusing on establishing pools will concentrate observations in this habitat. Projects that include floodplain re-vegetation along with bank stabilization work will likely have a terrestrial monitoring component to track the success of vegetation in addition to assessing bank stability.

12.2.4 Chemical Monitoring

The recommended chemical assessment for routine projects is a one-time measurement of basic water quality parameters as performed before implementation. Similar to before the project, monitoring should be performed during the appropriate flow condition for the parameter of interest. If continuous monitoring data-loggers were used to track water quality before construction, re-deploy the data-loggers to observe changes in water quality. This basic level of post-project chemical evaluation is also appropriate for moderate projects that do not include water quality goals.

For moderate projects that attempt to improve water quality, increased chemical monitoring is recommended. Measurement of both basic and priority water quality parameters is recommended one or two times for two to three years after implementation (for a total range of two to six measurements). This monitoring should allow for determining large chemical changes relative to pre-project collections. Make collections at the same location, discharge, and time of year as was used for pre-project monitoring to simplify data comparison. If sediment quality is a habitat concern, sediment analysis should be added to the chemical monitoring program.

For comprehensive projects that include a goal of determining project effectiveness, the chemical monitoring is expanded to increase the likelihood of identifying smaller changes in water quality that are more likely following projects. Sampling is recommended one to two times a year for three to five years (total of three to ten collections). Collections should focus on the priority water and sediment quality parameters.

As with the biological monitoring program, the details of the chemical monitoring program are aligned with the project goals and objectives. For example, monitoring for projects focusing on improving water clarity via reducing bank erosion may include an expanded set of turbidity measurements.

12.2.5 Monitoring Downstream Effects

It is important to consider downstream effects when making substantial changes to a river at a given site or reach. This consideration is most applicable to moderate and comprehensive projects where local hydraulics, and thus sediment transport rates, is changed. When hydraulic modeling for project design indicates that a substantial change in sediment transport rate could take place following implementation of the preferred alternative, monitoring the downstream channel via cross section survey is recommended. Ultimately, the likely resting location of transported sediment needs to be determined, along with its impacts to channel stability, aquatic habitat, biological assemblages, and water quality at locations downstream of the project. This proactive approach to consider downstream effects whenever possible will avoid inadvertently creating future downstream problems that can turn into long-term costly management obligations.

12.3 Project Management

12.3.1 Introduction

A well-designed naturalized river channel and bank stabilization project should generally be self-sustaining over the anticipated range of flows, yet some level of project management is often required following implementation. Management activities can either be regular operation and maintenance or adaptive management. Operation and maintenance is normally expected actions that are recommended following project installation, such as management of vegetation in bioengineering practices. Adaptive management includes activities beyond design and regular implementation to improve and fine-tune the project. An example of adaptive management is the adjustment of the shape of select cross sections in a constructed channel after major adjustment following the first large flood at the project site. Allocation of time and funding for project management should take place at the beginning of the project, when the project team collectively anticipates activities that are likely (normal operation and maintenance) or could be needed in the near future (adaptive management).

12.3.2 Operation and Maintenance

Operation and maintenance are normally expected actions that are recommended following implementation. For example, operation and maintenance for many bioengineering practices includes protecting, watering, and weeding young plantings. Another common form of operation and maintenance is cleaning out sediment from various kinds of traps or structures. The potential operation and maintenance needs can be obtained from the design specifications for various applications that can be found in existing manuals.

Time and funding should be allocated for anticipated regular operation and maintenance. By considering early alternatives and the range of practices that could be used in potential designs, the project team can make an informed estimate of the resources to set aside for operation and maintenance.

12.3.3 Adaptive Management

Adaptive management (Holling, 1978; OMNR, 2001) includes activities that are additional to design, implementation, and normal operation and maintenance such as replacing displaced or trampled young plantings, re-connecting features to bed and banks following dislocation due to flooding, and generally improving initial installations. Good designs improve the chances of a self-sustaining system; however, the dynamic nature of a river and changing watershed and climatic conditions can lead to the need for adaptive management in order to meet project goals. Adaptive management can include many different types of activities, and flexibility is required to be able to effectively fine-tune installations making them more self-sustaining. The project team should discuss potential adaptive management needs at an early phase in planning and design.

Allocating resources for adaptive management can be a challenge since the exact activities that may need to be performed are typically unknown. Sometimes adaptive management can be planned, such as when funds are allocated to actively adjust channel cross sections after some time period of passive adjustment. But more typically, the need for adaptive management results from unplanned events such as extreme flows, die-back of vegetative materials, or unexpected channel migration. Resource expenditures for adaptive management generally follow whether a project is routine, moderate or comprehensive. Adaptive management needs for less-involved routine and moderate projects are typically smaller than those for more-involved moderate and comprehensive projects. In addition, the more basic projects often only require a single adaptive management effort, while complex projects that are typically larger in scope may require several intervention steps to help move the channel towards a stable equilibrium. Accordingly, funding reserved for adaptive management should increase from routine to moderate to comprehensive projects. By considering the range of potential adaptive management activities that could be needed in the future, the project team can estimate the amount of funding needed for this post-implementation task. A rough estimate of adaptive management funds is 10 percent of the project cost.

CHAPTER 13.0: RIVER CROSSINGS, DAMS, AND NATURAL FLOWS

13.1 Introduction

Improving river crossings (e.g., bridges and culverts), removing dams, and establishing natural instream flows are all common practices used to improve river channel stability and ecosystem health. Although beyond the scope of this guidelines document primarily addressing naturalized river channel design and bank stabilization, these topics are included here to briefly summarize recommended practices in the State of New Hampshire, and to direct the reader to existing guidance manuals for additional information for projects in the greater New England region.

13.2 River Crossings

At the time of writing this document, the New Hampshire Fish and Game Department and other partners were working on guidelines for river crossings such as bridges and culverts. The goal of the standards is to promote the design and construction of crossings that do not obstruct the movement of aquatic life indigenous to the water body or impact the natural fluvial geomorphology of the stream channel. Structures should mimic nature and be invisible to the river channel as much as possible (i.e., follow the concept of 'stream simulation'). Specific recommendations include:

- Avoid stream crossings whenever possible;
- Bridges are preferred over culverts;
- If a culvert, then minimum embedded depths are required;

- Requiring a crossing width that is larger than bankfull width unless the applicant can demonstrate that a narrower crossing will not impact aquatic animal passage as per Article 19a of the Department of the Army (US Army Corps of Engineers) State of New Hampshire Programmatic General Permit and is the least impacting alternative as per Env-Wt 302.03 of the New Hampshire Department of Environmental Services Administrative Rules;
- Natural stream materials within the crossing; and
- Minimum openness ratio (cross section divided by the crossing length).

In addition to the forthcoming New Hampshire document on river crossings, the Commonwealth of Massachusetts (MARSCP, 2006) and State of Maine (MEDOT, 2004) have existing manuals that are useful for projects in New England. The State of Vermont regularly performs assessment of bridge and culverts and their protocols are quite useful for projects throughout New England (See Appendix G in VTANR, 2004).

13.3 Dam Removal

"When the costs associated with a dam outweigh its benefits, removal may be a wise decision, one that can result in significant environmental, economic and social benefits (http://www.des.nh.gov/Dam/DamRemoval/)." Information on dam removal is available through the Department of Environmental Services (DES) Dam Removal and River Restoration Program, within the Dam Bureau of the Water Division. A New Hampshire dam removal guidelines document (NHDES, 2003) highlights a four-step process for dam removal to assist with the regulatory process of removing a dam. The steps include:

- Obtain the necessary information;
- Research, plan, and design project;
- Permit application package preparation; and
- Permit review and issuance.

Additional guidance documents, information on previous and current projects, and contact information for the River Restoration Coordinator is also available on the DES website listed above.

Other useful information on dam removal is available, such as the Dam Removal Tool Kit by American Rivers (http://www.americanrivers.org/) and the Clearinghouse for Dam Removal (http://lib.berkeley.edu/WRCA/damremoval/).

13.4 Natural Instream Flows

As mentioned in Chapter 7, protection and restoration of the Natural Flow Regime (Poff et al., 1997) is recommended to maintain the quantity of water and natural flow variability (Richter et al., 1996) that supports habitats for native species.

New Hampshire Flow Criteria – State surface water quality regulations (Chapter Env-Ws; RSA 485-A:8, VI) – are in place to help achieve natural flows.

- PART Env-Ws 1703.01 Water Use Classifications.
  - (c) All surface waters shall provide, wherever attainable, for the protection and propagation of fish, shellfish and wildlife, and for recreation in and on the surface waters.
  - (d) Unless the flows are caused by naturally occurring conditions, surface water quantity shall be maintained at levels adequate to protect existing and designated uses.

- PART Env-Ws 1705.02 Low Flow Conditions
  - (d) For rivers and streams, the consecutive lowest seven-day flow that occurs once every ten years (7Q10) shall be used to apply aquatic life criteria and human health criteria for non-carcinogens.

Instream Flow protection under RSA 483 (http://www.des.state.nh.us/rivers/instream/) supports instream public uses including the flow-dependent components of navigation, recreation, fishing, conservation, maintenance and enhancement of aquatic life, fish and wildlife habitat, protection of water quality and public health, pollution abatement, aesthetic beauty, public water supply, and hydropower production. The current instream flow protection pilot program (Env-Ws 1900) is in effect for each designated river segment on the Lamprey River and the Souhegan River in order to maintain water for instream public uses and to protect the resources for which the river or river segment is designated. The rules indicate that a designated river is out of compliance with the general standard if:

1. The average monthly aggregate water use exceeds 5 percent of 7Q10 when average monthly stream flow is less than or equal to 0.5 cfsm;
2. The average monthly aggregate water use exceeds 0.02 cfsm when average monthly stream flow is greater than 0.5 cfsm and less than or equal to 1.0 cfsm;
3. The average monthly aggregate water use exceeds 0.04 cfsm when average monthly stream flow is greater than 1.0 cfsm and less than or equal to 4 cfsm; or
4. The average monthly aggregate water use exceeds 0.16 cfsm when average monthly stream flow is greater than 4 cfsm.

The over-arching goal is to return a natural regime to rivers to support native species and ecosystem services.

APPENDIX A: CHECKLISTS OF COMMON STEPS PERFORMED DURING NATURALIZED CHANNEL DESIGN AND BANK STABILIZATION PROJECTS

The guidelines provide detailed protocols for naturalized channel design and bank stabilization projects of various scales and complexity. To view the steps that are typically needed for these and related projects, the reader can refer to the following main checklist. Although each project is truly unique and requires specific design methods, an effort is made to illustrate the most frequently used design tools. In addition, the supplemental checklist contains other considerations that projects may require beyond the usual design sequence. In summary, the following checklists help identify main tasks following the procedure described in the guidelines document, plus supplemental tasks that may be needed.

MAIN CHECKLIST

Task	Channel Design	Bank Stabilization	Culvert	Bridge	Dam Removal	Instream Flows
Initial project work						
Project classification as routine, moderate, or comprehensive (Chapter 2.0)	☑	☑	☑	☑	☑	☑
Initial Assessment and project planning (Chapter 3.0)	☑	☑	☑	☑	☑	☑
Pre-project biological monitoring (Chapter 4.0)	Where applicable to project goals and objectives.					
Pre-project chemical monitoring (Chapter 5.0)	Where applicable to project goals and objectives.					
Identify natural stressors (Chapter 6.0)	☑	☑	☑	☑	☑	☑
Identify human-caused stressors (Chapter 6.0)	☑	☑	☑	☑	☑	☑
Hydrology (Chapter 7.0)						
Establish multiple design flows	☑	☑	☑	☑	☑	☑
Instantaneous flow measurements	R,M	M			☑	☑
Continuous flow measurements	M,C	C			☑	☑
Estimate bankfull flow with hydraulic geometry relationship	☑	☑	☑	☑	☑	☑
Estimate flows with National Flood Frequency Model	☑	☑	☑	☑	☑	☑
Estimate flows with regional approximations	☑	☑	☑	☑	☑	☑
Perform gage analysis	☑	☑	☑	☑	C	☑
Perform watershed hydrology model	C	C	M,C	M,C	C	C
Channel measurements and survey (Chapter 8.0)						
Site measurements	☑	☑	☑	☑	☑	
Site survey	M,C	C	C	C	☑	C
Geomorphic assessment	☑	☑	☑	☑	☑	C
Extended topographic survey	C		M,C	M,C	☑	
Geometric Design (Chapter 8.0)						
Design channel slope and pattern	☑	M,C	M,C	M,C	☑	☑
Design channel sinuosity	☑	☑	☑	☑	☑	
Design channel cross section	☑	☑	☑	☑	☑	M,C
Design channel profile	M,C	M,C	☑	☑	☑	M,C
Design channel banks	M,C	☑	M,C	M,C	☑	
Design channel flow capacity	M,C	M,C	M,C	M,C	☑	
Floodplain creation	Where applicable.		Where applicable.			
Ecological considerations	☑	☑	☑	☑	☑	☑
Empirical design tools (Chapter 9.0)						
Hydraulic Geometry Curves	☑	M,C	M,C	☑	☑	
Regime Equations	☑	M,C	M,C	☑	☑	
Analog design tools (Chapter 9.0)						
Reference reach approach	M,C	M,C	M,C	M,C	C	
Analytical design tools (Chapter 9.0)						
Basic hydraulics	☑	☑	☑	☑	☑	☑
Hydraulic modeling	M,C	C	M,C	☑	☑	
Channel stability and sediment transport	M,C		☑	☑	☑	
					M,C	
Channel and bank practices (Chapter 10.0)						
Grade control practices	M,C		M,C	☑	☑	
Bank stabilization practices	M,C	☑	M,C	☑	☑	
Habitat elements	☑	☑	☑	☑	☑	
Implementation (Chapter 11.0)						
Regulatory permits and reviews	☑	☑	☑	☑	☑	
Funding	☑	☑	☑	☑	☑	
Land rights and access	☑	☑	☑	☑	☑	
Construction	☑	☑	☑	☑	☑	
Evaluation and management (Chapter 12.0)						
Physical stability monitoring	☑	☑	☑	☑	☑	
Biological monitoring	Where applicable.		Where applicable.		☑	☑
Chemical monitoring	Where applicable.		Where applicable.		☑	M,C
Downstream effects	☑	☑	☑	☑	☑	C
Operation and maintenance	☑	☑	M,C	☑	☑	☑
Adaptive management	Where applicable.		Where applicable.		Where applicable.	

☑ = Applicable to all project types; R = applicable to routine projects; M = applicable to moderate projects; and C = applicable to comprehensive projects.

SUPPLEMENTAL CHECKLIST

Task	Channel Design	Bank Stabilization	Culvert	Bridge	Dam Removal	Instream Flows
Hydrology						
hazard analysis	M, C	M, C	☑	☑	☑	☑
design criteria	☑	☑	☑	☑		☑
fish passage criteria	☑	☑	☑		☑	☑
hydrograph routing	M, C	M, C			☑	☑
instream flow rates	M, C	M, C			☑	☑
Hydraulics						
allowable headwater	M, C		☑	☑		
tailwater rating curve	M, C		☑	☑	☑	
energy dissipater			☑			
stormwater treatment			☑	☑		
water profiles	M, C	M, C	☑	☑	☑	☑
Geomorphology						
sediment gradation	M, C	M, C	☑	☑	☑	
sediment probes					☑	
sediment quality tests					☑	
scour study	M, C	M, C	☑	☑	☑	
scour counter measures	M, C	M, C	☑	☑	☑	
channel bed profile	☑	☑	☑	☑	☑	
alignment stability	☑	☑	☑	☑	☑	
headcut potential	☑	☑		☑	☑	C
sediment transport	M, C			☑	☑	C
Design						
structure type study			☑	☑		
soil borings and STP tests				☑		
foundation design				☑		
bridge and dam inspection			☑	☑	☑	
utility maintenance			☑	☑	☑	
traffic maintenance			☑	☑		
headwalls, endwalls			☑	☑		
structural stability	☑	☑		☑		
ground water analysis						C
Other						
historic and archeological study	☑	☑			☑	☑
operation and maintenance	☑	☑		☑		
planting plan	☑	☑			☑	

☑ = Applicable to all project types; R = applicable to routine projects; M = applicable to moderate projects; and C = applicable to comprehensive projects.

