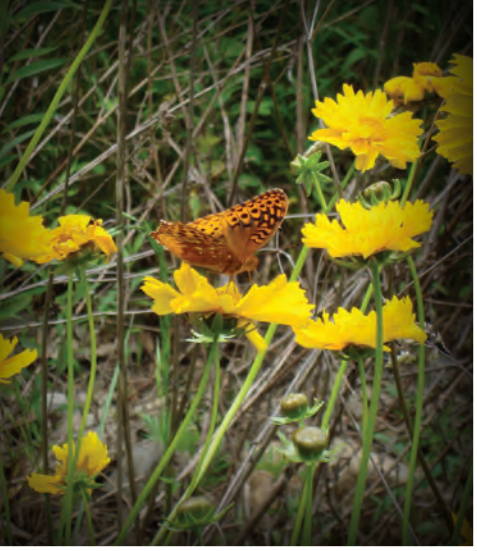

StreamMechanics

A Function-Based Framework

for Stream Assessment & Restoration Projects

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The findings and conclusions in this document are those of the authors and do not necessarily represent the views of the US Fish and Wildlife Service (FWS) or the US Environmental Protection Agency (EPA).

Authors' Note:

This document provides a new framework for approaching stream assessment and restoration from a function-based perspective; as such, it will benefit from review, comments, and example experiences and applications. Please share these with the authors so the concepts, examples and templates can be revised and expanded. Contact any one of the following: Will Harman, lead author (***wharman@stream-mechanics.com***, 919-747-9448), Brian Topping, EPA project sponsor (***topping.brian@epa.gov***, 202-566-5680) or Rich Starr, FWS project sponsor (***rich_starr@fws.gov***, 410-573-4583).

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The Framework presented in this document was tested through a pilot workshop at the FWS National Conservation Training Center in the summer of 2010. EPA staff from around the country attended the workshop and provided comments on how to improve the Framework and workshop. They also provided real-world examples of stream impacts and restoration needs from various regions that could be used to develop case studies. These scientists and managers included: Eric Somerville, Ed Reiner, Robert Montgomerie, Stephanie Chin, Carol Petrow, David Rider, Bill Ainslie, Mara Lindsley, Sue Elston, Melissa Gebien, Melanie Haveman, Scott McWhorter, Catherine Holston, Jason Daniels, Richard Clark, Toney Ott, Tracie Nadeau, Linda Storm, Brent Johnson, Greg Pond, Joy Gillespie, Brian Topping and Palmer Hough.

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4. Restoration of High-Gradient, Headwater Streams

GLOSSARY OF TERMS

Biology Function: Level 5 functions of the Stream Functions Pyramid that involve the biodiversity and the life histories of aquatic and riparian organisms. These functions are placed at the top of the Pyramid because they are affected by all underlying Levels (Chapters 4 and 10).

Condition: The relative ability of an aquatic resource to support and maintain a community of organisms having a species composition, diversity and functional organization comparable to reference aquatic resources in the region (Chapter 2).

Compensatory Mitigation: The restoration (re-establishment or rehabilitation), establishment (creation), enhancement and/or, in certain circumstances, preservation of aquatic resources for the purpose of offsetting unavoidable adverse impacts that remain after all appropriate and practicable avoidance and minimization has been achieved (Chapters 2 and 11).

Credit: A unit of measure representing the accrual or attainment of aquatic functions at a compensatory mitigation site. The measure of aquatic resource functions is based on the resources restored, established, enhanced or preserved (Chapters 2 and 11).

Credit Production: The number of credits should reflect the difference between pre- and post-compensatory mitigation project site conditions, as determined by a functional assessment or other suitable method (Chapters 2 and 11).

Debit: A unit of measure representing the loss of aquatic functions at an impact or project site. The measure of aquatic resource functions is based on the resources impacted by the authorized activity (Chapters 2 and 11).

Determination of Credits: A description of the number of credits to be provided, which includes a brief explanation of the rationale for this determination (Chapters 2 and 11).

Enhancement: The manipulation of the physical, chemical or biological characteristics of an aquatic resource to heighten, intensify or improve a specific aquatic resource function(s). Enhancement results in the gain of selected aquatic resource function(s), but may also lead to a decline in other aquatic resource function(s). Enhancement does not result in a gain in an aquatic resource area (Chapters 2, 4 and 11).

Functions: The physical, chemical and biological processes that occur in ecosystems.

Function-Based Parameters: Parameters that are used to quantify or describe the functional statement provided in the broad-level view of the Stream Functions Pyramid. They can be a structural type of parameter that describes a stream condition at a point in time, or they can be an actual function expressed as a rate that directly relates to a stream process (Chapter 4).

Functional Capacity: The degree to which an area of aquatic resource performs a specific function (Chapter 2).

Functional Category: The term for each level of the Stream Functions Pyramid, which includes five levels: Hydrology (Level 1), Hydraulics (Level 2), Geomorphology (Level 3), Physicochemical (Level 4), and Biology (Level 5) (Chapter 4).

Functional Statement: The statement that describes the functions for each Functional Category, e.g., the transport of water from the watershed to the channel for Level 1 (Chapter 4).

Geomorphology Function: Level 3 functions on the Stream Functions Pyramid that involve transport of wood and sediment within the channel to create diverse bed forms and dynamic equilibrium (Chapters 4 and 8).

Hydraulic Function: Level 2 functions on the Stream Functions Pyramid that involve transport of water in the channel, through sediments, and on the floodplain (Chapters 4 and 7).

Hydrology Function: Functions at the base of the Stream Functions Pyramid (Level 1) that involve the transport of water from the watershed to the channel (Chapter 6).

Impact: An adverse affect.

Interagency Review Team (IRT): An interagency group of federal, tribal, state and/or local regulatory and resource agency representatives that reviews documentation for, and advises the district engineer on, the establishment and management of a mitigation bank or in-lieu fee program.

Measurement Methods: A wide range of tools, techniques, metrics and assessment approaches that qualify or quantify the Function-Based Parameters. Each measurement method is assigned a category for Type, Level of Effort, Level of Complexity, and whether it is a Direct or Indirect measure. Refer to Chapter 4 and Appendix Ac for a comprehensive list of the measurement methods and their assigned categories.

Mitigation Rule: The 2008 Federal Compensatory Mitigation Rule administered by the US Corps of Engineers and the US Environmental Protection Agency (33 CFR Parts 325 and 332; 40 CFR Part 230).

Performance Standards: Observable or measurable physical (including hydrological), chemical and/or biological attributes that are used to determine if the compensatory mitigation project meets its objectives.

Physicochemical Function: Level 4 functions on the Stream Functions Pyramid that involve water quality associated with the Biology Function, including water chemistry, nutrients and organic matter (Chapters 4 and 9).

Reference Aquatic Resource: A set of aquatic resources that represents the full range of variability exhibited by a regional class of aquatic resources as a result of natural processes and anthropogenic disturbances (Chapter 2).

Reference Condition: A contextual background against which the degree of degradation, range of condition, and benefits of restoration can be measured.

Reference Reach: A term often used in Natural Channel Design for developing dimensionless ratios to assess channel dimension, pattern and profile.

Restoration: The manipulation of the physical, chemical and biological characteristics of a site with the goal of returning natural/historic functions to a former or degraded aquatic resource.

Restoration Priority Levels: Also referred to as the Rosgen Priority Levels of Restoration. Includes four restoration approaches for restoring incised channels (Chapters 3 and 11).

Riparian Areas: Lands adjacent to streams, rivers, lakes and estuarine shorelines that provide a variety of ecological functions and services and help improve or maintain water quality.

Service Area: The geographic area within which impacts can be mitigated at a specific mitigation bank or an in-lieu fee program.

Stream Functions Pyramid: The hierarchical representation of stream functions with five levels: Hydrology, Hydraulics, Geomorphology, Physicochemical and Biology.

Stream Functions Pyramid Framework: The four components of the Stream Functions Pyramid. First, broad-level view shows the five functional categories (Levels) with the underlying controlling variables of geology and climate. Second, function-based parameters are provided for each functional category. Third, measurement methods are provided for each function-based parameter. And fourth, where possible, performance standards are provided for the measurement methods.

EXECUTIVE SUMMARY

Stream restoration efforts have increased significantly in the US over the past few decades and are now recognized as a billion-dollar industry. These restoration efforts stem from centuries of abuse as humans continue to alter the riverine landscape for a variety of purposes, including farming, logging, mining and development on the floodplain, and the subsequent need for channelization and flood control. These activities have significantly diminished the natural functions of our stream corridors.