APPENDIX B: NEW HAMPSHIRE PHOTO DOCUMENTATION PROCEDURE

Photo Documentation Procedure for

Measuring the Success of Restoration Projects and Best Management Practices

Adapted from: Products of the 2000-2001 Technical Advisory Council on Citizen Monitoring, California Association of Resource Conservation Districts, working under 319(h) contract to the State Water Resources Control Board (contract No. 8-099-250-0)

Adapted by: Stephen Landry

Introduction:

Photographs provide a qualitative, and potentially semi-quantitative, record of conditions in a watershed or on a water body. Photographs can be used to document general conditions on a reach of a stream during a stream walk, pollution events or other impacts, assess resource conditions over time, or can be used to document temporal progress for restoration efforts or other projects designed to benefit water quality. Photographic technology is available to anyone and it does not require a large degree of training or expensive equipment. Photos can be used in reports, presentations, or uploaded onto a computer website or GIS program. This approach is useful in providing a visual portrait of water resources to those who may never have the opportunity to actually visit a monitoring site.

Equipment:

Use the same camera to the extent possible for each photo throughout the duration of the project. Either 35 mm color or digital color cameras are recommended, accompanied by a telephoto lens. If you must change cameras during the program, replace the original camera with a similar one comparable in terms of media (digital vs. 35 mm) and other characteristics. A complete equipment list is suggested as follows:

Required:
- Camera
- Folder with copies of previous photos (do not carry original photos in the field)
- Topographic and/or road map
- Compass
- Timepiece
- Extra film or digital disk capacity (whichever is applicable)
- Extra batteries for camera (if applicable)
- Photo-log data sheets or, alternatively, a bound notebook dedicated to the project
- Dry-erase board, and markers (bring extra markers)

Optional:
- GPS unit
- Ruler (for scale on close up views of streams and vegetation)
- Wooden stakes and flags or re-bar and flags for dedicating fixed photo points in the absence of available fixed landmarks

Roles and Duties of Team:

The team should be comprised of two people, for restoration or other water quality improvement projects, as follows:

1. Primary Photographer responsible for selecting photo angles, targets and GPS operation.
2. One person responsible for taking field notes, recording photos and preparing dry erase board.

Safety Concerns:

Persons involved in photo monitoring should **ALWAYS** put safety first. For safety reasons, always have at least two volunteers for the survey. Make sure that the area(s) you are surveying either are accessible to the public or that you have obtained permission from the landowner prior to the survey.

Some safety concerns that may be encountered during the survey include, but are not limited to:

- Inclement weather
- Flood conditions, fast flowing water, or very cold water
- Poisonous plants (e.g.: poison ivy)
- Dangerous insects and animals (e.g.: bees, ticks, livestock, etc.)
- Harmful or hazardous trash (e.g.: broken glass, hypodermic needles, human feces)

We recommend that the volunteer coordinator or restoration coordinator discuss the potential hazards with all volunteers prior to any fieldwork.

General Instructions:

From the inception of any photo documentation project until it is completed, always take each photo from the same position (photo point), and at the same bearing and vertical angle at that photo point. Photo point positions should be thoroughly documented, including photographs taken of the photo point. Refer to copies of previous photos when arriving at the photo point. Try to maintain a level (horizontal) camera view unless the terrain is sloped. When photo points are first being selected, consider the type of project (salt marsh, wetland, or stream restoration, ambient or event monitoring, etc.) and refer to the guidance listed on *Suggestions for Photo Points*.

When taking photographs, try to include landscape features that are unlikely to change over several years (buildings, other structures, and landscape features such as peaks, rock outcrops, large trees, etc.) so that repeat photos will be easy to position. Lighting is, of course, a key ingredient so give consideration to the angle of light, cloud cover, background, shadows, and contrasts. Close view photographs taken from the north (i.e., facing south) will minimize shadows. Medium and long view photos are best shot with the sun at the photographer's back. Some artistic expression is encouraged as some photos may be used on websites and in slide shows (early morning and late evening shots may be useful for this purpose). Seasonal changes can be used to advantage as foliage, stream flow, cloud cover, and site access fluctuate. It is often important to include a ruler, person, farm animal, or automobile in photos to convey the scale of the image. Of particular concern is the angle from which the photo is taken. Oftentimes an overhead or elevated shot from a bridge, peak, etc. will be instrumental in conveying the full dimensions of the project. Of most importance overall, however, is being aware of the goal(s) of the project and capturing images that clearly demonstrate progress towards achieving those goal(s). Again, reference to *Suggestions for Photo Points,* may be helpful.

If possible, try to include a dry-erase board in the view, marked at a minimum with the location, subject, time and date of the photograph. Use large font and position the dry-erase board in the lower corner of each photograph. The dry erase board should be positioned at a distance from the photographer that does not obscure the subject matter of the photo point but allows for the text to be legible. If using a digital camera (recommended), experiment on the first photo point to determine the optimum combination of font size, distance to photographer and position of dry erase board in the photo. Use of the flash is *not recommended* with the dry erase board as it tends to reflect off the surface obscuring the text. A blank photo sign form is included in this document. Copies of this sign form can be used in the photos if a dry-erase board is not available. Copying this form onto yellow sheets for field use provides the necessary contrast for the text to be visible in the photographs.

Recording Information:

Use a systematic method of recording information about each project, photo point, and photo. The following information should be entered on the photo-log forms (blank form included in this document) or in a dedicated notebook:

- Project or group name, and contract number (if applicable, e.g., for funded restoration projects)
- General location (stream, beach, city, etc.), and short narrative description of project's habitat type, goals, etc.
- Photographer and other team members
- Photo number
- Date
- Time (for each photograph)
- Photo point information, including:
    - Name or other unique identifier (abbreviated name and/or ID number)
    - Narrative description of location including proximity to and direction from notable landscape features like roads, fence lines, creeks, rock outcrops, large trees, buildings, previous photo points, etc. – sufficient for future photographers who have never visited the project to locate the photo point
    - Latitude, longitude, and altitude from map or GPS unit
- Magnetic compass bearing from the photo point to the subject
- Specific information about the subject of the photo
- Optional additional information: a true compass bearing (corrected for declination) from photo point to subject, time of sunrise and sunset (check newspaper or almanac), and cloud cover.

When monitoring the implementation of restoration, or Best Management Practices (BMP) projects, include or attach to the photo-log a narrative description of observable progress in achieving the goals of the project. Provide supplementary information along with the photo, such as noticeable changes in habitat, wildlife, and water quality and quantity. Archive all photos, along with the associated photo-log information, in a protected environment.

The Photo Point: Establishing Position of Photographer:

1. Bring a variety of methods for establishing position: maps, aerial photos, GPS, permanent markers and landmarks, etc. If the primary method fails (e.g., an inoperative GPS or lost marker post) have an alternate method available.

2. Select an existing structure or landmark (mailbox, telephone pole, benchmark, large rock, etc.), identify its latitude and longitude, and choose (and record for future use) the permanent position of the photographer relative to that landmark. If no such permanent landmark is convenient for establishing the photo point, the installation of grade stakes or rebar with flagging (with station ID on flagging) is recommended.

3. For restoration, and BMP projects, photograph the photo-points and carry copies of those photographs on subsequent field visits.

Determining the Compass Bearing:

1. Select and record the true compass bearing of the photo center view. Include a prominent landmark in a set position within the view. If possible, have an assistant stand at a fixed distance from both the photographer and the center of the view, holding the dry-erase board for scale.

2. When performing ambient or event photo monitoring, and when a compass is not available, then refer to a map and record the approximate bearing as north, south, east or west.

Suggestions for Photo Points:

1. When first beginning a monitoring program take representative long and/or medium view photos of stream reaches, segments of shoreline or other areas being monitored. Show the positions of these photos on a map or site sketch. Subjects to be photographed include a representative view of the stream or shore condition at the beginning and ending positions of the segment being monitored, storm drain outfalls, confluence of tributaries, structures (e.g., bridges, dams, culverts, etc.).

2. If possible, take a close view photograph of the substrate (streambed), algae, or submerged aquatic vegetation.

3. Take long view and medium view of streambed changes (thalweg, gravel, meanders, etc.)

4. Time series: Take photos immediately before and after construction, planting, or vegetation removal. Take medium and close views of structures, plantings, etc. Long term monitoring should allow for at least annual photography.

5. Event monitoring: this refers to any unusual or sporadic conditions encountered during a stream or shore walk, such as trash dumps, turbidity events, oil spills, etc. Photograph and record information on your photo-log. Report pollution events to the NH Department of Environmental Services (603-271-3503).

6. Optional: Use a tape set perpendicular across the stream channel at fixed points and include this tape in your photos. The tape will show the current depth of the stream relative to the tape.

PHOTO LOG FORM

Project: **Photographer:**

Location: **Team members:**

Date:

Photo# Time & Location	Photo PointID Bearing to Subject	Photo Point GPS Reading Subject Description	Photo Pt. Description

General Notes or Comments (weather, rainfall data, cloud cover, time of sunrise and sunset, other pertinent information):

PHOTO SIGN FORM: Print this form on yellow paper if a Dry-erase board is not available. Complete the following information in black marker for each photograph. Include in the photographic view so that it will be legible in the finished photo.

Location:

Subject Description:

Date:

Time:

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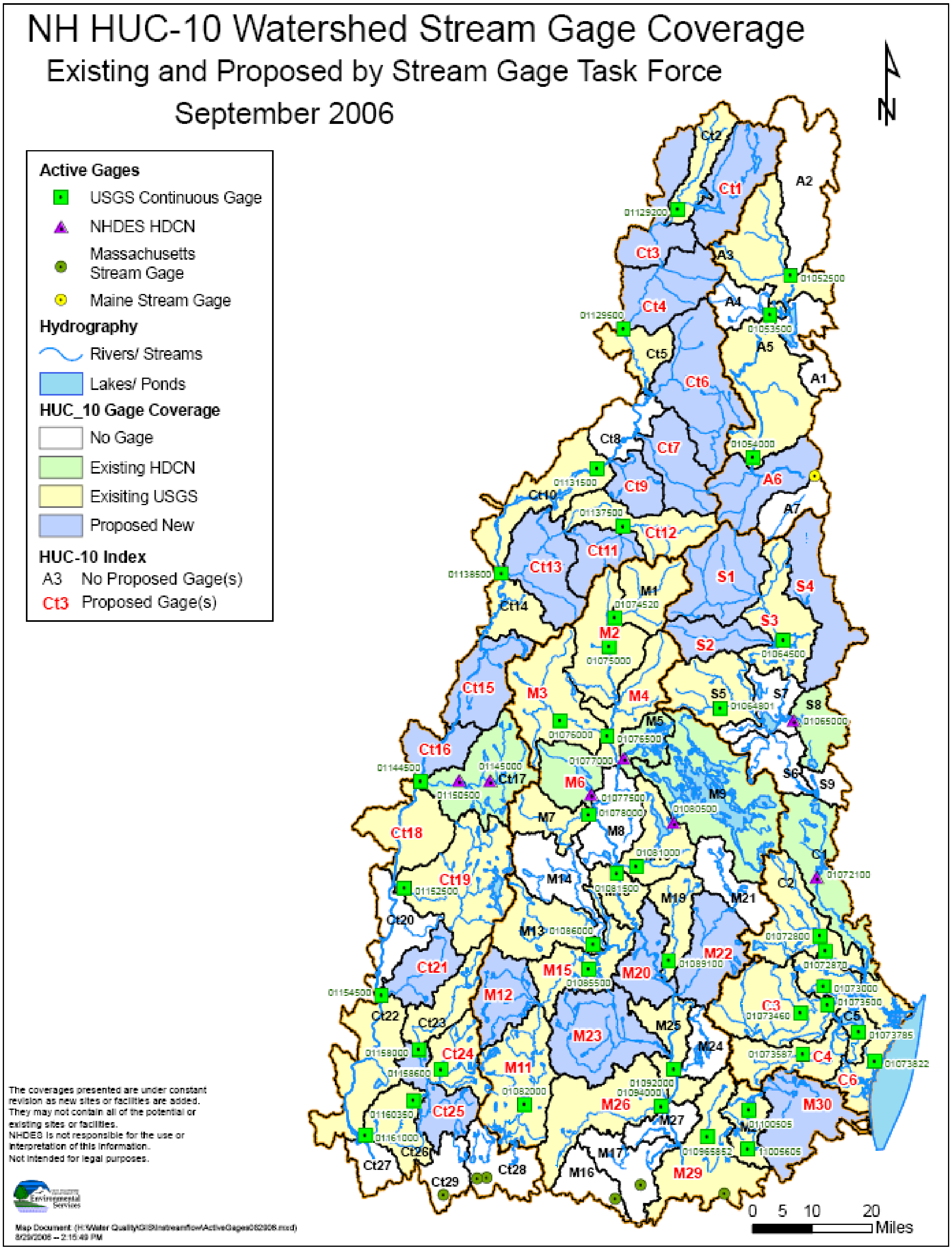
APPENDIX C: NEW HAMPSHIRE GAGE NETWORK AND HUC-10 CODES

USGS Stream Gages in the NH Network (9/15/06)

(Source: NHSGTF, 2006)

Gage Status	HUC-10 Index (6)	USGS or NHDES Gage Station number	Existing gage names
Continuous (1)	A3	1052500	DIAMOND RIVER NEAR WENTWORTH LOCATION, NH
Continuous	A5	1053500	ANDROSCOGGIN RIVER AT ERROL, NH
Continuous	A5	1054000	ANDROSCOGGIN RIVER NEAR GORHAM, NH
HDCN (2)	C1	SFMNH	MILTON 3-PONDS (Formerly 01072100 SALMON FALLS RIVER AT MILTON, NH)
Continuous	C2	1072800	COCHECO RIVER NEAR ROCHESTER, NH.
Closing - Continuous(3)	C2	1072870	ISINGLASS R AT ROCHESTER NECK RD, NR DOVER, NH
Closing - Continuous	C3	1073460	NORTH RIVER ABOVE NH 125, NEAR LEE, NH
Continuous	C3	1073500	LAMPREY RIVER NEAR NEWMARKET, NH
Continuous	C4	1073587	EXETER RIVER AT HAIGH ROAD, NEAR BRENTWOOD, NH
Continuous	C5	1073000	OYSTER RIVER NEAR DURHAM, NH
Closing - Continuous	C5	1073785	WINNICUT RIVER AT GREENLAND, NR PORTSMOUTH, NH
Closing - Continuous	C6	1073822	LITTLE RIVER AT WOODLAND ROAD, NEAR HAMPTON, NH
Continuous	Ct10	1131500	CONNECTICUT RIVER NEAR DALTON, NH
Continuous	Ct12	1137500	AMMONOOSUC RIVER AT BETHLEHEM JUNCTION, NH
Continuous	Ct14	1138500	CONNECTICUT RIVER AT WELLS RIVER, VT
HDCN	Ct17	MCAN3	MASCOMA LAKE (Formerly 01150500 MASCOMA RIVER AT MASCOMA, NH)
HDCN	Ct17	WCNN3	MASCOMA RIVER (Formerly 01145000 MASCOMA RIVER AT WEST CANAAN, NH)
Continuous	Ct18	1144500	CONNECTICUT RIVER AT WEST LEBANON, NH
Continuous	Ct19	1152500	SUGAR RIVER AT WEST CLAREMONT, NH
Continuous	Ct2	1129200	CONNECTICUT R BELOW INDIAN STREAM NR PITTSBURG, NH
Continuous	Ct22	1154500	CONNECTICUT RIVER AT NORTH WALPOLE, NH
Continuous	Ct23	1158000	ASHUELOT RIVER BELOW SURRY MT DAM, NEAR KEENE, NH
Continuous	Ct24	1158600	OTTER BROOK BELOW OTTER BROOK DAM, NEAR KEENE, NH
Stage-only (4)	Ct25	1158110	ASHUELOT RIVER ABOVE THE BRANCH, AT KEENE, NH (stage only)
Continuous	Ct26	1160350	ASHUELOT RIVER AT WEST SWANZEY, NH
Continuous	Ct26	1161000	ASHUELOT RIVER AT HINSDALE, NH
Continuous	Ct5	1129500	CONNECTICUT RIVER AT NORTH STRATFORD, NH
Continuous	M1	1074520	EAST BRANCH PEMIGEWASSET RIVER AT LINCOLN, NH
Continuous	M10	1081000	WINNIPESAUKEE RIVER AT TILTON, NH
Continuous	M11	1082000	CONTOOCOOK RIVER AT PETERBOROUGH, NH
PR (5)	M11	1083000	NUBANUSIT BK BLW MACDOWELL DAM NR PETERBOROUGH NH (partial record0
Continuous	M13	1086000	WARNER RIVER AT DAVISVILLE, NH
PR	M14	1087000	BLACKWATER RIVER NEAR WEBSTER, NH (partial record)
PR	M15	1085000	CONTOOCOOK RIVER NEAR HENNIKER, NH (partial record)
Continuous	M15	1085500	CONTOOCOOK R BL HOPKINTON DAM AT W HOPKINTON, NH
Stage-only	M15	1087850	CONTOOCOOK RIVER AT RIVER HILL, NEAR PENACOOK, NH (stage only)
Continuous	M18	1081500	MERRIMACK RIVER AT FRANKLIN JUNCTION, NH
Continuous	M19	1089100	SOUCOOK RIVER, AT PEMBROKE ROAD, NEAR CONCORD, NH
Continuous	M2	1075000	PEMIGEWASSET RIVER AT WOODSTOCK, NH
Stage-only	M20	1088400	MERRIMACK RIVER AT CONCORD, NH (stage only)
PR	M23	1090800	PISCATAQUOG RIVER BL EVERETT DAM, NR E WEARE, NH (partial record)
PR	M23	1091500	PISCATAQUOG RIVER NEAR GOFFSTOWN, NH (partial record)
Continuous	M25	1092000	MERRIMACK R NR GOFFS FALLS, BELOW MANCHESTER, NH
Continuous	M26	1094000	SOUHEGAN RIVER AT MERRIMACK, NH
Continuous	M28	1100505	SPICKET RIVER AT NORTH SALEM, NH
PR	M28	1100561	SPICKET RIVER NEAR METHUEN, MA (partial record)
Closing - Continuous	M28	11005605	POLICY BR @ I-93N REST STOP ENT RAMP, NR SALEM, NH
Continuous	M29	10965852	BEAVER BROOK AT NORTH PELHAM, NH
Continuous	M3	1076000	BAKER RIVER NEAR RUMNEY, NH
Continuous	M4	1076500	PEMIGEWASSET RIVER AT PLYMOUTH, NH
HDCN	M5	ASHNH	SQUAM RIVER AT ASHLAND, N.H. (formerly 01077000)
HDCN	M6	NFLNH	NEWFOUND LAKE DAM (formerly 01077500 Newfound Lake Near Bristol, NH)
Continuous	M7	1078000	SMITH RIVER NEAR BRISTOL, NH
HDCN	M9	LKPN3	LAKE WINNIPESAUKEE OUTLET AT LAKEPORT, N.H. (formerly 01080500)
Continuous	S3	1064500	SACO RIVER NEAR CONWAY, NH
Continuous	S5	1064801	BEARCAMP RIVER AT SOUTH TAMWORTH, NH
HDCN	S8	OSRNH	OSSIPEE RIVER AT EFFINGHAM FALLS, N.H. (formerly 01065000)
	(6) Index - for this study USGS HUC-10 numbers were renamed with the first letter of their major basin and sequential numbering.		
	A=Androscoggin, C=Coastal, Ct=Connecticut, M=Merrimack, S=Saco		
(1) Continuous = USGS continuous record gage (measurements accurate for full range of high and low flows)			
(2) HDCN = Hydrologic Data Collection Network (NHDES Dam Bureau station)			
(3) Closing - Continuous = Continuous gages without funding after either 2006 or 2007			
(4) Stage-only = USGS water height measurement station			
(5) PR = USGS partial record gage (measurements accurate only for some of the data such as the high or low flows)			


NH HUC-10 Watershed Stream Gage Coverage
Existing and Proposed by Stream Gage Task Force
September 2006
Active Gages
USGS Continuous Gage
NHDES HDCN
Massachusetts Stream Gage
Maine Stream Gage
Hydrography
Rivers/ Streams
Lakes/ Ponds
HUC_10 Gage Coverage
No Gage
Existing HDCN
Exisiting USGS
Proposed New
HUC-10 Index
A3 No Proposed Gage(s)
Ct3 Proposed Gage(s)
N
The coverages presented are under constant revision as new sites or facilities are added. They may not contain all of the potential or existing sites or facilities.
NHDES is not responsible for the use or interpretation of this information.
Not intended for legal purposes.
Environmental Services
0 5 10 20
Miles

DES DAM BUREAU GAGES

(Visit http://des.nh.gov/rti_home/ for data)

Winnipesaukee River Basin

Smith River near Bristol
Gilmanton
Winnisquam Lake at Winnisquam
Poorfarm Brook at Ellacoya State Park
Silver Lake at Lochmere
Lake Winnipesaukee at Weirs Beach
Merrimack River at Franklin
Lakeport Dam at Lakeport
Opechee Bay at Laconia
Shannon Brook near Moultonborough
Winnipesaukee River at Tilton
Wolfeboro

Pemigewasset River and Ossipee Lake Basins

Squam River near Ashland
Franklin Falls Dam at Franklin
Newfound Lake near Bristol
Ossipee River at Effingham Falls
Baker River near Rumney
Pemigewasset River at Woodstock
Bearcamp River at South Tamworth
East Br Pemigewasset River at Lincoln
Ossipee Lake near West Ossipee
Pemigewasset River at Plymouth
Squam Lake near Ashland

Mascoma, Suncook, Salmon Falls, Powwow, and Piscataquog River Basins

Blackwater Dam near Webster
Exeter River near Brentwood
Merrimack River near Goffs Falls
Lamprey River near Newmarket
Oyster River near Durham
Milton 3-Ponds & Salmon Falls River at Milton
Sunapee Lake at Sunapee Harbor
Mascoma River at West Canaan
Hopkinton Lake Dam & Contoocook River at Hopkinton
Merrimack River at Concord
Piscataquog River near Goffstown
Contoocook River at Henniker
Mascoma Lake Dam & Mascoma River at Mascoma
Contoocook River near River Hill
Soucook River near Concord
Blackwater River near Webster
Everett Lake Dam & Piscataquog River near Weare
Connecticut River at West Lebanon

Weekly Lake Elevation Stations

Angle Pond (Sandown)
Buck Street (Allenstown)
Crystal Lake (Gilmanton)
Deering Reservoir (Deering)
Goose Pond (Canaan)
Great Pond (Kingston)
Horn Pond (Wakefield)
Northwood Lake (Northwood)
Sunset Lake (Alton)
Barnstead Parade (Barnstead)
Crystal Lake (Enfield)
Kingswood Lake (Brookfield)
Great East Lake (Wakefield)
Grafton Pond (Grafton)
Horace Lake (Weare)
Lovell Lake (Wakefield)
Powwow Pond (East Kingston)
Suncook Lake (Barnstead)

Available References (Source: NHSGTF, 2006)

New Hampshire's Stream-gaging Network: Status and Future Needs by S.A. Olson, FS-050-03, http://pubs.usgs.gov/fs/fs-050-03/pdf/FS050-03_508.pdf

Effectiveness of the New Hampshire Stream-gaging Network in Providing Regional Streamflow Information by S.A. Olson, WRIR 03-4041
http://pubs.usgs.gov/wri/wrir03-4041/

A Stream-gaging Network Analysis for the 7-Day, 10-Year Annual Low Flow in New Hampshire Streams by R.H. Flynn, WRIR 03-4023
http://pubs.usgs.gov/wri/wrir03-4023/

Development of Regression Equations to Estimate Flow Durations and Low-Flow-Frequency Statistics in New Hampshire Streams by R.H. Flynn, WRIR 02-4298
http://pubs.usgs.gov/wri/wri02-4298/

The New Hampshire Watershed Tool: A Geographic Information System Tool to Estimate Streamflow Statistics and Ground-Water Recharge Rates by S.A. Olson, R.H. Flynn, C.M. Johnston, and G.D. Tasker, OFR 2005-1172
http://pubs.usgs.gov/of/2005/1172/

Cost Effectiveness of the U.S. Geological Survey's Stream-Gaging Programs in New Hampshire and Vermont by J.A. Smath and F.E. Blackey, WRIR 85-4173

Expansion of the USGS Cooperative Streamgage Network in Massachusetts
http://ma.water.usgs.gov/nwis/images/eoea.expansion.htm

New Hampshire-Vermont Water Science Center Newsletter, April 2006, USGS publication,
http://nh.water.usgs.gov/Publications/online_publications.htm

List of gages discontinued in 2004:
http://nh.water.usgs.gov/WaterData/NHdiscont05.htm

Rivers Management Advisory Committee Strategy for Stream Gaging in New Hampshire, December 20, 2005

Rivers Management Advisory Committee Recommendations For Stream Gaging In New Hampshire To the Commissioner of the Department of Environmental Services, December 20, 2005

Footnotes:

[1] Rivers are **designated** under RSA 483: New Hampshire Rivers Management and Protection Program. There are 14 rivers in NH designated for special protections because of their unique and outstanding characteristics.
http://www.des.state.nh.us/rivers/rsa483.htm

[2] The USGS's **Hydrologic Unit Codes** are numbers that divide the nation's watersheds on a hierarchical basis with an increasing number of digits from regional to more local watersheds. The Merrimack basin has a four-digit HUC (0107) and therefore is a HUC-4. In the Merrimack basin, HUC-0107000609 (a ten-digit HUC) is the Souhegan watershed, which is a subdivision of the Merrimack watershed. New Hampshire is part of four HUC-4s, but is part of 81 HUC-10s. For simplicity of mapping in this report these 10-digit HUCs were renamed with HUC index values made up of a letter indicating the major water watershed and sequential numbering.

Table A4-HUC-10 Index Key (Source: NHSGTF, 2006)		
HUC Index	USGS HUC_10	HUC_10_NAME
A1	104000102	UMBAGOG LAKE DRAINAGE
A2	104000103	AZISCOHOS LAKE DRAINAGE
A3	104000104	MAGALLOWAY RIVER
A4	104000105	CLEAR STREAM
A5	104000106	MIDDLE ANDROSCOGGIN RIVER
A6	104000201	GORHAM-SHELBURNE TRIBUTARIES
A7	104000202	ANDROSCOGGIN RIVER AT RUMFORD POINT
C1	106000304	SALMON FALLS RIVER
C2	106000306	COCHECO RIVER
C3	106000307	LAMPREY RIVER
C4	106000308	EXETER RIVER
C5	106000309	GREAT BAY DRAINAGE
C6	106000310	COASTAL DRAINAGE
Ct1	108010101	CONNECTICUT LAKES DRAINAGE
Ct10	108010302	CONNECTICUT RIVER-JOHNS RIVER TO AMMONOOSUC RIVER
Ct11	108010303	GALE RIVER
Ct12	108010304	AMMONOOSUC RIVER
Ct13	108010305	LOWER AMMONOOSUC RIVER
Ct14	108010307	CONNECTICUT RIVER-AMMONOOSUC RIVER TO WAITS RIVER
Ct15	108010402	CONNECTICUT RIVER-WAITS RIVER TO HEWES BROOK
Ct16	108010404	CONNECTICUT RIVER-OMPOMPANOOSUC RIVER TO WHITE RIVER
Ct17	108010601	MASCOMA RIVER
Ct18	108010603	CONNECTICUT RIVER-WHITE RIVER TO SUGAR RIVER
Ct19	108010604	SUGAR RIVER
Ct2	108010102	HEADWATER TRIBUTARIES
Ct20	108010607	CONNECTICUT RIVER-SUGAR RIVER TO BELLOWS FALLS
Ct21	108010702	COLD RIVER
Ct22	108010705	CONNECTICUT RIVER-BELLOWS FALLS TO VERNON DAM
Ct23	108020101	UPPER ASHUELOT RIVER
Ct24	108020102	THE BRANCH
Ct25	108020103	MIDDLE ASHUELOT RIVER
Ct26	108020104	LOWER ASHUELOT RIVER
Ct27	108020105	CONNECTICUT RIVER-VERNON DAM TO DEERFIELD RIVER
Ct28	108020201	UPPER MILLERS RIVER
Ct29	108020202	LOWER MILLERS RIVER
Ct3	108010103	MOHAWK RIVER-STEWARTSTOWN TRIBUTARIES
Ct4	108010104	CONNECTICUT RIVER-MOHAWK RIVER TO NULHEGAN RIVER
Ct5	108010106	CONNECTICUT RIVER-NULHEGAN RIVER TO UPPER AMMONOOSUC RIVER
Ct6	108010107	UPPER AMMONOOSUC RIVER
Ct7	108010108	ISRAEL RIVER
Ct8	108010109	CONNECTICUT RIVER-UPPER AMMONOOSUC RIVER TO JOHNS RIVER
Ct9	108010301	JOHNS RIVER
M1	107000101	EAST BRANCH PEMIGEWASSET RIVER
M10	107000202	WINNIPESAUKEE RIVER
M11	107000301	UPPER CONTOOCOOK RIVER
M12	107000302	NORTH BRANCH
M13	107000303	WARNER RIVER
M14	107000304	BLACKWATER RIVER
M15	107000305	LOWER CONTOOCOOK RIVER
M16	107000403	SQUANNACOOK RIVER
M17	107000404	NASHUA RIVER-SQUANNACOOK RIVER TO MOUTH
M18	107000601	UPPER MERRIMACK RIVER
M19	107000602	SOUCOOK RIVER
M2	107000102	UPPER PEMIGEWASSET RIVER
M20	107000603	CONCORD TRIBUTARIES
M21	107000604	UPPER SUNCOOK RIVER
M22	107000605	SUNCOOK RIVER
M23	107000606	PISCATAQUOG RIVER
M24	107000607	COHAS BROOK
M25	107000608	MANCHESTER TRIBUTARIES
M26	107000609	SOUHEGAN RIVER
M27	107000610	LITCHFIELD-HUDSON TRIBUTARIES
M28	107000611	SPICKETT RIVER
M29	107000612	MERRIMACK RIVER-NASHUA RIVER TO SHAWSHEEN RIVER
M3	107000103	BAKER RIVER
M30	107000614	MERRIMACK RIVER-SHAWSHEEN RIVER TO MOUTH
M4	107000104	MIDDLE PEMIGEWASSET RIVER
M5	107000105	SQUAM RIVER
M6	107000106	NEWFOUND RIVER
M7	107000107	SMITH RIVER
M8	107000108	LOWER PEMIGEWASSET RIVER
M9	107000201	LAKE WINNIPESAUKEE DRAINAGE
S1	106000201	UPPER SACO RIVER
S2	106000202	SWIFT RIVER
S3	106000203	CONWAY TRIBUTARIES
S4	106000204	SACO RIVER-LOVEWELL POND
S5	106000206	BEARCAMP RIVER
S6	106000207	PINE RIVER
S7	106000208	OSSIPEE LAKE DRAINAGE
S8	106000209	OSSIPEE RIVER
S9	106000210	LITTLE OSSIPEE RIVER

APPENDIX D: NATIONAL FLOOD FREQUENCY HYDROLOGY MODEL FOR NEW HAMPSHIRE

NEW HAMPSHIRE - STATEWIDE RURAL

Summary

New Hampshire is considered to be one hydrologic region. The regression equations developed for the State are for estimating peak discharges (QT) having recurrence intervals T that range from 2 to 100 years. The explanatory basin variables used in the equations are drainage area (A), in square miles; channel slope (S), in feet per mile; and the 2-year 24-hour precipitation (I2,24), in inches. The variables A and S can be measured from topographic maps, and I2,24 taken from the U.S. Weather Bureau Technical Paper (TP) 29 is shown (fig. 1).