Today stream corridor restoration efforts seek to improve or restore these lost functions. A variety of federal, state and local programs, along with efforts from non-profit organizations, provide funding for these programs. The goals are varied and range from simple streambank stabilization projects to watershed scale restoration. For these projects to be successful it is important to know *why* the project is being completed and *what techniques* are best suited to restore the lost functions. **Knowing why a project is needed requires some form of functional assessment followed by clear project goals. To successfully restore stream functions, it is necessary to understand how these different functions work together and which restoration techniques influence a given function. It is also imperative to understand that stream functions are interrelated and build on each other in a specific order, a functional hierarchy. If this hierarchy is understood, it is easier to establish project goals. And with clearer goals, it is easier to evaluate project success.**

A large amount of funding for stream restoration is related to compensatory mitigation required as part of Clean Water Act (FWPCA, 1972) Section 404 permits issued by the US Army Corps of Engineers (USACE). As part of a 404 permit authorizing impacts to streams in one location, the 404 permit may require the permittee to conduct stream restoration or enhancement activities in a nearby stream to compensate or offset the loss of stream functions at the permitted impact site. The 2008 Federal Mitigation Rule recommends that a functional or condition assessment be completed at the impact site to quantify ecological losses (debits) and at the mitigation site to quantify projected ecological gains (credits), which would be realized if the mitigation project is successfully implemented (33 CFR 332.3(f)(1), 2008). Credits generated at the mitigation site should offset the debits estimated at the impact site. Success criteria and performance standards are required to measure mitigation project success and ensure that mitigation projects do indeed generate the amount of credits initially projected.

Interagency Review Teams (IRTs) associated with each USACE District can provide valuable support in the effective implementation of the 2008 Mitigation Rule, including the development of region-specific Standard Operating Procedures (SOPs) designed to aid in assessing debits and credits. However, the science of stream assessment is complex and the practice of stream restoration is relatively young and rapidly evolving. Additionally, many IRT staff have a stronger background in wetland science than fluvial geomorphology or stream ecology, making the development of effective SOPs a significant challenge for IRTs.

Document Goals

In order to address the central stream restoration issues delineated above, this document presents three primary goals:

1. Help the restoration community understand that stream functions are interrelated and generally build on each other in a specific order, a functional hierarchy, and understand that parameters can be used to assess those functions even if some parameters are functions and others are structural measures.

This goal is addressed in the document in several ways. First, an overview of watershed and stream corridor processes is provided in Chapter 3. This chapter describes the basic interplay of processes that work together in order for the watershed and stream corridor to function; it serves as a watershed science "refresher" and includes references to other sources for a deeper understanding of how watersheds work. Also provided in this chapter is the background science necessary to understand the Stream Functions Pyramid Framework that is presented in Chapter 4 and fully described throughout the remainder of the document. The Stream Functions Pyramid Framework illustrates the hierarchy of stream functions and provides a list of function-based parameters and measurement methods that can be used to describe the functions. Performance standards are also provided for each measurement method, when available.

2. Place reach scale restoration projects into watershed context and recognize that site selection is as important as the reach scale activities themselves.

The importance of site selection is discussed in several places throughout the document, including in Chapters 3 and 11. Site selection is a critical part of a stream restoration project, especially if the goal is to provide physicochemical and/or biological improvements. This step can make the difference between a successful and an unsuccessful project.

3. Provide informal guidance and ideas on how SOPs might incorporate stream functions into debit/credit determination methods, function-based assessments and performance standards.

This is a core element of the document. Chapter 11 provides examples of how the Stream Functions Pyramid can be used to develop these parts of the SOP. Chapters 6 through 10 provide detailed information about the relative importance of each function-based parameter, their measurement method and performance standard, where applicable.

This document is not a stand-alone stream assessment method, list of performance standards or mitigation SOP, and in no cases should all of the measures or example performance standards be used on a single project. In addition, there may be special projects that require parameters, measurement methods and performance standards that are not included in this framework; it is not all-inclusive. As discussed in each chapter, many of the measures are only appropriate in certain stream types or landscape positions, and often multiple measures of the same function are reviewed. Practitioners should take care to ensure the measures used are appropriate for the stream type, fully capture the existing condition and can accurately measure achievement of the goals of the project.

Stream Functions Pyramid Framework

The Framework used in this document was inspired by Fischenich (2006), where the USACE and a group of scientists and practitioners developed functional objectives for stream restoration projects. This document uses different terminology than the Fischenich (2006) document in an attempt to tie stream functions to common parameters that can be used to describe functions. This document does not delineate between parameters that are functions versus those that are structural measures. Rather, the parameters are called function-based because each parameter can be used to help understand the overall function for a given category, which is described below. Stream functions are separated into a hierarchy of categories, ranging from Level 1 to Level 5 and include:

- Hydrology (Level 1)
- Hydraulic (Level 2)
- Geomorphology (Level 3)
- Physicochemical (Level 4)
- Biology (Level 5)

Within this hierarchical Framework, higher-level functions are supported by lower-level functions, like a pyramid. For example, Hydraulic functions cannot occur without Hydrologic functions, and so on. Chapter 4 describes each level in detail, and the full Pyramid Framework synopsis, including measurement methods and performance standards, is provided in Appendix A.

Social and recreational functions and values like fishing or boating are not included in this document, and the hierarchy of functions is not all-inclusive. There are many other parameters that can be assessed in order to describe a given function. However, this document provides a structure and organization that can easily be adapted to fit individual project goals and environmental settings. Since the lower-level functions of Hydrology, Hydraulics and Geomorphology are required before Physicochemical and Biology functions can be realized, this document places more focus on the lower-level functions. In addition, these lower-level foundational functions have traditionally been addressed more in stream restoration designs.

Stream Functions Pyramid Application

Chapter 11 provides detailed information about how the Pyramid can be applied. But in general, there are three main areas where the Pyramid can provide guidance: setting project goals and objectives, developing/reviewing specific function-based stream assessment methods, and creating SOPs for stream mitigation programs.

Setting Project Goals and Objectives

A common stream restoration goal that is often stated in stream mitigation plans is the improvement of channel dimension, pattern and profile so that the channel does not aggrade or degrade. This goal primarily addresses channel stability. The Pyramid can be used to develop goals that more directly relate to the improvement of functions. Well-conceived goals should help answer the question, "Why is this project being pursued and what functional improvements are being targeted?" Once a goal has been established, the Pyramid can be used to develop objectives that call out which parameters, measurement methods, or even performance standards will be used to evaluate the functional improvement. In addition, once function-based goals and objectives have been selected and identified within a certain level, the Pyramid can be used to determine which supporting functions (lower levels) also need to be addressed.

Developing Function-based Stream Assessment Methods

Although it is not a functional assessment methodology, the Pyramid is a Framework that can be used to create functional assessments or at least function-based assessments. Using the Pyramid as a guide for developing function-based stream assessments will help ensure that a protocol addresses parameters in the correct order based on function. These assessment methodologies should include parameters from each level as it applies to site and/or regional conditions and constraints. In addition, simple parameters may be selected for rapid-based assessments, and more time-intensive parameters may be selected for more complex studies. Parameters could also be selected to show functional gain or improvement at a restoration or mitigation site, or functional loss at a proposed impact site. Somerville (2010) provides a good overview of existing function-based assessments, including their strengths and weaknesses.

Creating SOPs for Stream Mitigation Programs

The Pyramid can also be used by Interagency Review Teams (IRTs) to develop debit and credit determination methods and performance standards for stream mitigation projects. In addition, if reference reaches are also assessed using a function-based approach, the functional capacity of the mitigation site can be addressed. This will help IRTs to move away from attaching credits to restoring dimension, pattern and profile, and move toward changes in parameters that describe or are themselves functions. Example templates are provided in Chapter 11 to give IRTs ideas about how to create function-based debit/credit determination methods. Additional case studies representing a variety of scenarios are also provided in Appendix B. These example templates and case studies are truly meant to be examples and are not a policy recommendation. They should be considered "food for thought" as each IRT develops an SOP that fits their region.

Understanding the functional hierarchy of stream restoration is vital to our nation's efforts to reclaim and restore its riverine landscapes. This document is meant to become a comprehensive resource for the public, private and non-profit organizations and agencies whose goals include stream restoration. The hope is that when this hierarchy (the Stream Functions Pyramid) is fully comprehended, embraced and applied, the efforts to restore our nation's streams will become more focused, precise…and successful.