The regression equations were developed from peak-discharge records for 59 stations. The equations are applicable to streams whose flows are not significantly affected by regulation, diversion or urbanization, and whose drainage areas are between 0.27 and 622 square miles. The standard errors of estimate of the regression equations range from 35 to 58 percent. The report by LeBlanc (1978) also includes selected basin and flood characteristics for gaging stations.

Procedure

Topographic maps, the 2-year 24-hour precipitation map (fig. 1), and the following equations are used to estimate the needed peak discharges QT, in cubic feet per second, having selected recurrence intervals T.

$$Q2 = 1.34A^{1.06}S^{0.37}(I2,24)^{1.24}$$

$$Q5 = 1.00A^{1.06}S^{0.44}(I2,24)^{1.69}$$

$$Q10 = 0.84A^{1.06}S^{0.46}(I2,24)^{1.98}$$

$$Q25 = 0.70A^{1.05}S^{0.52}(I2,24)^{2.29}$$

$$Q50 = 0.62A^{1.05}S^{0.54}(I2,24)^{2.50}$$

$$Q100 = 0.55A^{1.05}S^{0.56}(I2,24)^{2.72}$$

Reference

Source:
http://water.usgs.gov/software/nff_manual/nh/index.html

U.S. Geological Survey Water-Resources Investigations Report 94-4002:
Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993

LeBlanc, D.R., 1978, Progress report on hydrologic investigations of small drainage areas in New Hampshire-Preliminary relations for estimating peak discharges on rural, unregulated streams: U.S. Geological Survey Water-Resources Investigations Report 78-47, 10 p.

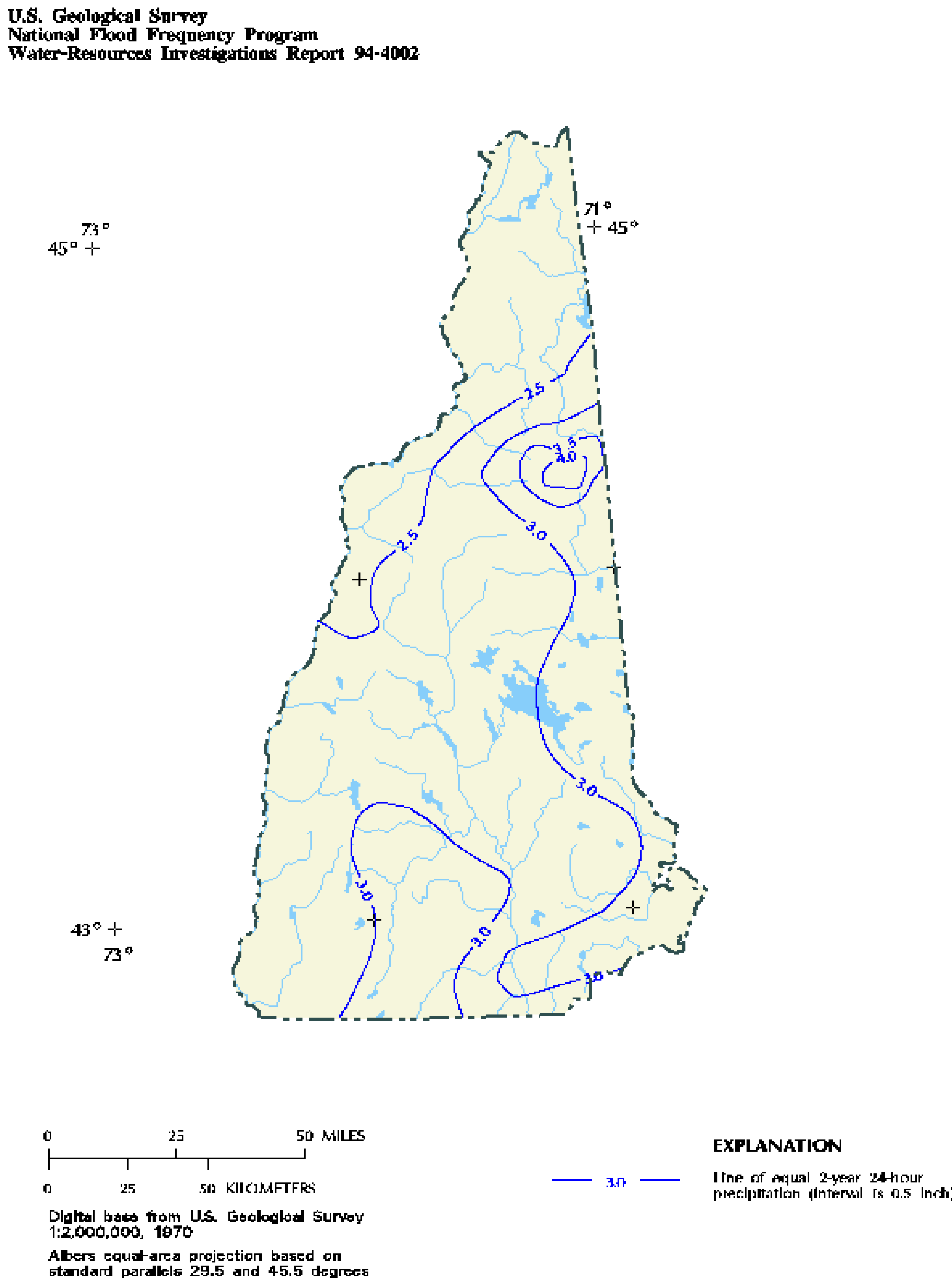


Figure 1. The 2-year 24-hour precipitation in New Hampshire.

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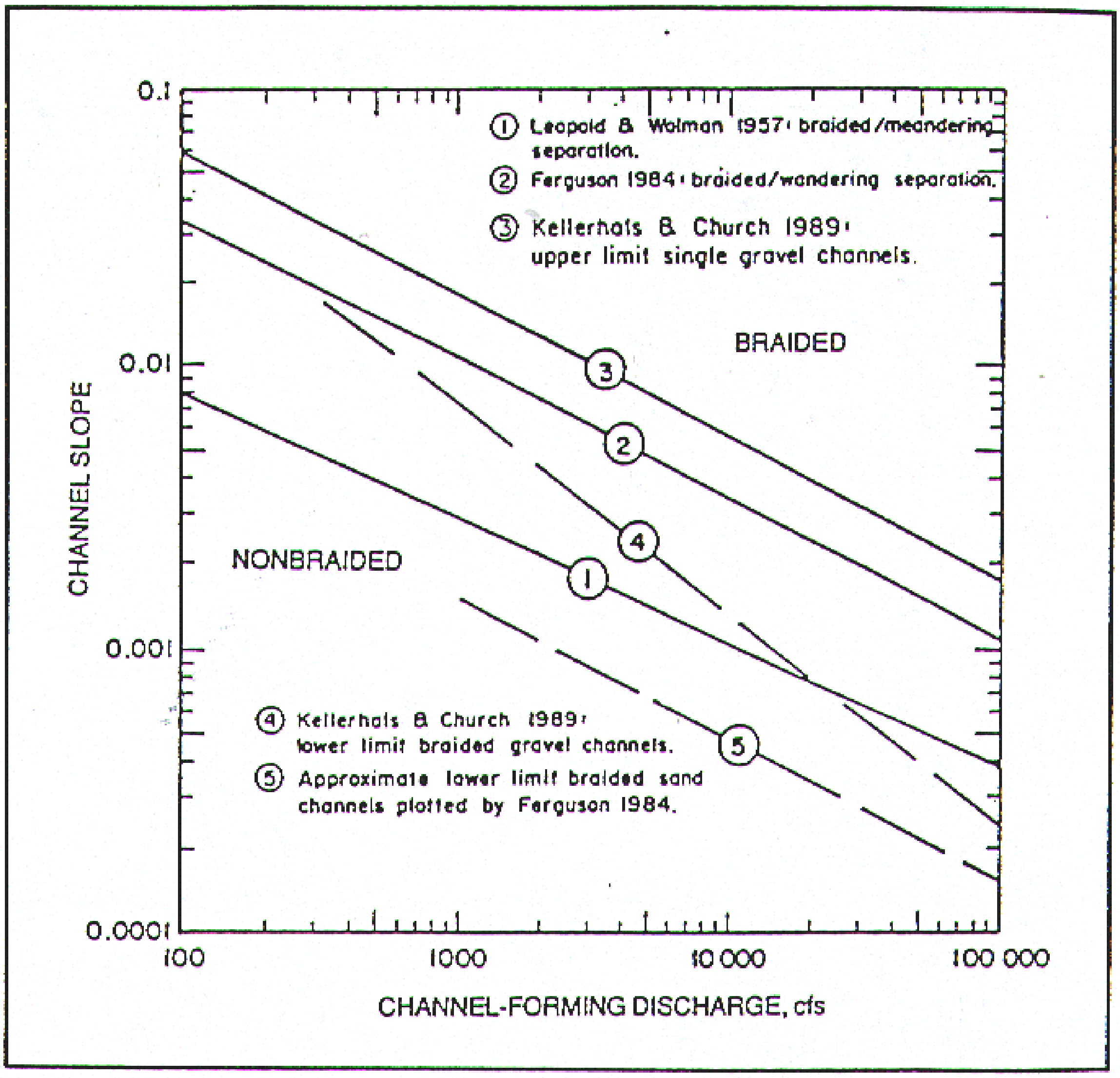
APPENDIX E: CHARTS FOR DETERMINING STABLE EQUILIBRIUM SLOPE


0.1
0.01
0.001
0.0001
100
1000
10 000
100 000
CHANNEL SLOPE
CHANNEL-FORMING DISCHARGE, cfs
① Leopold & Wolman 1957 braided/meandering separation.
② Ferguson 1984 braided/wandering separation.
③ Kellerhals & Church 1989 upper limit single gravel channels.
BRAIDED
NONBRAIDED
④ Kellerhals & Church 1989 lower limit braided gravel channels.
⑤ Approximate lower limit braided sand channels plotted by Ferguson 1984.

(USACOE, 1994)

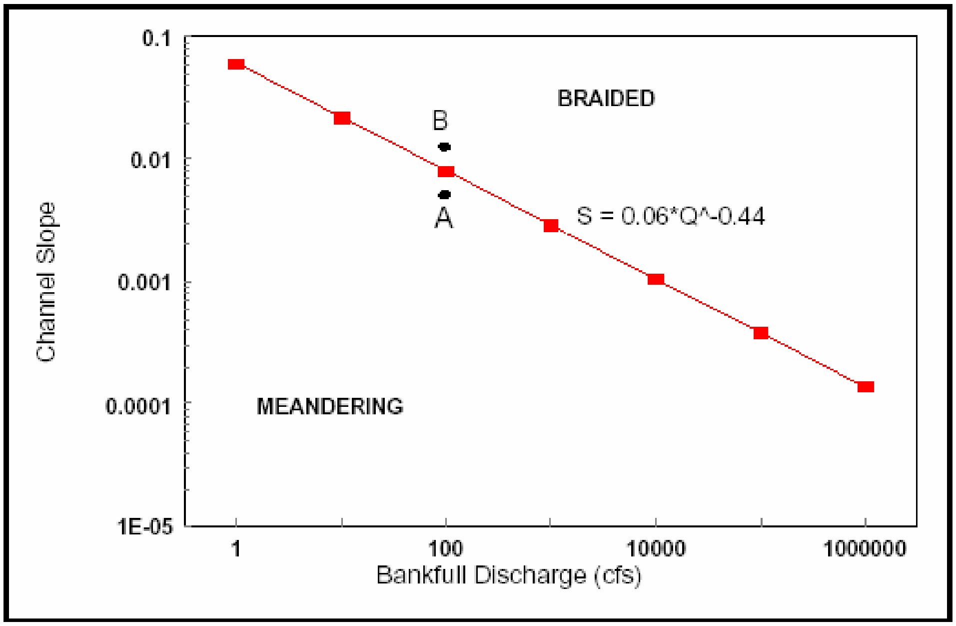


Figure 3.11 Leopold and Wolman's (1957) Relationship Between Channel Patterns, Channel Gradient, and Bankfull Discharge

"Rivers that are near the threshold lines may exhibit segments that transitions between the two planforms (Watson et al., 1999)."