Chapter 1
Introduction

Stream restoration efforts have increased significantly in the US over the past few decades and are now recognized as a billion-dollar industry (Bernhardt et al., 2005). These restoration efforts stem from centuries of abuse as humans continue to alter the riverine landscape for a variety of purposes, including farming, logging, mining and development on the floodplain with its subsequent need for channelization and flood control. These activities have significantly diminished the natural functions of our stream corridors (Wohl, 2004).

Today stream corridor restoration efforts seek to improve or restore these lost functions. A variety of federal, state and local programs, along with efforts from non-profit organizations, provide funding for restoration efforts. The goals are varied and range from simple streambank stabilization to watershed scale restoration. Stream/wetland mitigation for permitted impacts to aquatic resources also contributes to a large portion of the overall restoration effort. For these projects to be successful, it is important to know *why* the project is being completed and *what techniques* are best suited to restore the lost functions. Knowing why a project is needed requires some form of functional assessment to determine the nature and magnitude of the impairment, followed by clear project goals designed to best address the impairment. To successfully restore stream functions, it is necessary to understand how these different functions work together and which restoration techniques influence a given function.

It is also important to know that stream functions are interrelated and build on each other in a specific order, a functional hierarchy. If this hierarchy is understood, it is easier to establish project goals. And with clearer goals, it is easier to evaluate project success. **One goal of this document is to help the restoration community understand that stream functions occur in a general order, and that parameters can be used to assess those functions even if some parameters are functions and others are structural measures. Functions should be addressed in the order shown to have a successful project. Another goal is to place reach scale restoration projects into a watershed context and recognize that site selection is as important, if not more important, than the reach scale activities themselves.**

A large amount of funding for stream restoration is related to compensatory mitigation required as part of Clean Water Act Section 404 permits issued by the US Army Corps of Engineers (USACE). As part of a 404 permit authorizing impacts to streams in one location, the 404 permit may require the permittee to conduct stream restoration or enhancement activities in a nearby stream to compensate or offset the loss of stream functions at the permitted impact site. The 2008 Federal Mitigation Rule recommends

that a functional or condition assessment be completed at the impact site to quantify ecological losses (debits) and at the mitigation site to quantify projected ecological gains (credits), which would be realized if the mitigation project is successfully implemented (33 CFR 332.3(f)(1), 2008). Credits generated at the mitigation site should offset the debits estimated at the impact site. Success criteria and performance standards are required to measure mitigation project success and ensure that mitigation projects do indeed generate the amount of credits necessary to offset permitted impacts.

Interagency Review Teams (IRTs) associated with each USACE District can provide valuable support in the effective implementation of the 2008 Mitigation Rule, including the development of region-specific Standard Operating Procedures (SOPs) designed to aid in assessing debits and credits. However, the science of stream assessment is complex and the practice of stream restoration is relatively young and rapidly evolving. Additionally, many IRT staff have a stronger background in wetland science than fluvial geomorphology or stream ecology, making the development of effective SOPs a significant challenge for IRTs. **Consequently, another goal of this document is to provide recommendations and ideas on how SOPs might incorporate stream functions into debit/credit determination methods, function-based assessments and performance standards.**

1.1 » DOCUMENT OVERVIEW

The document is organized as follows:

Chapter 2: Overview of Federal Compensatory Mitigation Regulations: This chapter provides a brief overview of the 2008 Federal Compensatory Mitigation Rule and how this document supports the implementation of this Mitigation Rule. This chapter may be helpful to those who are not familiar with stream mitigation and its associated terminology.

Chapter 3: Watershed and River Corridor Processes: This chapter describes the basic interplay of processes that work together for the watershed and stream corridor to function; it serves as a watershed science "refresher" and includes references to other sources for a deeper understanding of how watersheds work, as well as provides the background science necessary to understand the Stream Functions Pyramid and Framework described in Chapter 4.

Chapter 4: The Stream Functions Pyramid: This chapter provides a detailed overview of the Framework used in this document to assess stream functions. This Framework, called the Stream Functions Pyramid Framework, describes the proposed hierarchy of stream functions and provides a list of function-based parameters, measurement methods and performance standards that can be used to describe the functions. *It is important to read this chapter before proceeding to the Hydrology through Biology chapters (Chapters 6 through 10).*

Chapter 5: Reference Streams: This chapter provides an overview of how reference stream reaches are used in natural channel design, stream assessments and stream mitiga-

tion. An introduction section provides a discussion about why a reference reach is important and the different ways it can be used. Information is also provided about how to select a reference reach based on project goals and objectives. A variety of existing field assessment and data analysis methods are provided.

Chapters 6-10: Hydrology, Hydraulic, Geomorphology, Physicochemical and Biology — These five chapters provide detailed information about the relative importance of each function-based parameter, their measurement methods and performance standards, where applicable. Some parameters and measurement methods do not have performance standards, but instead have design standards. Design standard sections are included for those parameters that are critical for understanding stream processes but are not appropriate for performance standards (typically because the research does not currently support a standard, and sometimes because the parameter is too variable or too site specific). Sediment transport competency and capacity are examples of parameters that include a section on design standards but not performance standards. These chapters represent the bulk of the document and are intended to serve as a reference or guide for those who are developing function-based assessments, restoration goals or performance standards.

Chapter 11: Applications — This chapter shows how the Stream Functions Pyramid can be used to help develop stream restoration goals, function-based assessments and debit/credit determination methods for stream mitigation SOPs. Examples of each are provided. For the SOP example, different scenarios are provided that represent the bulk of stream impacts and restoration needs from across the country.

It should be noted that this document is not a stand-alone stream assessment method, list of performance standards or mitigation SOP, and it is not necessary or recommended to apply all of the measures or example performance standards for a single project. In addition, there may be important parameters that are not included, especially for rare or unique settings. As discussed in each chapter, many of the measures are only appropriate in certain stream types, environmental settings, climates or landscape positions, and often multiple measures of the same parameter are provided. In addition, actual stream assessments may utilize a combination of parameters to determine an overall functional score, something that this document does not provide. Practitioners should take care to ensure the measures used are appropriate for the stream type, fully capture the existing condition, and can accurately measure achievement of the project goals.

1.2 » WHAT THE DOCUMENT DOES AND DOES NOT PROVIDE

This document does provide:

- An overview of watershed and riverine processes.
- A hierarchical framework illustrating the relative relationship of stream functions and parameters that can be used to describe those functions. The hierarchical Framework,

called the Stream Functions Pyramid, shows that functions build on each other in a general order and that physical functions — like the transport of water and sediment — support physicochemical and biological functions. Parameters include structural and functional measures, which together are considered to be function-based. Most importantly, the hierarchy provides a logical framework of parameters that practitioners can use to evaluate stream functions.
- The state of the science and tools to help create function-based goals, assessment methods, debit/credit determination methods and performance standards.
- Examples of how the Stream Functions Pyramid can be applied to setting project goals and objectives, developing specific function-based stream assessment methods, and creating debit/credit determination methods for stream mitigation programs.
- References to key textbooks, peer-reviewed papers and websites for more in-depth information.

This document does not provide:
- A Standard Operating Procedure for stream assessments and mitigation.
- Stream debit and credit formulas. However, IRTs can use select parameters and their corresponding methods of measurement and performance standards as a guide for creating formulas for their region.
- A specific functional assessment methodology.
- A specific monitoring approach.
- Even though the Framework includes a wide range of parameters that can be used to describe functions in their respective category, the document does not promote using all of these parameters in a given assessment or restoration project. The same is true for the measurement methods. A variety of measurement methods are provided for each parameter. Rather than use all of the measurement methods for a given parameter, the user should pick the best methods given the project goals and budget.
- A manual or textbook on fluvial processes and stream assessment. However, references are provided that cover a wide range of stream processes and functions.
- Function-based parameters in this document are not all-inclusive. Other function-based parameters, measurement methods and performance standards may exist that are more suitable based on project objectives.

1.3 » PROJECT PARTNERSHIPS

The development of this document is through a partnership between the US Fish and Wildlife Service (FWS) and US Environmental Protection Agency (EPA). The FWS and EPA entered into a partnership in 2006 to develop and provide standardized tools and training modules on how to evaluate stream assessments and restoration designs. The FWS and EPA recognized the need for these tools and training modules to improve the link between stream restoration and compensatory mitigation under Section 404 of the Clean Water Act. Additionally, such tools and training modules are relevant to a suite of state, local and federal natural resource agencies that are regularly tasked with reviewing

the merits of stream restoration, enhancement and/or protection projects proposed as restoration, or to compensate for authorized impacts to streams.