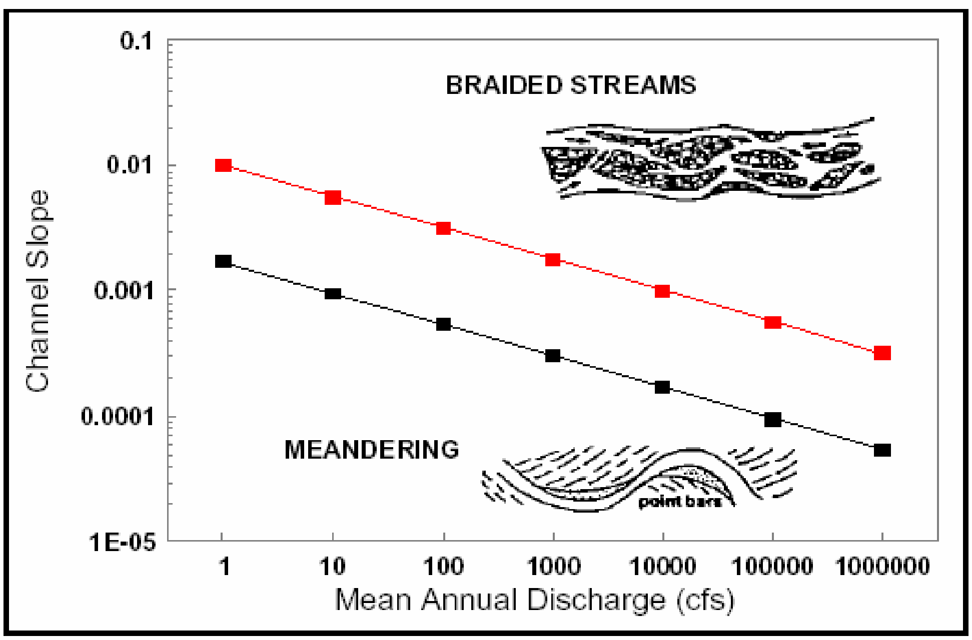
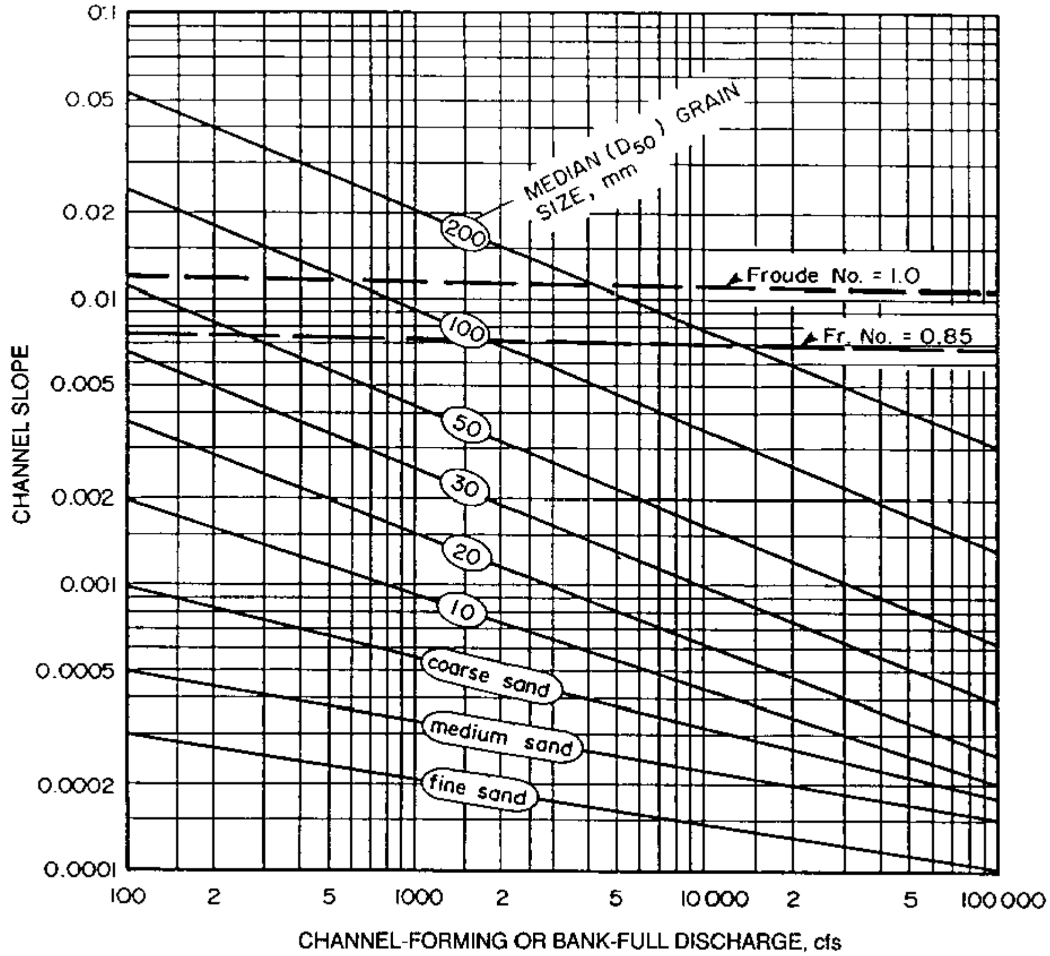


Figure 3.10 Lane's (1957) Relationship Between Channel Patterns, Channel Gradient, and Mean Discharge

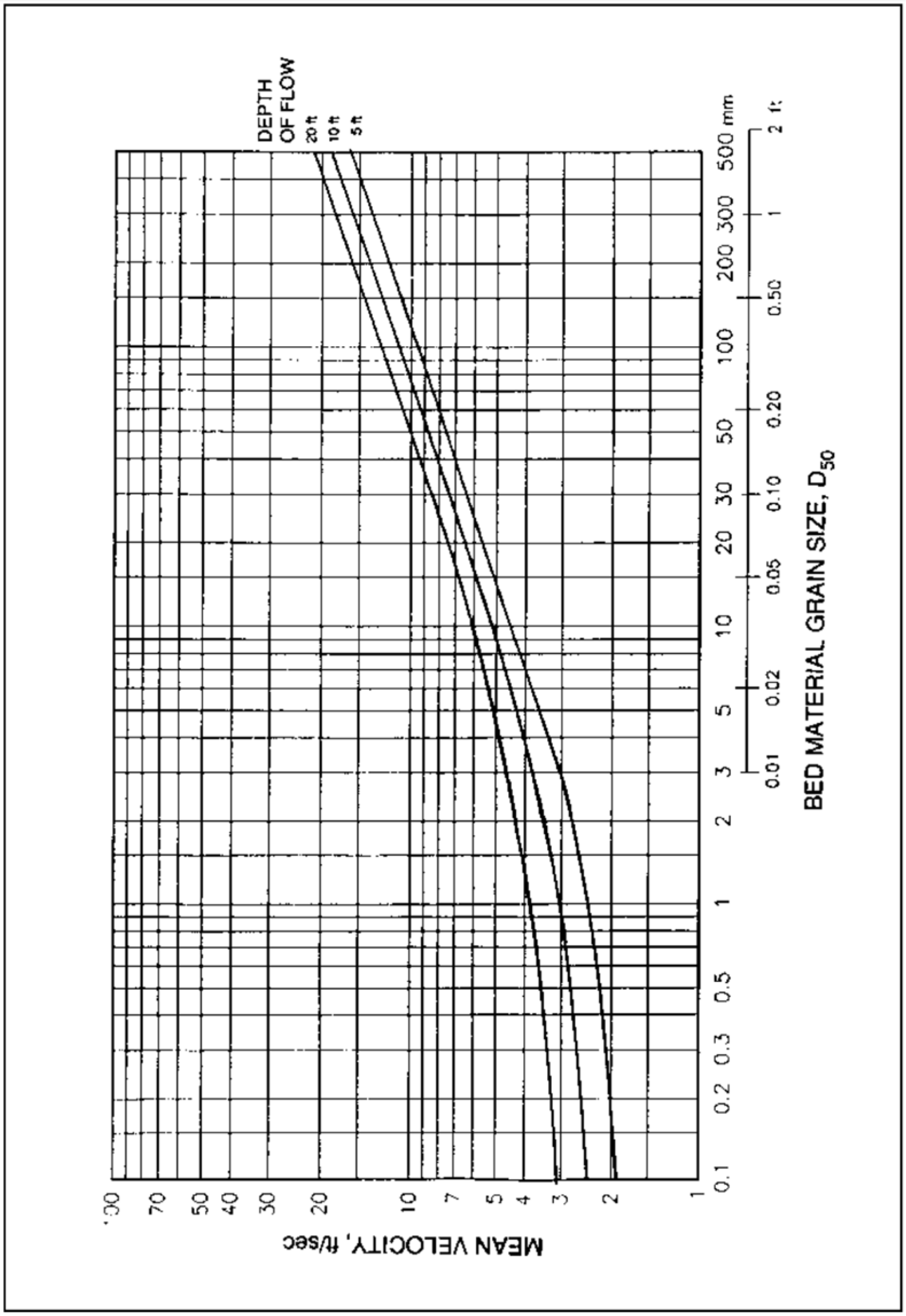


NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.

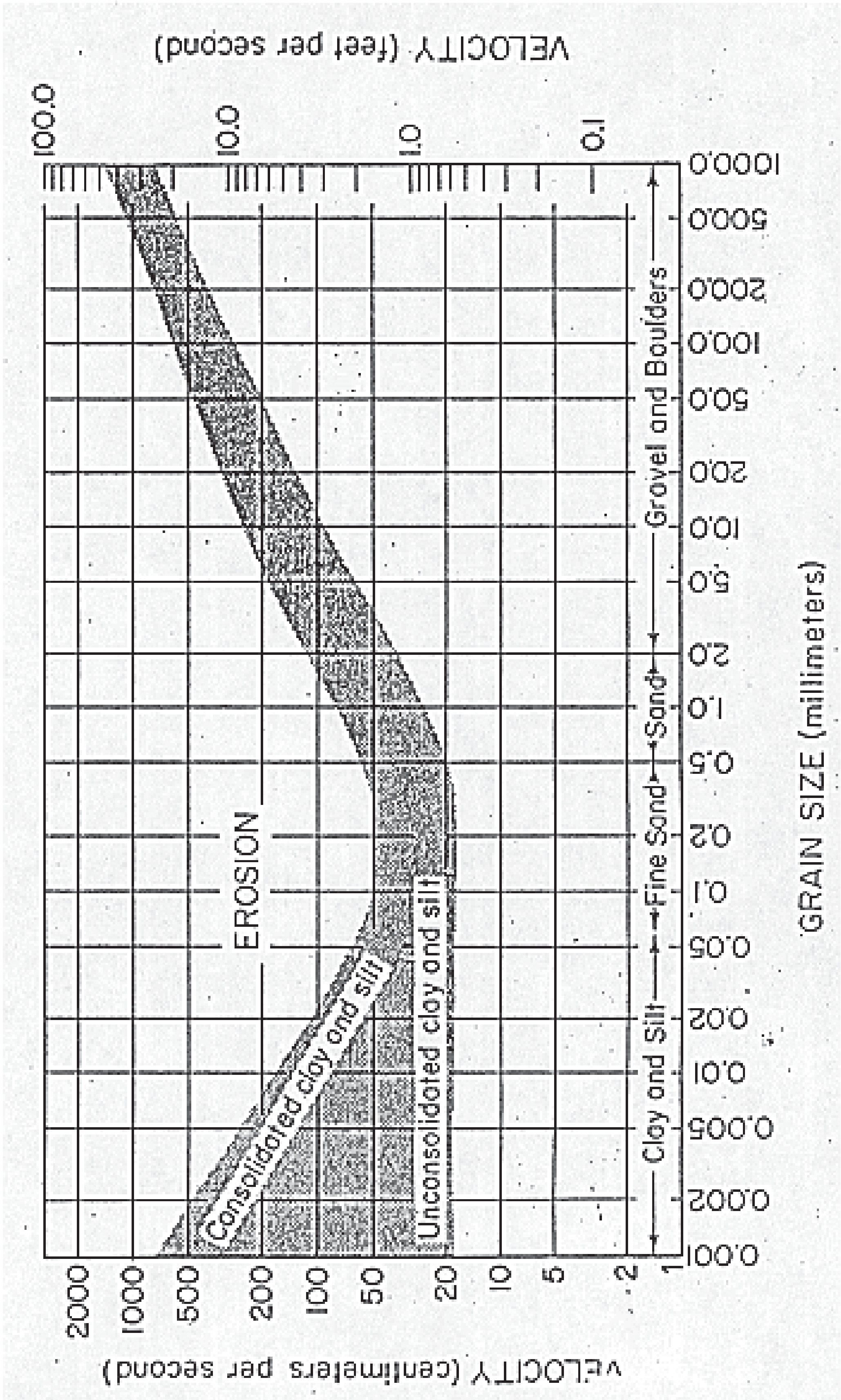
(USACOE, 1994)

APPENDIX F: CHARTS FOR DETERMINING THRESHOLD VELOCITY

USACOE, 1994


DEPTH
OF FLOW
20 ft
10 ft
5 ft
MEAN VELOCITY, ft/sec
BED MATERIAL GRAIN SIZE, D50
0.1 0.2 0.3 0.5 1 2 3 5 10 20 30 50 100 200 300 500 mm
0.01 0.02 0.05 0.10 0.20 0.50 1 2 ft
1 2 3 4 5 7 10 20 30 40 50 70 100

Hjulstrom's Diagram



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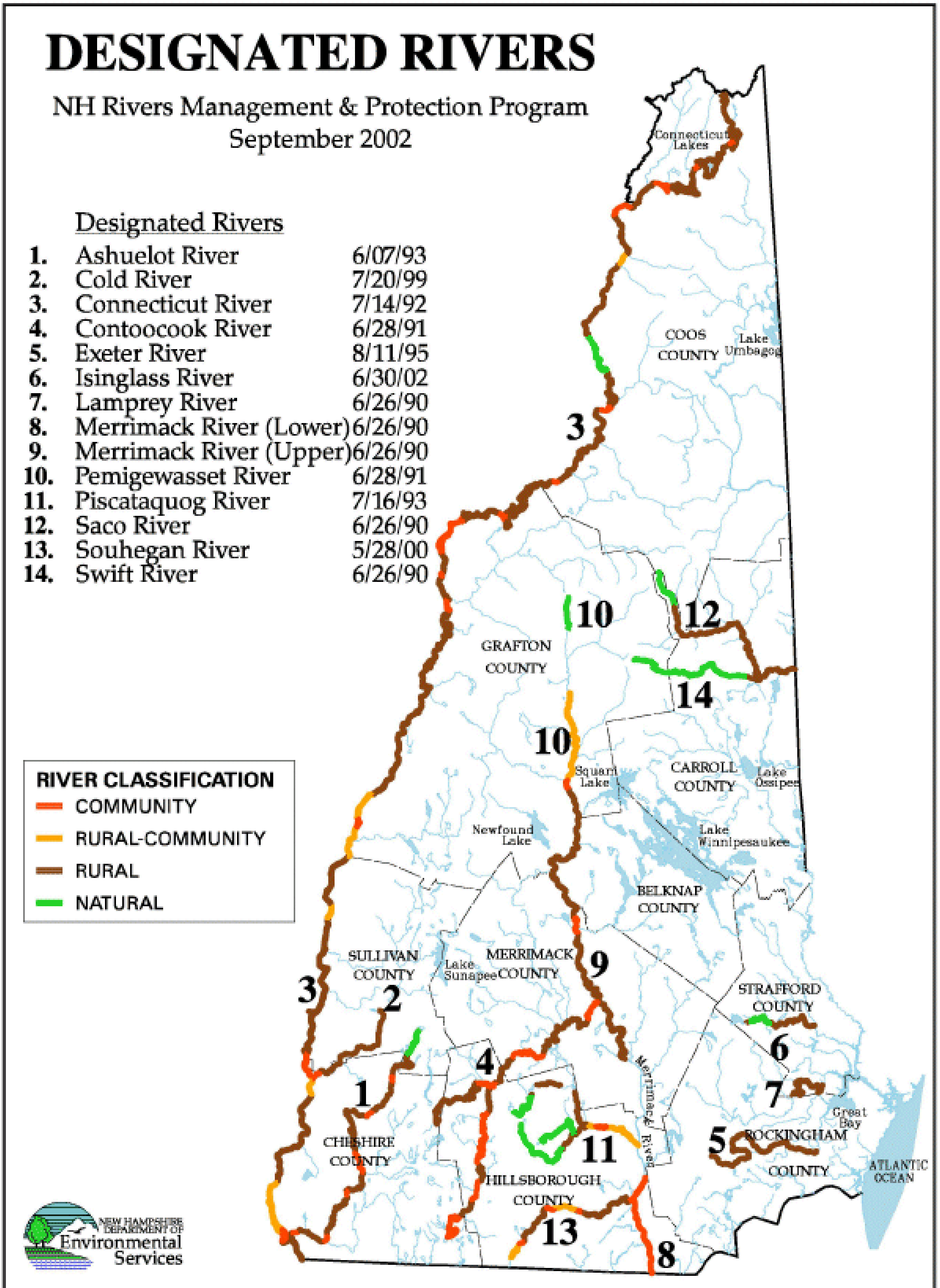
APPENDIX G: NEW HAMPSHIRE DESIGNATED RIVERS UNDER RSA 483



NHDES Watershed Management Bureau

What is a designated river?

A river managed and protected for its outstanding natural and cultural resources in accordance with RSA 483 - The Rivers Management & Protection Act.

New Hampshire's Designated Rivers

Ashuelot River

From the dam at Butterfield Pond in Washington to the confluence with the Connecticut River in Hinsdale. Effective 6/7/93. Municipalities: Washington, Lempster, Marlow, Gilsum, Sullivan, Surry, Keene, Swanzey, Winchester, and Hinsdale.