The first stream tool and training module developed under this agreement was the *Natural Channel Design Review Checklist*. The Checklist provides guidance on important factors to consider when reviewing natural channel designs. It is intended to provide the reviewer with a rapid method for determining whether a project design contains an appropriate level of information. The Checklist consists of a list of questions that must be answered as part of a design review and includes the following sections: Watershed and Geomorphic Assessment, Preliminary Design, Final Design, and Maintenance and Monitoring Plans. The training module uses a 3.5-day training course and includes an overview of stream processes, channel stability and function, restoration potential, and natural channel design techniques.

More information on offerings of the trainings can be found at *training.fws.gov* and *www.stream-mechanics.com*. The *Natural Channel Design Review Checklist* and other stream mitigation resources can be found on EPA's website for compensatory mitigation under the "Technical Resources for Stream Mitigation" section: *water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm*.

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Chapter 2

Overview of Federal Compensatory Mitigation Regulations

2.1 » OVERVIEW

Since a major goal of this document is to provide IRTs with tools that can be used to develop Standard Operating Procedures (SOPs), a brief background is provided on the Federal Mitigation Regulations as it pertains to credit determination methods, functional assessments and performance standards. This overview is provided for informational purposes only and should not be considered an official source of regulatory information. The interpretations are those of the authors and do not necessarily represent the views of the EPA or the USACE.

In April 2008 the USACE and the EPA jointly issued new regulations clarifying compensatory mitigation requirements for Department of the Army permits (33 C.F.R. § 332/40 C.F.R. § 230). The 2008 Mitigation Rule was designed to improve the planning, implementation and management of compensatory mitigation projects. It emphasizes a watershed approach in selecting compensatory mitigation project locations, requires measurable performance standards, requires regular monitoring for all types of compensation, and specifies the components of a complete compensatory mitigation plan. This plan includes assurances for long-term protection of compensation sites, financial assurances, and identification of parties responsible for specific project tasks. The 2008 Mitigation Rule also applies equivalent standards to the three mechanisms for providing compensatory mitigation: permittee-responsible compensatory mitigation, mitigation banks and in-lieu fee mitigation.

While traditional approaches to determining the appropriate amount of compensation involved reliance on measures of acres or linear feet, the USACE and EPA explicitly stated in the preamble to the Final Rule that, *"With this rule, we are encouraging the use of functional and condition assessments to determine the appropriate amount of compensatory mitigation needed to offset authorized impacts, instead of relying primarily on surrogate measures such as acres and linear feet. In the future, there will be more assessment methods available to quantify impacts and compensatory mitigation."* (FR Vol 73, 19633) The Rule recognizes that science-based rapid function or condition assessment methodologies provide a more objective, systematic and reliable approach to characterize and quantify the expected aquatic resource losses or debits at impact sites, as well as the potential aquatic resource gains or credits at compensatory mitigation sites.

To ensure that functional gains have indeed occurred at a mitigation site, the permittee (or mitigation provider in the case of mitigation banks or in-lieu fee programs) must meet a set of ecological performance standards tailored to its specific compensation project.

The 2008 Mitigation Rule requires that these performance standards be based on the best available science that can be measured or assessed in a practicable manner. The rule states that performance standards must be based on attributes that are objective and verifiable, which may include variables or measures of functional capacity from the following:

- Functional assessment methodologies,
- Measurements of aquatic resource structural characteristics, and/or
- Comparisons to reference aquatic resources of similar type and landscape position.

Implementation of effective performance standards provides the USACE, other members of the IRT and other regulatory agencies with observable and measurable parameters to ensure that compensatory mitigation is meeting its objectives. To ensure that performance standards are met, a project's mitigation plan must also include mechanisms to provide adequate monitoring, maintenance strategies and long-term stewardship.

2.2 » RESOURCES

The EPA provides stream and wetland mitigation resources on their website (*water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm*). The Federal Mitigation Regulations can be downloaded from this website along with a wealth of additional information, including fact sheets, guidance manuals, training resources and technical resources. Terms from the regulations are used throughout this document, and their definitions are provided in the glossary.

Chapter 3

Watershed and River Corridor Processes

3.1 » WATERSHED PROCESSES

Streams and rivers are integral parts of the landscape, carrying water and sediment from higher elevations to downstream lakes, estuaries and oceans. Along the way, they provide life-giving water to a wide array of ecosystems, including wetlands, bogs, ponds, forests and floodplains.

The land area draining to a stream or river is called its watershed. When rain falls in a watershed, it runs off the land surface, infiltrates the soil or evaporates, forming the fundamental components of the hydrologic cycle (Figure 3.1). From the standpoint of stream formation, the greatest concern is with the hydrologic processes of runoff and infiltration. Surface runoff, whereby excess water collects on the ground surface and flows over land toward watershed valleys and stream systems, is produced when rainfall exceeds the rate at which water can infiltrate the soil. Surface runoff is the process by which stream levels rise and fall during and following rainfall events.

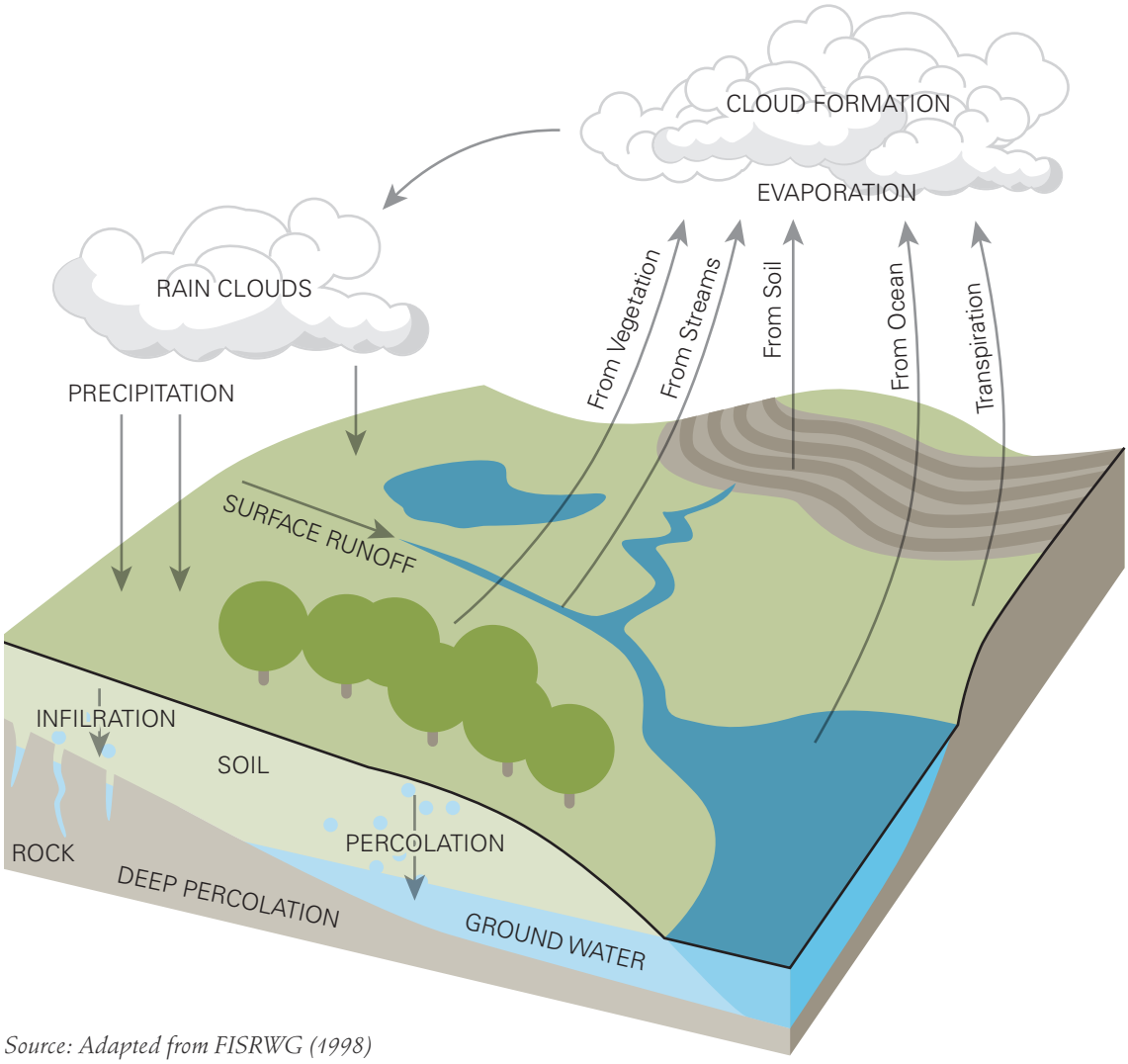
In most systems, a large portion of the water that infiltrates the soil also reaches the stream system, but by sub-surface or groundwater flow. This process occurs much more slowly and steadily than surface runoff. Groundwater discharge is the main source of water that produces baseflow conditions in stream channels.

The hydrologic processes (precipitation, infiltration, runoff, evaporation) that occur at the watershed level influence the character and functions of streams. Small stream channels form at the higher elevations, or headwater regions, of a watershed and become progressively larger in size as the watershed size increases (i.e., moving downstream). In the headwater regions of a watershed, surface runoff concentrates and moves downhill, forming small ephemeral channels and gullies. Ephemeral channels carry only surface runoff and thus flow only for short periods of time (generally less than 24 hours) following rainfall events. Moving down the watershed, ephemeral channels carry more and more water and become intermittent channels, which carry water for extended periods following rainfall events and during wet seasons. Intermittent channels carry surface runoff but also receive discharge from shallow groundwater, particularly during wet portions of the year. Farther downstream, intermittent channels give way to perennial channels, which generally flow year round. Perennial channels carry not only surface runoff, but also groundwater discharge that maintains baseflow conditions in the stream. During drought periods, groundwater levels can drop, and even perennial stream channels can stop flowing for periods of time. But in general, perennial channels maintain some permanent water level that sustains aquatic life and provides the functions that are

most associated with creeks and rivers. (For more information on the hydrologic cycle and its role in the development of streams, see *Stream Corridor Restoration: Principles, Processes and Practices* (FISRWG, 1998) www.nrcs.usda.gov/technical/stream_restoration.)

A stream and its watershed comprise a dynamic balance where the floodplain, channel and stream bed evolve through natural processes that erode, transport, sort and deposit sediments. Land-use changes in the watershed, channel straightening, culverts, removal of streambank vegetation, impoundments and other activities can upset this balance. As a result, adjustments in channel form often occur with changes in the watershed. A new equilibrium may eventually result, but not before the associated aquatic and terrestrial environment are altered, often severely. By understanding the processes that occur at the watershed scale, the role and function of the river is better understood, and proper decisions for its care and protection can be made.

FIGURE 3.1 THE HYDROLOGIC CYCLE



Source: Adapted from FISRWG (1998)

3.2 » RIVER CORRIDOR PROCESSES

River Form and Function

The interaction of streamflow with the banks and bed produces a wide variety of stream channel forms (Knighton, 1998). Though streams and rivers vary in size, shape, slope and bed materials, all streams share common characteristics and functions. Streams have banks and beds consisting of mixtures of substrate (i.e., cobble, gravel, sand or silt/clay) that usually differ from the surrounding floodplain soils. Other physical characteristics shared by some stream types include pools, riffles, steps, point bars, meanders, floodplains and terraces. All of these stream characteristics collectively describe the river's form and are driven by the interactions between climate, geology, topography, vegetation and land use changes in the watershed.

Stable streams in wide valleys migrate across the landscape slowly over geologic time, while maintaining their overall form and function. Naturally stable streams must be able to transport the sediment load supplied by their watershed. Instability occurs when scouring causes the channel bed to erode (degrade), or excessive deposition causes the channel bed to rise (aggrade). Often, instability results from changes in the watershed. For example, stream degradation can result from urbanization influences. During storm events, increased impervious surfaces in a watershed produce greater runoff amounts, and stream flooding frequency and intensity also increase, leading to excessive stream bed scour and degradation. Stream aggradation can result from poor land-use practices that lead to excess sediment in runoff reaching the stream, increasing the sediment load of a stream above that which it can adequately transport.

A generalized relationship of stream stability is shown as a schematic drawing in Figure 3.2, often referred to as Lane's Diagram (Lane, 1955). The drawing illustrates that sediment size and load is proportional to channel slope and discharge. A change in any one of these variables can cause a physical adjustment in the stream channel form. Therefore, channel form characteristics and changes in channel form over time are often used to assess channel stability and whether the channel is in equilibrium with its watershed. The most commonly used parameters to describe and quantify channel form are dimension, pattern and profile, each of which is described below.

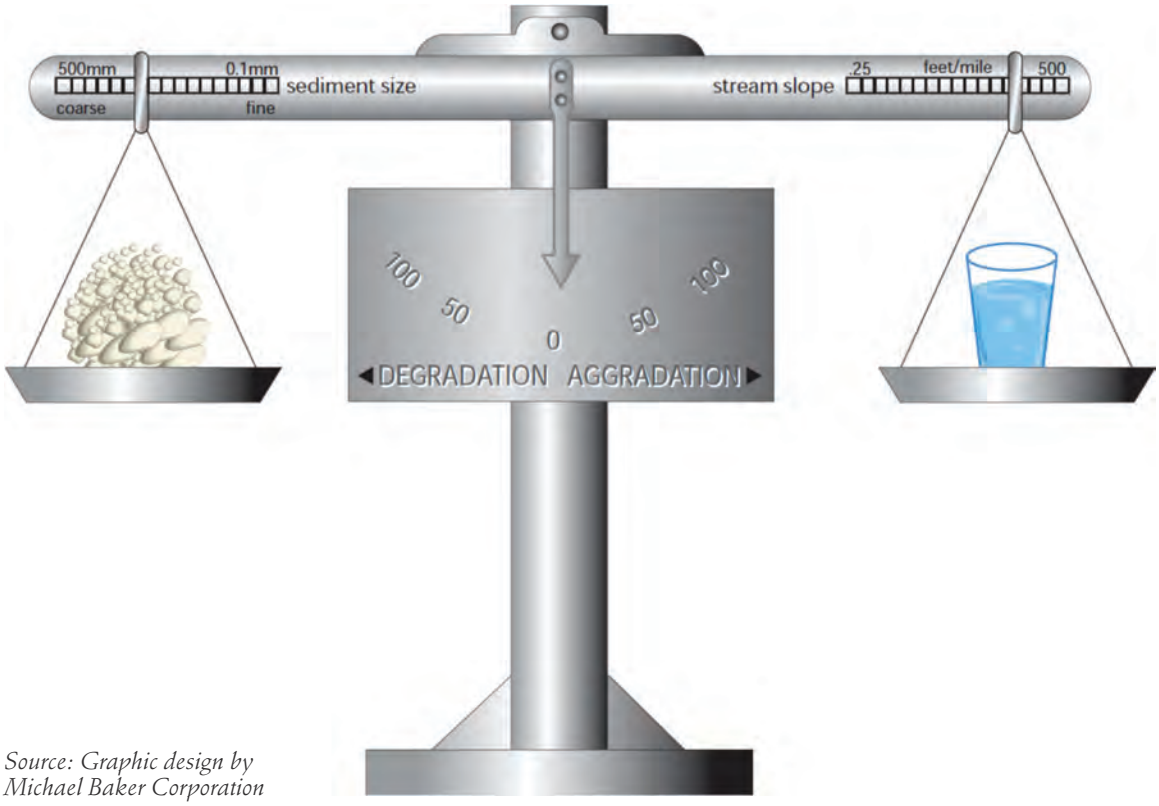
3.3 » CHANNEL FORM

Channel Dimension

The dimension of a stream refers to the cross-sectional shape of the channel and includes such parameters as width, depth, bank height, hydraulic radius, etc. The width of a stream generally increases in the downstream direction in proportion to the square root of discharge. The width and depth of a stream are also influenced by discharge (occurrence and magnitude), the sediment the stream transports (size and type), stream bank vegetation, and the stream bed and bank materials. For example, in the humid, Southeastern portions of the US, stream channels tend to have narrow widths and deeper depths due to dense vegetation and cohesive floodplain soils. In the arid to semi-arid

Southwestern regions, stream channels tend to be much wider and shallower, with less streambank vegetation and more erodible bank sediments.