Cold River

From the outlet of Crescent Lake Dam in Acworth to its confluence with the Connecticut River in Walpole. Effective 07/20/99. Municipalities: Acworth, Lempster, Langdon, Alstead, and Walpole.

Connecticut River

From the outlet of Fourth Connecticut Lake to the New Hampshire/Massachusetts state line. Effective 7/14/92. Municipalities: Pittsburg, Clarksville, Stewartstown, Colebrook, Columbia, Stratford, Northumberland, Lancaster, Dalton, Littleton, Monroe, Bath, Haverhill, Piermont, Orford, Lyme, Hanover, Lebanon, Plainfield, Cornish, Claremont, Charlestown, Walpole, Westmoreland, Chesterfield, and Hinsdale.

Contoocook River - Mainstem and North Branch

Mainstem - From the outlet of Poole Pond in Rindge to the confluence with the Merrimack River at the Boscawen/Concord municipal boundary. North Branch - From the outlet of Rye Pond in Stoddard to the confluence of the Contoocook River in Hillsborough. Effective 6/28/91. Municipalities: Rindge, Jaffrey, Peterborough, Hancock, Greenfield, Bennington, Stoddard, Antrim, Deering, Hillsborough, Henniker, Hopkinton, Concord, and Boscawen.

Exeter River

From the headwaters at the Route 102 bridge in Chester to its confluence with Great Brook in Exeter. Effective 8/11/95. Municipalities: Chester, Sandown, Danville, Fremont, Raymond, Brentwood, and Exeter.

Isinglass River

From the outflow of Bow Lake Dam in Strafford to its confluence with the Cocheco River in Rochester. Effective 6/30/02. Municipalities: Strafford, Barrington, Rochester.

Lamprey River

From the Epping/Lee town line to the Durham/Newmarket town line. Effective 6/26/90. Municipalities: Lee and Durham.

Merrimack River - Lower

From the Bedford/Merrimack town line to the New Hampshire/Massachusetts state line. Effective 6/26/90. Municipalities: Merrimack, Litchfield, Nashua and Hudson.

Merrimack River - Upper

From the confluence of the Winnipesaukee and Pemigewasset Rivers in Franklin to Garvins Falls in Bow. Effective 6/26/90. Municipalities: Franklin, Northfield, Boscawen, Canterbury, Concord, and Bow.

Pemigewasset River

From the outlet of Profile Lake in Franconia Notch State Park to the southern boundary of Franconia Notch State Park and from the northernmost Thornton town line to the confluence with the Merrimack River in Franklin. Effective 6/28/91. Municipalities: Franconia Notch State Park, Franconia, Thornton, Campton, Plymouth, Holderness, Ashland, Bridgewater, New Hampton, Bristol, Hill, Sanbornton, and Franklin.

Piscataquog River - South, Middle and North Branches

North Branch—From the outlet of Deering Lake Dam in Deering to the confluence with the South Branch in Goffstown (omitting Lake Horace and Everett Flood Control Area). South Branch—From the outlet of Pleasant Pond in Francestown to the river's mouth at Bass Island in Manchester. Middle Branch—From the outlet of Scobie Pond in Francestown to the confluence with the South Branch in New Boston. Effective 7/16/93. Municipalities: Deering, Weare, New Boston, Francestown, Lyndeborough, Goffstown, and Manchester.

Saco River

From the base of Saco Lake dam in Crawford Notch State Park to the New Hampshire/Maine state line. Effective 6/26/90. Municipalities: Crawford Notch State Park, Harts Location, Bartlett, and Conway.

Souhegan River

From the confluence of the south and west branches in New Ipswich to the confluence with the Merrimack River in Merrimack. Effective May 28, 2000. Municipalities: New Ipswich, Greenville, Wilton, Milford, Amherst, Merrimack.

Swift River

From its headwaters in Livermore to its confluence with the Saco River in Conway. Effective 6/26/90. Municipalities: White Mountain National Forest, Livermore, Waterville Valley, Albany, and Conway.

GLOSSARY OF TECHNICAL TERMS

1.5-year flow – Often approximated as the channel-forming, bankfull, or effective discharge because of its large contribution to sediment transport and channel shaping. The flood of a magnitude that is expected to be equaled or exceeded, on average, once during any 1.5-year period. The 1.5-year flood has a 67 percent chance of being equaled or exceeded in any given year.

100-year flow – The flood of a magnitude that is expected to be equaled or exceeded, on average, once during any 100-year period. The 100-year flood has a 1 percent chance of being equaled or exceeded in any given year.

10-year flow – The flood of a magnitude that is expected to be equaled or exceeded, on average, once during any 10-year period. The 10-year flood has a 10 percent chance of being equaled or exceeded in any given year.

Adaptive management – When results are utilized in a feedback loop to adjust activities and goals associated with a monitoring project (Holling, 1978).

Aggradation – The building up of the river channel due to the deposition of sediment materials on the channel bed. This process can lead to channel widening if the flow area in the channel is reduced enough that flow is pushed towards the banks.

Alluvial – Transported by flowing water. The transported material itself is called alluvium (Merriam-Webster's Collegiate Dictionary). An alluvial river channel is one that is formed from the constant erosion and deposition of alluvium in a dynamic balance between sediment and water, and thus can be prone to channel instability when disturbed.

Analog – An approach to naturalized channel design and bank stabilization where stable channel dimensions at a single dominant design discharge at the project site are determined from observation of the geomorphic characteristics of a nearby stable reference reach.

Analytical – An approach to naturalized channel design and bank stabilization where characteristics of the project site such as cross-sectional discharge, stable channel dimensions, or sediment transport rates are approximated via physical-based equations or models.

Aquatic ecosystem – The combination of physical, chemical, and biological structure (e.g., substrate, habitat, biological communities) and process (e.g., sediment transport, nutrient cycling, and drift) taking place in rivers and other surface waters.

AutoCAD – A computer-assisted drafting and design tool.

Autotrophic inputs – Originating within the river channel, such as the primary production by aquatic plants at the bottom of the food web.

Avulsion – The sudden creation of a new river channel where flow leaves the existing channel during large floods and carves a new channel with a new slope and length. Avulsions typically occur when flood waters carve a new flow path across a sharp meander bend, access a nearby low spot such as an old gravel pit, impinge on the banks due to the formation of a large debris jam, or overtop an under-sized channel.

BACI – Before-after-control-impact (Stewart-Oaten et al., 1986). A popular study design to evaluate the effects of river management activates where both control and impact sites are monitored before and after a treatment.

Backwater – The backing-up of water due to a constriction where flow velocities and sediment transport decrease and water surface elevations increase. A common example of backwatering is when water ponds upstream of an undersized bridge or culvert leading to channel aggradation, widening, and instability. Backwater also regularly occurs near the confluence of a tributary and larger mainstem river due to higher flows on the larger river.

Bank angle – The angle between the water surface and a river bank. 90^{o} represents a vertical bank, smaller angles indicate overhanging banks, and larger angles represent less steep banks.

Bank armoring – The application of hard materials to riverbanks to fix them in place, reducing or eliminating lateral channel migration that takes place in a naturally meandering river. Armoring is often carried out with riprap, and if applied over large portions of a river can lead to channel instability in other locations as water, sediment, and energy is reflected to downstream river locations. This is often called "chasing the river." Bank armoring is a temporary fix where the source of the problem in the watershed remains unaddressed.

Bank logs – Logs that are located either perpendicular or parallel to the riverbank that act as barriers to bank erosion and offer near-bank habitat for macroinvertebrates and fish. The term bank logs typically is reserved for material naturally finding its way to the river banks, whereas log revetment and root wad revetment are often used to signify installed practices.

Bank soil texture profile – The charting of the soil texture in the river banks, often by touch, to identify potential for erosion. The presence of more adhesive materials such as silts and clays tend to hold riverbanks together, whereas sandy banks are prone to sloughing after cycles of wetting and drying.

Bank vegetative cover – The amount of woody and non-woody vegetation covering the river banks.

Bankfull flow or discharge – For undisturbed alluvial rivers, the flow where water begins to spill over the channel and access the floodplain. In the majority of river systems that are altered and have undergone some level of channel down-cutting, the elevation of the bankfull flow is located at lower elevations than the top of bank and more accurately defined by the field indicators such as the top of point bars on the inside of meanders, the limit of perennial vegetation on the banks (i.e., ferns, shrubs, trees), and a well-formed low bench on the bank where some sediment deposition is evident. A common design flow that typically has a mean recurrence interval of 1.5 years, the bankfull flow is central to the formation of a given channel plan form and cross-section for meandering rivers (Wolman and Miller, 1960). Many discussions of bankfull flow are available for review (e.g., FISRWG, 1998; Schiff et al., 2006, and http://www.epa.gov/WARSSS/sedsource/bankfull.htm).

Bankfull width – The width of the wetted channel during bankfull flow.

Baseflow – Discharge that is not associated with a storm event, but is due to ground water supply and local climate.

Benthic – Bottom. For example, benthic macroinvertebrates indicate those that spend much of their early life on the bed.

Bernoulli equation ($E=Y+V^2/2g$) – The equation for energy in the river where the depth (Y) is the potential energy component and $V^2/2g$ is the kinetic energy component where V is the water velocity and g is the acceleration of gravity constant.

Bioengineering – River bank stabilization using natural vegetative materials such as coconut fiber rolls, jute mats, live plantings and dormant stakes. Habitat benefits of bioengineering over traditional hard practices include rehabilitation of bank and riparian vegetation, promotion of important habitat features such as undercut banks and low overhanging vegetation, and importation of detritus and large woody debris into the river channel. Bioengineered practices are desirable for improving habitat, allowing more natural physical river processes to occur, and creating more pleasing aesthetics.

Bottleneck – Anything that limits the potential rate of growth in an organism or population (Hunter, 1991). Potential bottlenecks include lack of physical habitat, excessive bed mobility, lack of food, or the increase in abundance of predators.

Boulder – Particles with diameter > 256 mm (10.1 in) (Wentworth scale), approximately equal to or larger than volleyballs.

Boulder clusters – A grouping of boulders in the river that diversify habitat by offering velocity refuge and snag habitat in the channel.

Braided channel – A channel pattern consisting of large aggradational features and multiple flow paths, which has a large overall bankfull channel width. Braided sections of a river are dominated by aggradation and are often unstable prohibiting the creation of healthy aquatic habitat. Although channel braiding is often a potential sign of impairment, some rivers are naturally braided based on their watershed position (i.e., channel slope and bankfull discharge) and have healthy aquatic habitats.

Buffer – The naturally vegetated and relatively undisturbed area between the top of bank out to the location of a land use change. Buffers are essential for storing and filtering runoff, in addition to contributing to near and instream habitat via delivery of large woody debris and coarse particulate organic matter. Naturally vegetated buffers are an important river protection measure and remain a primary means of water quality and habitat protection today.

Canopy cover – The amount of canopy closure over a river due to the presence of trees.

Channel evolution model (CEM) – A type of channel classification system that follows the temporal changes a river tends to go through as a nick point moves up the valley and the channel incises, widens, aggrades and eventually stabilizes once floodplains are formed at a lower elevation than the old abandoned floodplain (Schumm et al., 1984). Channel evolution also provides information of the likely future channel form and stability. For example, based on the stage of evolution it may be possible to know if a channel is expected to tend towards degradation (Class III), widening (Class IV), aggradation (Class V), or equilibrium (Classes I and VI) following modification (FISRWG, 1998).

Channel pattern – A description of the general configuration of the channel as seen from overhead, such as straight, meandering, or braided.

Channel widening – The increase of channel width when banks are more erodable than bed. Widening occurs naturally such as when the bed is naturally armored due to selective removal of fine particles. Removing bank vegetation that destabilizes river banks and increasing sediment transport rates leading to excessive aggradation and flow paths impinging on the banks are ways humans cause channel widening. Widening can create flood and erosion hazards near the channel if there is development in the river corridor.

Channel-forming discharge – The discharge that is primarily responsible for shaping a river channel. Originally thought to be due to large floods, it is now known that smaller more frequent floods that occur once every one to two years collectively move the most sediment (i.e., the effective discharge) and thus are central to determining channel dimensions and stability (Wolman and Miller, 1960).

Cobble – Particles with diameter between 64 and 256 mm (2.4 and 10.1 in) (Wentworth scale), approximately between the size of tennis balls and volleyball.

Community indices – Quantitative descriptors of biological communities to facilitate comparisons between sites and statistical analysis. Indices or metrics are often broken down into four categories: taxa structure, balance, pollution tolerance, and feeding groups.

Competency – The maximum size of particles that a river can move.

Comprehensive Project – A project category used in these guidelines to represent a project that is medium to large in scope; attempts to improve stability, rehabilitate or enhance local habitat, or restore system processes; has medium to high site constraints and ecological risk; and low to medium public acceptance. Design procedures for comprehensive projects are generally more involved than other smaller scale projects and pre-and post-project monitoring is often performed.

Conductivity (µmho/cm) – The ability of water to conduct electricity as normalized to the standard geometry of an electric cell. Specific conductivity is closely correlated to the concentration of total dissolved solids.

Continuity equation (Q=VA) – Discharge (Q, cfs) is equal to the product of mean water velocity (V, fps) and cross sectional area (A, sq ft). Without inflow, outflow, or changes in storage, discharge is constant between cross sections ($Q_1=V_1A_1=V_2A_2=Q_2$).

Control – A site that represents the background or baseline conditions present in a system. Control sites are used to explore the natural range of variability and serve as a moderate benchmark for improvement or impairment.

Copeland method (1994) – Method of determining stable channel dimensions where stability is achieved when sediment inflow equals sediment outflow. Output from this model in the HEC-RAS hydraulics model includes stability curves of width and depth versus slope, including indications of when aggradation and degradation may occur.

CPOM – Coarse particulate organic matter. Non-living organic matter that is larger than 1 mm (0.04 in) consisting of materials such as leaves, needles, small woody debris, and animal inputs.

Critical depth – The water depth in a river channel at which the specific energy is the minimum for a given rate of flow.

Critical shear stress – The maximum permissible shear stress before which particle movement begins.

Cross section – A slice across the river channel that is taken perpendicular to the direction of flow and illustrates the width, depth, cross-sectional area, and shape at the given location. A cross section can also extend across the floodplain or valley to get measurements of these features.

d_{50} – The particle size for which 50 percent (of the total particle count for coarse material counted on the bed or by weight for finer material collected and sieved in the lab) of the sediment mixture is finer.

Dam removal – The demolition of dams to permit free flowing conditions. Dam removal can take place for a variety of reasons that include safety, economics, environmental health, and public desire.

Deflectors – See wing deflectors.

Deformable boundary – A soft boundary, such as naturally loose sands and small gravels, which can erode over a wide range of flows. Deformable banks and channels are design components that are typically used in less-developed areas where infrastructure is absent and ample room is available to let the river move as it would like.

Degradation – The down-cutting of the river channel due to erosion of the bed. Excessive degradation is often called incision.

Dendritic network – A network of channels in a watershed that is analogous to a tree, with numerous small tributaries in the upper watershed that connect to form larger channels in the mid-watershed, which eventually all connect to the mainstem river channel in the low watershed.

Deposition – A natural process in a river when sediment is distributed along the bed after floods recede or a change in cross-section leads to slower velocities, such as moving from a riffle to a pool. Sediment deposition is often altered in developed watersheds.

Detritus – Fragmented and decomposed non-living organic material that has a dimension that is larger than 0.45 µm, along with associated microorganisms (fungi, bacteria, protozoa, and microinvertebrates).

Diel cycle – The daily, or diurnal, cycle as evident in the changing of water temperature, dissolved oxygen, and pH controlled mainly by changes in solar energy.

Discharge (cfs) – Flow. The volume of flow moving past a location over a unit of time.

DO (mg/l or %) – Dissolved oxygen. The amount of oxygen dissolved in water. Concentrations in rivers are often a function of exchange with the atmosphere, which is highest in turbulent riffles. DO is produced by plants during photosynthesis, and consumed when organisms respire.

DOM – Dissolved organic matter. Non-living organic matter that is less than 0.45 microns, and dissolved in the surface and groundwater.

Dominant discharge theory – The theory that there is one flow that is most responsible for creating a channel's morphology, and that a channel that is designed using this dominant discharge should maintain itself in a stable form in dynamic equilibrium (FISRWG, 1998). Channel-forming discharge with recurrence interval of one to two years is common.

Dynamic equilibrium – Refers to the physical balance between water and sediment in a river where the product of the flow and the bed slope is proportional to the product of the sediment discharge and the grain size (Lane, 1955). This balance is often lost under watershed development, at which point the river tends to degrade or aggrade and lead to bank and channel instability.

Effective discharge – The flow that transports the most sediment over the long term. Effective discharge is approximated by the dominant discharge, which in turn is typically approximated by the flow that occurs every 1.5 years.

Effectiveness monitoring – "Monitoring which evaluates both areas and individual projects and activities; to assess their effectiveness in meeting desired results and meeting the purpose and need for which they were established (USDA, 1996)."

Embeddedness (%) – The average percentage that the vertical dimensions of the dominant (larger) bed particles are covered by finer particles. A completely embedded river would lack interstitial spaces important to macroinvertebrates.

Empirical design approach – A design approach where stable channel dimensions at the project site are predicted using regression relationships established from extensive data sets of channel geometry and flow characteristics measured at relatively healthy rivers.

Enhancement – The improvement of an average site. Typically refers to the use of instream structures to expand usable habitat.

Entrenchment ratio – A measure of the vertical containment of a river channel where the floodprone width, or the width of flow at two times the bankfull depth, is divided by the bankfull width (Rosgen and Silvey, 1998).

EPA-RBP – The US Environmental Protection Agency's Rapid Bioassessment Protocols for periphyton, macroinvertebrates, and fish. A popular approach to biomonitoring and habitat assessment used by many state and federal government agencies (http://www.epa.gov/owow/monitoring/rbp/).

Equilibrium slope – The optimum channel bed slope for conveying water and sediment of a given size with limited scour or deposition.

Evapotranspiration – The part of the hydrologic cycle where water is moved to the atmosphere from the ground by evaporation from the soil surface and groundwater table, and the transpiration of groundwater by plants.

Event flow – Flood flow. Flow that is largely influenced by runoff from a storm event.

Exotic species – Species that are not native to an area.

Floodplain – The area adjacent to a river that is prone to periodic inundation for floods larger than bankfull. Different parts of floodplains are designated by the frequency of the flood that is large enough to cover them. For example, the low or active floodplain terrace may be equal to the 5-year floodplain while the upper floodplain terrace may be equal to the 100-year floodplain. The increased wetting cycle typically alters processes in the floodplain and creates habitat different from that of adjacent uplands. Floodplains serve vital functions that include attenuating flood water, absorbing nutrients, and capturing fine sediment. In addition, floodplains are important fish refuge areas during high flows. Floodplain connectivity indicates the accessibility of a river's floodplain.

Floodprone width – The area adjacent to a river that is prone to inundation, often synonymous with floodplain. The floodprone width is most commonly measured as the width of flow at two times the bankfull depth (Rosgen and Silvey, 1998).

Flow (cfs) – Flow rate. Discharge. The volume of water (ft^3) passing a specific point over a given time (sec).

Flow capacity – The amount of flow a river can hold.

Flow velocity (fps or mps) – The distance water moves over a given unit of time, or the speed at which water moves.

Fluvial geomorphology – The discipline of studying the shape of river channels, how they are formed in a landscape, and their stability in relation to the transport of water and sediment.

FPOM – Fine particulate organic matter. Non-living organic matter that is between 0.45 microns and 1 mm in size ($1.8*10^{-8}$ and 0.04 in), and consists of broken down coarse particulate organic matter, algae, small particles from the river bank, and animal feces.

Gabions – Rock filled baskets that can be stacked along river banks to increase resistance to erosion. Gabions are often applied with joint plantings between the rocks to add a natural vegetation feature to the banks.

Glacial till – Unsorted material that is compacted due to past glaciations and that has tightly compacted particles and limited infiltration capacity.

Glide – A low velocity hydraulic feature, typically situated on the rising bed between pools and riffles, where flow is smooth, yet flow movement is visible. Glides are typically shallower than pools.

Goals – Over-arching statements of broad, general intentions. Because they are so wide-ranging and consist of themes of project success rather than specific objectives, goals are typically not evaluated in a rigorous scientific manner.

Grade control – A local immobile spot on a river bed where channel degradation is halted. Natural grade control includes large rock outcrops on larger rivers, and large immobile trees on smaller channels. Grade control can also be installed using rock cross vanes, log check dams, and piling structures.

Gradually varied flow – Flow that steadily changes its depth and width without abrupt changes, as opposed to rapidly varied flow. Gradually varied flow can occur at subcritical and supercritical flow depths.

Gravel – Particles with diameter between 2 and 64 mm (0.08 and 2.5 in) (Wentworth scale), approximately between the size of the head of a match to a pea.

Groins – Small rock vanes that protrude perpendicularly from the banks that are used to divert flow away from the banks, create downstream scour holes for habitat, and diversify riprap applications.

Hard bank stabilization components – Practices that consist of rock (e.g., riprap) or walls that are used to fix river channels in place. These traditional engineering fixes are typically applied in unnatural rigid channel designs to protect infrastructure, particularly after damaging floods. Although hard components are effective at increasing bank strength and reducing local risks in the river corridor, they often reduce habitat quality and transfer erosion problems downstream. In systems with high flow velocities and unstable channels, soft and hard bank stabilization components can be used together in a combined approach, with hard components on the low to mid bank and soft components on the mid to upper bank.

Head cuts – The progressive down-cutting of a river channel that result from the upstream movement of a locally steep erosion face. Head cuts are part of natural channel evolution, and in disturbed channels can lead to excessive erosion and channel incision. Disturbances that can increase the amount of head cutting include increased frequency of flooding and installing excessively large culverts.

HEC-RAS (USACOE, 2005) – Hydrologic Engineering Center River Analysis System by the US Army Corps of Engineers that is the most popular one-dimensional hydraulics model used in the US. HEC-RAS is a common analytical tool used in moderate and comprehensive projects to determine water surface elevations, water velocities, stable channel dimensions, and sediment transport.

Heterotrophic inputs – Particulate and dissolved non-living organic matter important to supplying energy to the lotic food web and originating outside of the river (i.e., allochthonous). For example, organic matter entering rivers during autumn leaf shed.

Hydraulic geometry relationships (HGRs) – Empirically derived power relationships useful for approximating width, depth, and velocity at a given location in a river with known bankfull discharge or drainage area. Early HGRs (Leopold and Maddock, 1953) were created for channels within a single watershed; however, data for multiple rivers were eventually plotted together to form the first regionalized version of HGRs (i.e., regional curves). Provisional New Hampshire regional curves are available (NHST, 2005).

Hydraulic unit – Riffle, run, pool, and glide that determine the velocity-depth combinations that exist in the channel.

Hydrologic cycle – The movement of water from the oceans, to atmosphere, to rivers, and back again via precipitation, evapotranspiration, infiltration, runoff, groundwater flow, and river flow. The emphasis here is on the river flow component – the movement of freshwater from uplands to oceans.

Impaired – A site that has a lower habitat quality than the average, or control, condition and where obvious signs of poor habitat, such as excessive erosion, the absence of habitat diversity, and the presence of stormwater outfalls, are present.

Impervious cover – Roads, parking lots, buildings, sidewalks, and compacted soils that are often abundant in urban areas, and cause many direct and indirect harmful effects to aquatic ecosystems. The USGS study on impervious cover in the New Hampshire seacoast watershed (2006) indicated impacts at less than 10% imperviousness. The 10% level is a common watershed development threshold often cited in the scientific literature (e.g., CWP, 2003), beyond which impacts to hydrology, fluvial geomorphology, water quality, and aquatic habitat take place.

Incipient motion – The point at which a particle begins to move due to the force of flowing water. This includes a range of analytical techniques that use critical shear stress and threshold velocity to create stable channels by determining how particles of different sizes on the river bed and installed practices with different materials may move over the range of flows at the project site.

Incision – The process of extreme channel degradation when a channel cuts down in its valley, destabilizing banks, introducing increased sediment loads into the channel, reducing access to floodplains, and decreasing habitat quality.

Inner channel – The portion of the channel cross section between the thalweg and the bankfull level. This part of the channel contains the majority of the aquatic habitat associated with the channel bed, and typically carries the mean spring flow.

Instream flows – The amount of flow in a river, and specifically used to refer to maintenance of the natural flow regime (Poff et al., 1997), which includes maintaining the appropriate quantity of water and variation of flows (Richter et al., 1996) within each season.

Interstitial spaces – The small cavities located in between large rocks and woody debris that are important refuge locations for some macroinvertebrates and juvenile fish.

Invasive species – Species that are aggressive pioneers and can readily out-compete others. Many invasive species are also exotic, or not native to an area, as they have competitive advantages to take over an area once moved out of their natural environment (http://www.des.state.nh.us/wmb/ExoticSpecies/). Japanese knotweed (*Fallopia japonica*) is an example of an exotic invasive plant species that lines many river banks preventing the establishment of other natural plant communities.

Irregular sinuous – A meandering river channel pattern where meanders are more irregular than uniform leading to different meander amplitudes and wavelengths.

J-hook vanes – Rock structures that protrude upstream and direct water away from the river bank. Vanes also stabilize the low bank and create downstream scour holes that are good habitat features. J-hooks also have a small curl or hook on the end to enhance pool formation at the tip of the structure.

Joint plantings – Plantings in the small openings (i.e., joints) within other practices such as riprap and gabions that offer a natural vegetation component to traditional hard bank stabilization projects.

Lane's scale (1955) – An image of a scale that shows the balance between the product of discharge and channel slope and the product of sediment discharge and the median particle size ($Q*S \sim Q_d*d_{50}$). This relationship is a useful conceptual tool to understand the root causes of channel degradation and aggradation, and how to slow the on-going process that is destabilizing the channel.

Large woody debris (LWD) – Pieces of wood in a river that have at least one dimension greater than or equal to 1 m (3.3 ft). This decaying wood is essential for habitat and food in a river and has been shown to be closely linked to the health of the river biota.

Longitudinal – In the direction up and down the river corridor. Used here to indicate one of the 'conceptual dimensions of fluvial hydrosystems': longitudinal space, lateral space, vertical space, and time (Pedroli et al., 2001). Longitudinal connectivity refers to the level of access along the river that can be fragmented by dams, undersized or perched culverts, lack of flow, and poor water quality.

Low bank – The lower portion of the bank that is submerged under all but extreme low flow conditions. This portion of the bank is commonly exposed to scour on the outside of meanders, and when erosion increases the low bank is often eroded away first leading to the subsequent collapse of the mid and upper bank.

Main channel – The portion of the channel cross section below the elevation described by the bankfull level. This part of the channel is important for flood conveyance and sediment transport, and typically carries the channel-forming discharge.

Manning's equation ($V = (1.49/N)R^{2/3}S^{1/2}$) – A common equation used to calculate mean uniform velocity (V, fps). N is the Manning's roughness coefficient and is determined by the bed particle size, type of debris present, and condition of the channel. R (ft) is the hydraulic radius, which is the cross sectional flow area divided by the wetted perimeter of the channel. For uniform steady flow, S is the slope of the channel.

Material stability threshold – The critical shear stress or threshold velocity at which a material will begin to erode, such as soils comprising the river bank.

Mean annual flood (cfs) – The average annual peak flow.

Meander chute cut-off – A feature in a highly meandering river channel where water cuts across a meander bend and reduces its flow path. Chutes are a type of channel avulsion that typically form during a large flood.

Meanders – Bends in a river associated with the channel pattern. Meanders are characterized by their amplitude (width from the channel center line) and wavelength (spacing). The degree of meandering is measured by sinuosity. The amount of meandering is generally higher for low-gradient alluvial channels.

Mesohabitat – The term often used for habitat units on the scale of riffles, runs, and pools.

Microhabitat – Small-scale habitat features less than or equal to one meter across, such as components of the substrate in a riffle, that are important elements of aquatic habitat in a river.

Mid bank – The middle portion of the bank that is above the low bank and below the bankfull elevation.

Moderate project – A project category used in these guidelines to represent a project that is medium in scope; has limited goals, attempts to improve channel stability, or tries to rehabilitate or enhance local habitat; has medium to high site constraints and ecological risk; and low to high public acceptance. Design procedures for moderate projects can vary.

Mottling – Spots of colors in the soil that form due to deposition of iron and manganese due to oxidation-reduction reactions that take place in saturated conditions.

Natural bed armoring – A layer of large particles on the bed surface that limit the removal of underlying small size particles due to sheltering from applied shear stresses that is an important consideration when investigating channel stability. The armor layer is typically one to three particles thick, and forms initially along the thalweg before spreading laterally.

Natural form and processes – A general reference to undisturbed shape of channel and banks, as well as the processes that lead to this shape and other natural features of a river. Form is often characterized by channel geometry, pattern, and geomorphic classification. Processes are typically more difficult to observe and include sediment transport, debris processing, nutrient cycling, biological activity, and more, all of which hinge on the range of flows and their variability.

Natural process design - Natural process design restores channel form and processes where all dimensions remain unconstrained and channel evolution may take place. This truly natural channel design method leads to a heterogeneous and deformable channel in dynamic equilibrium. Natural process design is only possible where constraints are limited so that longitudinal barriers are absent and lateral connectivity to the floodplain is a realistic objective.

Nick point – A localized change in bed slope, formerly called cataracts. Nick points that result from movement of an upstream erosion face are called head cuts, while those that are associated with the downstream deposition commonly due to backwatering are called steep riffles.

No action – The first alternative considered in every alternatives analysis where nothing is done, or a passive approach is used. This is not the same as passive recovery, which often includes the initial removal of a stressor so subsequent improvement can take place without additional intervention.

Non-alluvial channel – Channels that are not formed by carving through sediments transported down the river (i.e., alluvium), which tend to be relatively steep, straight, hydraulically rough and stable. Non-alluvial channels often carry sediment source material down from the upper watershed.

NRCS – Natural Resource Conservation Service of the US Department of Agriculture (http://www.nrcs.usda.gov). This agency was formerly called the Soil Conservation Service (SCS).

Objectives – Narrow, precise statements of tangible accomplishments that are anticipated. Objectives are concrete and are usually evaluated.

Operation and maintenance – Normally expected actions that are recommended following project implementation, such as protecting, watering, and weeding young plantings when bioengineering practices are used.

Particle size distribution – The distribution of particle sizes on the river bed that is typically measured using the Wolman (1954) pebble count for coarse beds and sieve analysis for fine beds. Particle size data is typically presented as a cumulative distribution where percent finer is on the vertical axis and particle size is on the horizontal (log) axis.

Passive approach – An alternative where limited actions are taken to eliminate a stressor and recovery takes place over time naturally rather than with the use of installed practices or manipulated cross sections. An example of passive recovery is allowing an unstable channel upstream of an undersized bridge that is prone to excessive aggradation to adjust naturally after the bridge span is increased. In this case, monitoring channel dimensions and profile would be used to track the changes and determine if some intervention should be used (assisted passive recovery).

pH (-log{H^+}) – A measure of the acidity of a solution in terms of the activity of hydrogen ion {H^+}where 7 indicates neutrality, smaller pH values (i.e., more H^+) indicate acidic conditions, and larger pH values (i.e., less H^+) indicate basic conditions. pH is a more than 14 order of magnitude scale, and the typical range of pH in natural waters is 5 to 9. Note that pH increases during photosynthesis and decreases during respiration in waters having a pH above 6.3, and strong variations can impact aquatic organisms.