FIGURE 3.2 LANE'S DIAGRAM
(Illustrating factors affecting channel degradation and aggradation)



Source: Graphic design by Michael Baker Corporation

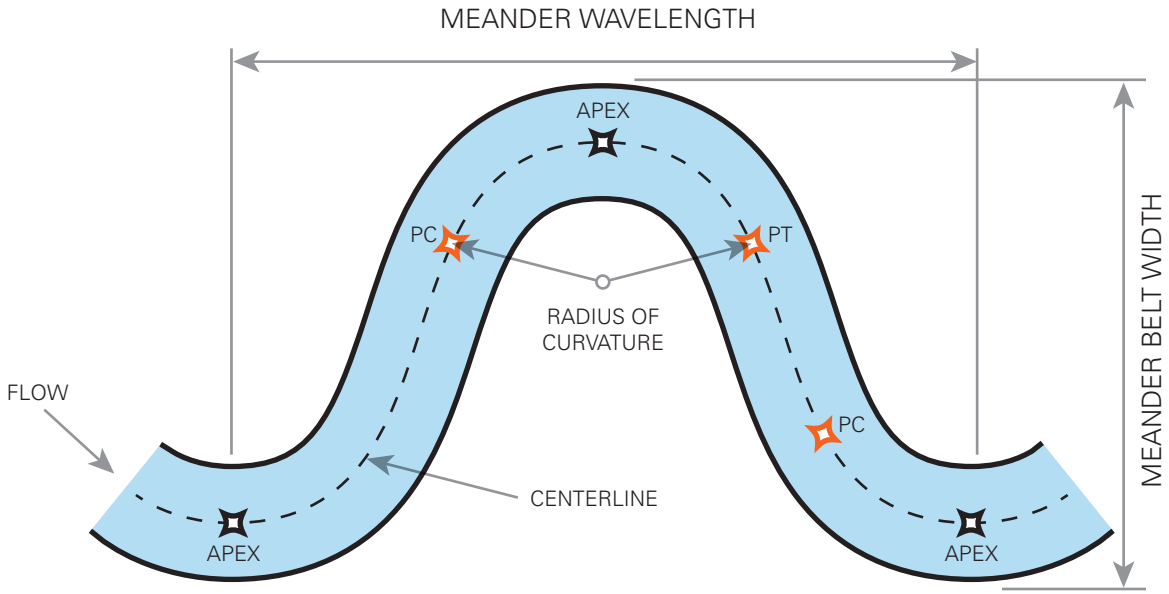
Channel Pattern

Stream pattern refers to the aerial view of a channel. Streams located in steep, narrow valleys tend to be straighter and follow the alignment of the valley, whereas streams on broad, flat floodplains tend to follow a more sinuous path. Quantitatively, stream pattern can be defined by measuring sinuosity, meander wavelength, radius of curvature, amplitude, and belt width (Figure 3.3). The sinuosity of a stream is defined as the channel length divided by the valley length, which is measured along the direction of fall of the valley. A meandering stream reach increases resistance and reduces channel gradient relative to a straight reach. The geometry of the meander and spacing of riffles and pools adjust so that the stream performs minimal work and balances its energy.

Channel Profile

The profile of a stream refers to its longitudinal slope. At the watershed scale, channel slope generally decreases as you move downstream. The size of the bed material also

FIGURE 3.3 PATTERN MEASUREMENTS OF A MEANDER BEND

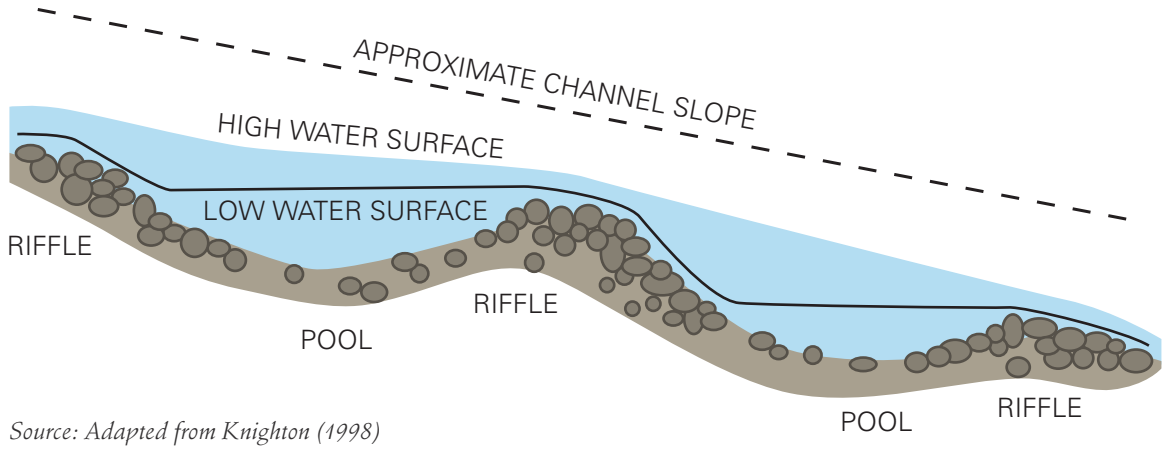


PC = Point of Curvature = point at which the straight section of a riffle meets the curved section of a meander bend.

PT = Point of Tangency = point at which the curved section of a meander bend meets the straight section of a riffle.

Source: Adapted from Rosgen (1996)

FIGURE 3.4 LONGITUDINAL PROFILE OF A STREAM



Source: Adapted from Knighton (1998)

typically decreases in the downstream direction. Channel slope is inversely related to sinuosity. This means that steep streams have low sinuosity and flat streams have high sinuosity. The profile of the stream bed can be irregular because of variations in bed material size and shape, riffle-pool spacing and other variables. The water surface profile mimics the bed profile at low flows. As water rises in a channel during storms, the water surface profile becomes more uniform (Figure 3.4).

3.4 » OVERVIEW OF STREAM FUNCTIONS

Streams carry the water supplied by their watershed. The resulting hydrology and hydraulic processes provide the basic foundation for all other functions that streams provide. The relationships between precipitation, runoff, infiltration and groundwater flow determine the amount of water that the stream carries at any given time, the energy of the water to move sediment, the physicochemical processes that affect water quality, and the biological processes that the stream will support. Stream channels that are connected with their floodplains attenuate flood pulses and spread nutrients and organic matter during flooding events. Streamflows rise and fall with precipitation and snowmelt events, resulting in the dynamic range of flows, which defines the channel form on which many other processes and functions rely. Groundwater is both recharged and discharged along stream channels, providing another hydrologic link between the stream channel and the landscape.

At the interface between the stream channel and the soil surface lays the hyporheic zone, a layer of sediment, soil and porous space where interchanges between streamflow and groundwater occur. Water that moves from the stream into the hyporheic zone is held for a longer retention time than normal streamflow. In addition, because of the intermixing between nutrient rich groundwater and oxygen rich stream water, the hyporheic zone is of critical importance to the chemical transformations that affect nutrients and other compounds within stream systems.

The transport of water and sediment is reflected in the bed features that are formed within a stream channel. Natural streams have sequences of riffles and pools or steps and pools that maintain channel slope and stability (Figure 3.4). The riffle is a bed feature that may have gravel or larger rock particles. The water depth is relatively shallow, and the slope is steeper than the average slope of the channel. At low flows, water moves faster over riffles, which removes fine sediments and provides oxygen to the stream. Riffles enter and exit meanders and control the stream bed elevation. Pools are located on the outside bends of meanders between riffles. The pool has a near-flat water surface (very low slope) and is much deeper than the stream's average depth. At low flows, pools are depositional features and riffles are scour features. At high flows, however, the pool scours and the bed material deposits on the riffle. This occurs because a force applied to the stream bed, called shear stress, increases with depth and slope. Depth and slope increase rapidly over the pools during large storms, increasing shear stress and causing scour.

Stream channels, corridors and floodplains form a valuable ecosystem network. In addition to transporting water and sediment, natural streams provide habitat for many

aquatic organisms including fish, amphibians, aquatic insects, mollusks and plants.

Riffles and pools, and other bed features such as runs and glides, form a diversity of aquatic habitats and provide the foundation for many of the biological and water quality functions that streams provide. Macrobenthic organisms cling to rocks and coarse substrates in riffle areas, filtering food from the flowing water and thriving on the oxygen-rich water. Many fish species utilize meander pool areas due to the cover provided for protection and ambush and for cooler water temperatures afforded by the deeper water depth. Even within a single meander pool, there are aquatic organisms that prefer to live at varying water depths and locations within the pool, illustrating the natural diversity and biological functions that stream systems provide. The hyporheic zone also serves as a habitat zone for certain aquatic species and microbial life that is especially suited for life in this transition zone between groundwater and surface waters.