Photosynthesis (Energy+H^++HCO_3^-→$C_6H_{12}O_6$+O_2) – The production of oxygen (O_2) and conversion of inorganic carbon (HCO_3^-, or bicarbonate) to organic matter (represented by $C_6H_{12}O_6$) by primary producers using the sun's energy. Note that in water with pH larger than 6.3, the pH increases during photosynthesis as hydrogen ion (H^+) is consumed.

Plan view – Map view from above, as in looking down on a river from an airplane and seeing its meander pattern.

Pool – A relatively deep, low velocity hydraulic feature that can occur on the outside of meanders, where the channel contracts, or where boulders or logs span the channel such as in small step-pool systems.

Practice – A single component installed in a river channel or on the banks to improve stability or habitat (Brown, 2000). For example, a cross vane, log revetment, or lunker structure. Naturalized river channel and bank stabilization projects tend to use many practices.

Preliminary alternatives matrix – A table of initial alternatives and other potential management activities to eliminate watershed stressors assembled after review of existing and initial assessment data, to determine how effective each alternative is at meeting specific project objectives with the given site constraints. The preliminary alternatives matrix is a mechanism to for the project team to discuss the alternatives to be eliminated and those that are recommended for further consideration and analysis.

Protection – The act of keeping from damage (American Heritage Dictionary).

Reach – A relatively homogenous portion of a river on the order of 10-100 m (33 to 330 ft) long (Frissell et al. 1986).

Regime methods – Empirically-based approach where power relations are used to determine stable channel dimensions where net annual erosion or deposition is low.

Regular repeating meandering patterns – A meandering channel pattern where the amplitude and wavelength of the meander bends is relatively constant leading to a consistent channel pattern.

Rehabilitation – To improve local river conditions rather than re-establish natural processes that historically created desired conditions. An understanding of the nature, scope, and extent of historical changes is needed to increase the likelihood of project success under contemporary conditions (Montgomery and Bolton, 2003). To restore for use (American Heritage Dictionary).

Resilient – When a system is able to return to normal after a disturbance. In terms of naturalized channel design and bank stabilization projects, resiliency indicates that after a disturbance the system will either remain in or move towards a stable equilibrium between sediment and water.

Respiration ($C_6H_{12}O_6+O_2 \rightarrow Energy+H^++HCO_3^-$) – The consumption of oxygen (O_2) and conversion of organic matter (represented by $C_6H_{12}O_6$) to inorganic carbon (HCO_3^-, or bicarbonate) via respiring organisms. In rivers with pH above 6.3, respiration will cause the pH to decreases as hydrogen ion (H^+) is produced.

Restoration – Restoration means not only reestablishing prior conditions, but reestablishing the processes that create those conditions. An understanding of the nature, scope, and extent of historical changes is needed to define a reference against which to set restoration objectives (Montgomery and Bolton, 2003). The act of bringing something back to its original condition (American Heritage Dictionary). "Return of an ecosystem to a close approximation of its condition prior to disturbance (NRC, 1992)".

Revetments – Materials or structures placed on banks to increase resistance to erosion. Common types of revetments used in naturalized channel design and bank stabilization projects are made from angular rock (riprap), large boulders, logs, root wads, and trees.

Riffle – A high velocity hydraulic feature where flow is shallow and turbulent and has pockets of broken water where there is mixing with the atmosphere.

Riffle stability index (RSI) (Kappesser, 2002) – A measure of bed stability in a riffle that is gaining popularity in river assessment. RSI is calculated by determining the particle size distribution in a riffle, measuring the largest mobile particles on a nearby deposition bar, and using the cumulative particle size distribution to identify the associated percent finer of the largest mobile particle size. This percentage is the RSI, which describes the percentage of the riffle that is mobile.

Rigid boundary – A non-deformable boundary, such as when channel bed or banks are reinforced with non-erodable materials over a wide range of flows. Rigid channels are common design components in developed areas where roads, structures, and other human infrastructure are in the river corridor.

Riprap – Angular rock that is commonly applied to river banks to reduce erosion.

River channel classification – Grouping river channel types to facilitate comparisons for design. Classification can be based on a wide range of characteristics (see review by Niezgoda and Johnson, 2005) such as watershed position (Schumm, 1977), location in the network of channels (Strahler, 1952), channel slope and position along the longitudinal continuum (Montgomery and Buffington, 1993), and channel shape, particle size, and relationship to floodplain (Rosgen, 1994; Rosgen and Silvey, 1996).

River continuum concept – A widely used conceptual model describing a continuous relationship between channel size and its biological communities (Vannote et al., 1980). Coarse particulate organic matter (CPOM), periphyton, shredders and collectors, and invertivorous fish dominate small rivers. Medium-sized rivers mostly have fine particulate organic matter (FPOM), periphyton and macrophytes, collectors and grazers, and more diverse fish assemblages. Large rivers typically have FPOM and dissolved organic matter (DOM), phytoplankton, collectors, and bottom-feeding fish.

River crossings – Where roads, railroads, and trails cross rivers. Common river crossing structures include bridges, culverts, and fords.

River gage – A water-level monitoring station that has had a rating curve developed to transform stage readings to discharge. The USGS maintains a network of river gages in the US that have data accessible via the Internet. New Hampshire data are located at http://nh.water.usgs.gov/.

River order – The size and location of a river relative to the others in the network of channels (Strahler, 1952). Headwater rivers are 1st order, and when two 1st order rivers meet they form a 2nd order river. When two 2nd order rivers meet they form a 3rd order river, and so on. If two rivers of different orders join, they retain the higher order downstream of the confluence. New Hampshire hydrography data includes both intermittent and perennial small headwater rivers as 1st order.

River profile – A longitudinal view of a river where a slice is taken in the direction of flow. The longitudinal (long) river profile reveals the normal repeating configuration of riffle, run, pool, and glide bed features, which are also described as hydraulic units based on their surface water characteristics.

Rosgen method – A popular river channel classification system that is based on entrenchment ratio, width to depth ratio, sinuosity, slope, and dominant particle size (Rosgen, 1994; Rosgen and Silvey, 1996, 1998).

Routine project – A project category used in these guidelines to represent a project that is small to medium in scope; has limited goals, attempts to improve channel stability, or tries to rehabilitate or enhance local habitat; has low to medium site constraints and ecological risk; and medium to high public acceptance. Design procedures for routine projects can be limited.

Run – A moderate velocity hydraulic feature where the water surface is rough, yet not very turbulent.

Salinity wedge – Used to generally describe the extent that salt water reaches upstream in a tidally-influenced river. Technically refers to a high density layer of salt water moving along the bottom in an estuary or coastal river.

Sand – Particles with diameter between 0.063 and 2.0 mm (0.003 and 0.08 in) (Wentworth), approximately smaller than the size of the head of a match.

Scale – Quantification of space (spatial) and time (temporal).

Scour – Local erosion where flow plunges towards the bed or banks. Common examples of scour include the regular erosion found on the outside of a meander bend, the scour hole formed under an undersized bridge, and the scour holes intentionally created downstream of rock vanes.

Sediment transport capacity (tons per day) – The ability for a reach to transport sediment. When adjacent reaches are compared, aggradation is predicted when downstream capacity drops, while degradation is likely when downstream capacity increases.

Self-sustaining – When a system is able to sustain itself independently. For naturalized channel design and bank stabilization projects, self-sustaining indicates maintenance of stable channel equilibrium, which is always a goal to minimize and possibly eliminate the need for future management activities at a given site.

Semi-natural form design – Commonly referred to as 'natural channel design', a design approach based on replicating a reference reach where a stable channel exists. This form-based method has popularized the analog approach to river restoration, where fluvial morphology is the primary means of assessment and project design. Semi-natural form design typically has a partially constrained planform to limit channel migration, and thus channel evolution is halted. It is this control that both limits full restoration potential, but allows for a more naturalized design approach over rigid channels where site constraints and human investments are present in the river corridor.

Sinuosity – The curvilinear nature of the plan form of a river channel. Sinuosity is determined by dividing the length of the river channel, as measured along the thalweg, by the straight valley length between two points.

Slope – The difference in elevation between two points on the riverbed divided by the distance between the two points. When measuring in the field, it is important to make measurements in a consistent location within the same type of hydraulic unit (e.g., the head of a riffle) and at the same cross-sectional location (e.g., in the thalweg) to ensure measurement of the slope of the riverbed rather than changes due to local features along the profile. The riverbed slope is a fundamental parameter of the river that leads to its dynamic equilibrium between water and sediment transport. Note that beyond the channel bed slope described above, water surface slope and slope of the energy grade line are also used in hydraulic calculations. Under the approximation of uniform and steady flows, all three of these slopes are equal.

Soft bank stabilization components – Practices that consist of deformable materials such as logs, stakes, plants, and fiber rolls that are used to increase bank strength while also naturalizing the river and improving near-bank habitat quality. These bioengineering approaches are typically applied in semi-natural form and natural process designs.

Soil augers – A hand-held or mechanical tool used to extract soil samples. Augers typically consist of either two split spoons or a large cork screw on the end of a pole that are twisted in and out of the soil.

Stadia rod - A graduated metal, plastic, or wood rod used during survey to determine distances and elevations.

Stakeholders – The varied group of people that are interested in the project. There is a growing awareness that inclusion of all possible stakeholders is important to come up with plans that have support throughout the design, construction, and monitoring phases.

Steady flow – Flow with constant stream velocity and depth during the time period considered. Steady flow rarely takes place in nature, but is a very common approximation used to simplify hydraulic calculations.

Steep riffle – An abrupt change in slope in the river bed that results from the downstream movement of a localized deposition face.

Storm flow – Event flow. Discharge that is a result of a storm event increasing flow beyond baseflow conditions.

Stressors – General sources of problems. Stressors to river systems lead to changes in response variables such as reduced channel stability and impaired aquatic habitat.

Subcritical flow –When the water depth is larger than the critical depth and flow is slow and tranquil (Chanson, 2004). Under subcritical flow, water depth will decrease if the river bed is raised and will increase if the bed is lowered.

Substrate – The river bed, or the sediment that constitutes the bed of a river at a given location and time. Substrate can be moved via erosion and placed via deposition depending on flow conditions.

Supercritical flow – When the water depth is less than the critical depth and flow is fast and torrential (Chanson, 2004). Under supercritical flow, water depth will increase if the river bed is raised, and depth will decrease if the bed is lowered.

Target species – The species that is (are) targeted for recovery. Salmonids, such as trout, are a common target species for naturalized channel design and bank stabilization projects. Target species are often monitored both before and after implementation.

Terrace – The flat surface on top of a topographical step in the landscape. Terrace is often used to describe the different parts of the floodplain such as the low active terrace that is regularly inundated and the upper terraces that are inundated less frequently.

Terrace riser – A topographical step in the landscape that often marks the boundary between different parts of a floodplain and uplands.

Thalweg – A line up and down a river channel that connects the lowest bed elevation at each cross section. The area immediate to the thalweg concentrates low flows and typically carries the mean dry season flow.

Theodolite – An optical survey instrument that accurately measures horizontal and vertical angles while mounted on a tripod. Most theodolites in use today include electronics to rapidly record data in digital format, and are often called total stations. Modern survey equipment includes GPS stations where optics are replaced with a receiver to pick up a transmitted signal that is directly tied into the local datum. A transit is simplified version of a theodolite that performs the same functions.

Threshold velocity – The minimum water velocity required to move a particle of a given size or a material.

Toe – The bottom part of the low bank. Toe is often used when describing the reinforcing of the bottom of the low bank for combination practices used on the banks (e.g., rock toe or log toe).

Tractive force methods – A design approach that considers a channel stable when there is no net movement of particles on the bed.

Tractive shear stress ($\tau = \gamma RS$) – The downstream force on the riverbed and bank particles due to flowing water. τ is the shear stress (lb per sq ft), γ is the density of water (62.4 lb per cu ft), R is the hydraulic radius (ft), and S is the slope of the energy grade line. S equals the slope of the river channel, which is also equal to the slope of the water surface, under the assumption of steady uniform flow.

Tripod-mounted level – An optical surveying instrument that measures the height of distant points relative to an arbitrary datum with an accompanying stadia rod. If a vertical benchmark exists near the survey site, the height of the instrument can be determined to transform measurements into actual elevations. Levels are commonly used for small survey tasks such as follow up monitoring when cross sections have been monumented.

Trophic level – The nutrient level of a water body or river. Also used to indicate the levels of the food chain.

Turbidity (NTU or nephelometric turbidity units) – The cloudiness of water measured by the optical scatter produced when passing a beam of light through a sample.

Undercut bank – A bank that has had its base cut away by water action in the river. Undercuts that stabilize for some period of time form deep pockets of habitat at the base of a riverbank that offer shelter, access to food, and cool water temperatures during summer baseflow. These areas are often associated with overhanging vegetation and steep banks.

Undermined – When the base support is removed and upper parts collapse. Commonly used to describe bank collapse when excessive erosion on the low bank leads to collapse of the mid and upper bank as well.

Uniform flow – Constant velocity and depth over a portion of the channel considered where flow is considered to be smooth. Uniform flow rarely takes place in nature, but is a very common approximation used to simplify hydraulic calculations.

Unnatural rigid channel design - Unnatural rigid channel design uses hard materials to fix channels in place in some or all dimensions, and eliminates natural processes and channel evolution. This river management method is often applied after large flood events to stabilize streambanks in developed areas where human investments are abundant in the river corridor. Although rigid design is effective at reducing local risks in the river corridor, problems can be transferred downstream by isolating channels from their floodplains and reducing habitat quality due to a homogenization of features.

Upland – Land not subject to periodic inundation. Typically dry areas in a watershed.

Upper bank – The portion of the bank above the bankfull level to the break in slope at the physical top of the bank. This portion of the bank is typically inundated only for medium and large floods, and is a good place to always consider bioengineering and re-vegetation options before hard practices such as riprap.

USDA – United States Department of Agriculture (http://www.usda.gov).

USEPA – United States Environmental Protection Agency (http://www.epa.gov).

USGS – United States Geological Survey (http://www.usgs.gov).

Valley slope – The change in elevation divided by the straight-line distance between two distant points in a valley. This slope ultimately regulates the channel slope and thus is useful for comparison to channel slope when investigating channel alignment. Recall that sinuosity is equal to the length of the channel centerline divided by the straight-line length in the valley, which is equal to the valley slope divided by the channel slope since the change in elevation between two points is the same for the valley and channel.

Vanes – Common structural practices typically made of large rock on bigger rivers and logs on smaller rivers, which are installed protruding upstream from the bank that diverts flow away from the bank towards the center of the channel. The result is less shear stress on the low and mid bank, and a downstream scour hole that is useful habitat.

Velocity-area method – A field method of calculating river flow where velocity and depth are measured at intervals across a river and then total discharge is determined by summing the calculated discharge through each cross sectional element.

Watershed – The area of up-gradient land surface that contributes precipitation as runoff or groundwater flow to a specific point in a river or lake. The boundaries of a watershed are known as divides and are located at topographical high points in a landscape. All of the surface water in a watershed flows out of that watershed via the outlet.

Width:depth ratio – The bankfull width divided by the mean bankfull depth, which gives a dimensionless measure of the size of a river cannel.

Wing deflectors – Rock/log triangular practices that are typically used to deflect flow away from the banks, create downstream scour holes for refuge, and diversify local hydraulics. Deflectors often have the long side of the triangle along the river bank and thus also help stabilize the low bank during high flows.

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