Trees and shrubs along the streambanks regulate water temperatures through shading and provide organic matter to the system, which is stored and transported forming the energy web that supports aquatic life and diversity. The processes of energy transfer in streams are simplistically described by the river continuum concept (RCC). The RCC is a generalization that is based on the idea that a watercourse is an open ecosystem in constant interaction with the streambank and bed, and moving from source to mouth, constantly changing (Gordon et al., 2004). Beginning in its headwaters, the energy available to a river is highly influenced by the organic material that is delivered from its watershed, or sources external to the stream itself. Moving downstream, the impact of direct contributions of new material to the river becomes less important as the material delivered from upstream continues to be processed and transformed, and primary production within the river becomes a more dominant source of energy than external inputs of organic matter. The RCC provides a theoretical model for visualizing the importance that energy relationships have on biodiversity and chemical functions of a stream system.

Streams affect groundwater levels and the transfer of water and nutrients between adjacent wetlands and riparian areas, supporting ecosystem diversity beyond the limits of the stream channel itself. Riparian buffers along streams filter sediment and pollutants from runoff, and promote uptake of nutrients and chemical reactions in the soil and water column that improve water quality. Streams also provide recreational functions, such as fishing, boating, swimming, wildlife viewing and green space.

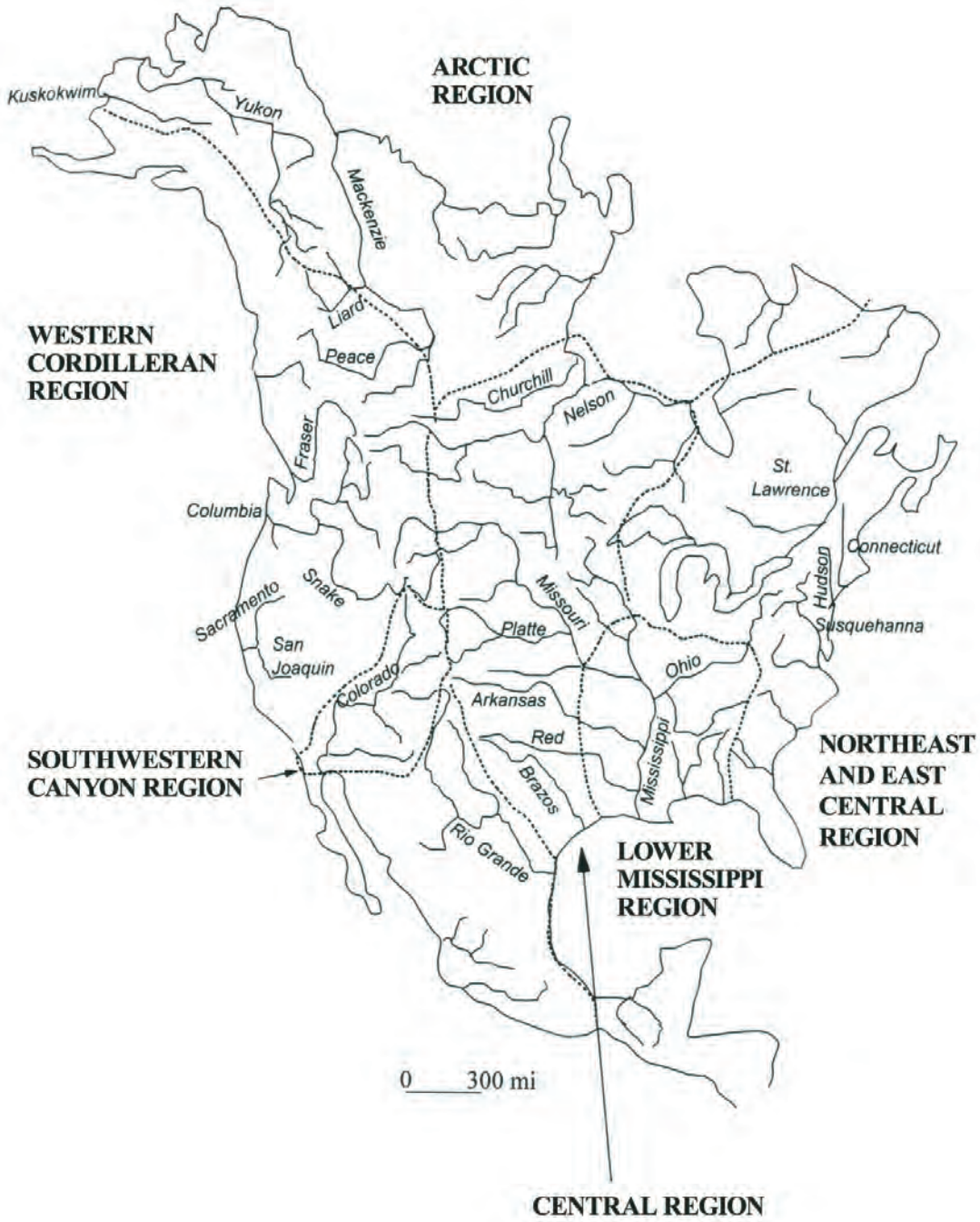
All the functions described above relate back to the river's form and its relationship with its watershed. For more information regarding the river's form and its relationship to processes and functions, see Knighton (1998), Leopold et al., (1992) and Wohl (2004).

3.5 » AMERICAN RIVER REGIONS

North America supports a wide variety of river and stream systems, owing to the wide range of climatic and geologic conditions across the continent. River systems of the continent can be divided into six major regions, as proposed by Wohl (2004). Figure 3.5 shows the location of each of these regions, and a brief summary of each region (as described by Wohl, 2004), is provided below. Wohl's river regions can be considered a

broad delineation for North America. For more detailed information on major river basins within North America and the functions they provide, see *Rivers of North America*, edited by Benke and Cushing (2005).

FIGURE 3.5 RIVER REGIONS MAP OF NORTH AMERICA (Wohl, 2004)



Source: Adapted from Wohl (2004)

Arctic Region

The rivers in the Arctic Region drain north to the Arctic Ocean. Rivers of this region are characterized by high sediment loads (in part from glacier melt and streambank erosion due to freeze/thaw cycles) and ice flows, and often exhibit braided channel forms. The Mackenzie and Yukon Rivers are the largest river drainages within the region. Streams of the region support very little year-round aquatic species, but are host to some of the largest yearly runs of anadromous fish species, such as salmon, anywhere in the world.

Western Cordilleran Region

The Western Cordilleran rivers drain primarily to the Pacific Ocean, although some originate east of the continental divide and drain to the Atlantic Ocean. The region stretches from southern California north to Alaska, and from the Pacific Ocean to roughly the continental divide. Rivers of the region are diverse but are commonly characterized as steep, mountain streams. Many of this region's rivers begin at their headwaters as high-gradient, step-pool channels, where high sediment loads, debris flows and landslides are common. Moving further down gradient, the rivers become large and meandering, with moderate sediment loads and course substrates. Like the Arctic Region rivers, rivers of the Western Cordilleran Region were once home to large populations of trout and seasonal runs of salmon; however, degraded stream habitat, flow durations and water quality in the region have reduced or eliminated many of these populations.

Central Region

Rivers of the Central Region are generally characterized as broad, shallow, meandering river systems. Streams of the northern Central Region drain to Hudson Bay, while streams of the central and lower portion of the region drain to the Mississippi River and the Gulf of Mexico. Peak flows occur during spring and early summer, as a result of snow melt and intense rains. Fine sediment loads are often high. The streams of the region are very diverse biologically, supporting a wide range of fish and aquatic species.

Northeast and East-Central Region

The Northeast and East-Central Region rivers drain east to the Atlantic Ocean. The St. Lawrence River drains the upper portion of the region. Along the central-Atlantic Coast, a variety of rivers begin in the Appalachian Mountains, crossing the Piedmont and Coastal Plain physiographic regions on their way to the Atlantic Ocean. Rivers of the region mostly drain densely vegetated catchments, keeping sediment loads relatively low. High flows typically occur in the fall and winter, with the exception of large tropical systems that can drop large amounts of rainfall quickly and cause significant flooding during the summer and early fall months. Rivers of this region, like those of the Lower Mississippi Region, support the greatest species richness and highest number of endemic species of any of the rivers in North America.

Lower Mississippi Region

Rivers of the Lower Mississippi Region drain to the Gulf of Mexico and originate in

the southwestern portion of the Appalachian Mountains and the eastern edges of the great interior plains. These rivers meander broadly over low-slope floodplains created by long-term sediment deposition. Suspended sediment loads are often high, as commonly observed with the lower Mississippi River. Rivers of this region have been highly manipulated with levees and channelization to decrease the threat of flooding and provide more land for development. Species diversity is high throughout the region.

Southwestern Canyon Region

The Southwestern Canyon Region rivers and streams are characterized by deeply-incised channels and canyon valleys that have downcut over geologic time to keep pace with uplift of the Colorado Plateau by geologic forces. These streams flow through desert lands, with the larger rivers being perennial streams that flow year-round, while many of the smaller streams only flow for portions of the year. Suspended sediment loads are high due to the highly erodible soils and sedimentary rocks of the region. Many of the native fish species are endemic species that are limited to the Colorado River Basin.

3.6 » STREAM CLASSIFICATION

Stream classification is an important tool to communicate information about streams using a common language. There have been many stream classification systems published over the past century, beginning with Davis (1899) that classified streams in terms of age (youthful, mature and old age). These classification systems use different approaches to categorize streams based on qualitative and quantitative assessment at different spatial and temporal scales, e.g., Montgomery and Buffington (1993) developed a stream classification system that is applicable to the Pacific Northwest region. For further details about stream classification history, refer to Naiman et al. (1992) and Rosgen (1994). In general, the most useful stream classification system should encompass a broad spatial and temporal scale, integrate structural and functional characteristics under different disturbance regimes, provide information about form and process mechanisms that control stream features, and be easily applied by stream practitioners (Naiman et al., 1992). For the purposes of this publication, the Rosgen (1994) stream classification system will be referenced when describing stream types. This system can be applied consistently over a large geographic area using quantitative descriptions. It has also been referenced by many USACE Districts as part of the compensatory mitigation program (USACE Wilmington District et al., 2003; USACE Savannah District, 2004; USACE Norfolk District and VDEQ, 2007; and USACE Charleston District, 2010).

The specific objectives of the Rosgen stream classification system (Rosgen, 1996) include:

1. Predict a river's behavior from its appearance.
2. Develop specific hydraulic and sediment relationships for a given stream type.
3. Provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics.
4. Provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties.

The Rosgen (1994) classification and assessment system consists of four levels (Levels I through IV), ranging from broad qualitative descriptions to detailed quantitative assessments (Figure 3.6). Level I and Level II are the predominant parts used to characterize the stream. Level I is a broad geomorphic characterization that categorizes streams into eight different stream types (A through G) using the integration of landform and fluvial features of valley morphology with channel slope, pattern, profile and dimension. Level II is called the morphological description and requires field measurements. The stream types are divided into discrete slope ranges and dominant channel-material particle sizes, which are given numbers 1 (bedrock) through 6 (silt/clay). Figure 3.7 presents a key for the Rosgen system for Level I and Level II.

Details for Level III and Level IV are not provided in this publication but can be found in Rosgen (1994; 1996). In general, Level III is an evaluation of stream condition and stability that requires an assessment and prediction of channel erosion, riparian condition, channel modification and other characteristics. Level IV is verification of predictions made in Level III and consists of sediment transport, streamflow and stability measurements.

3.7 » WATERSHED AND STREAM RESTORATION

Watershed Scale Restoration

Many of the impairments present in today's rivers and streams are a result of processes that occur at the watershed level. Poor sediment and erosion control practices lead to excess fine sediments that are delivered to water courses. Increased urbanization and impervious surfaces result in increased runoff during rainfall events, and higher peak streamflows that cause erosion and stream down-cutting. Pollution, both from point sources and non-point sources, enters streams and impairs water quality. To address these impairments, improvements and restoration must be performed at a watershed scale.

"A watershed approach is the most effective framework to address today's water resource challenges. Watersheds supply drinking water, provide recreation and respite, and sustain life. More than $450 billion in food and fiber, manufactured goods, and tourism depends on clean water and healthy watersheds."

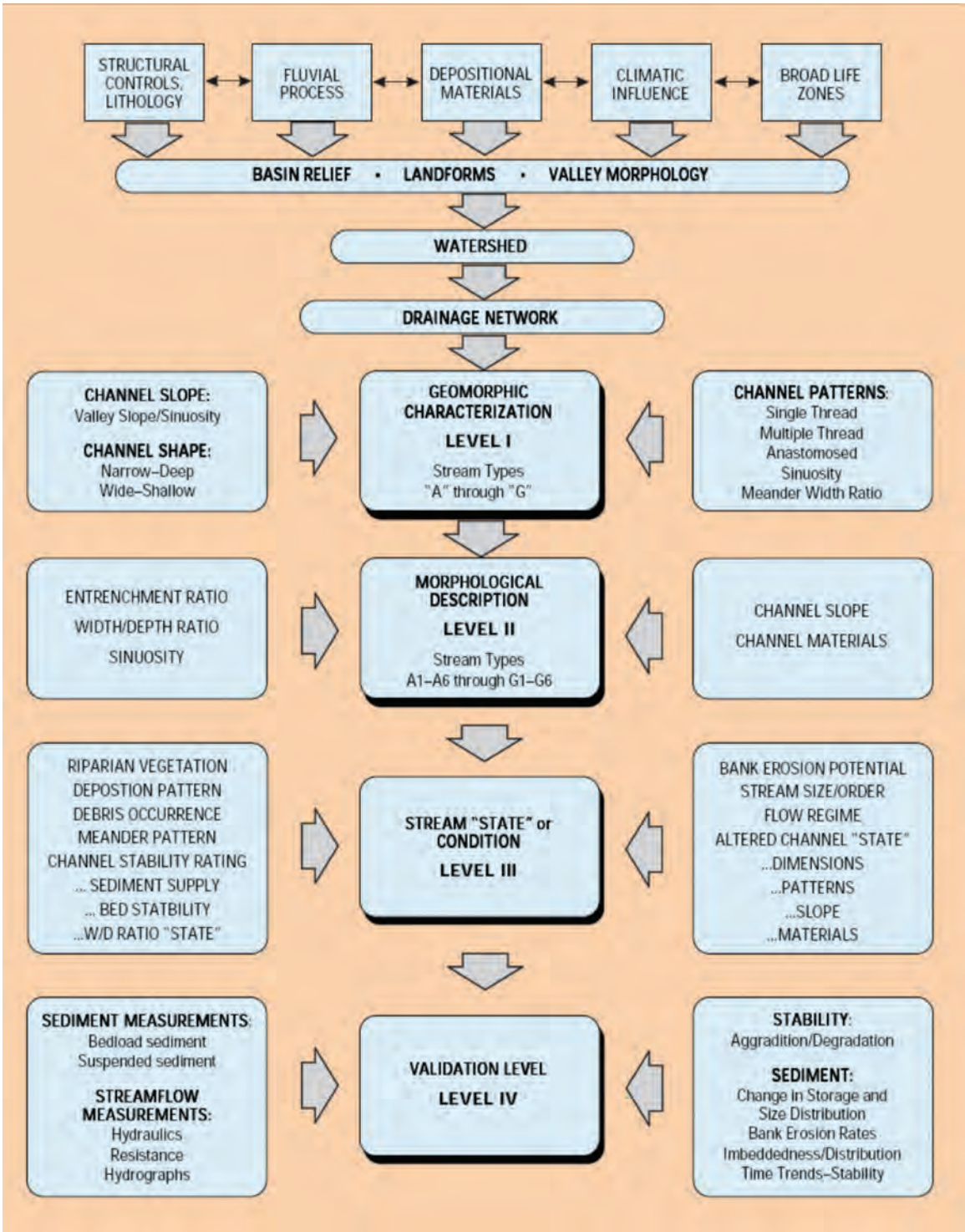
~US Environmental Protection Agency
(*water.epa.gov/type/watersheds/approach.cfm*)

"We cannot save trout without saving their river and floodplain habitats. We cannot save river and floodplain habitats — and the plants and insects of the trout's food web — if we do not also maintain the processes controlling water and sediment entering the river corridor from the surrounding hillslopes and uplands. They go hand in hand."

~Ellen Wohl, Disconnected Rivers, 2004

Emphasis on watershed-level restoration and water-quality improvements is increasing, and the tools being used are also expanding. Over the past two decades, there have been considerable interest and use of best management practices (BMPs) as a tool for address-

FIGURE 3.6 THE HIERARCHY OF RIVER INVENTORY AND ASSESSMENT (Rosgen, 1996)



Source: Reproduced with permission from Wildland Hydrology

FIGURE 3.7 KEY TO THE ROSGEN STREAM CLASSIFICATION OF NATURAL RIVERS (Rosgen, 1996)

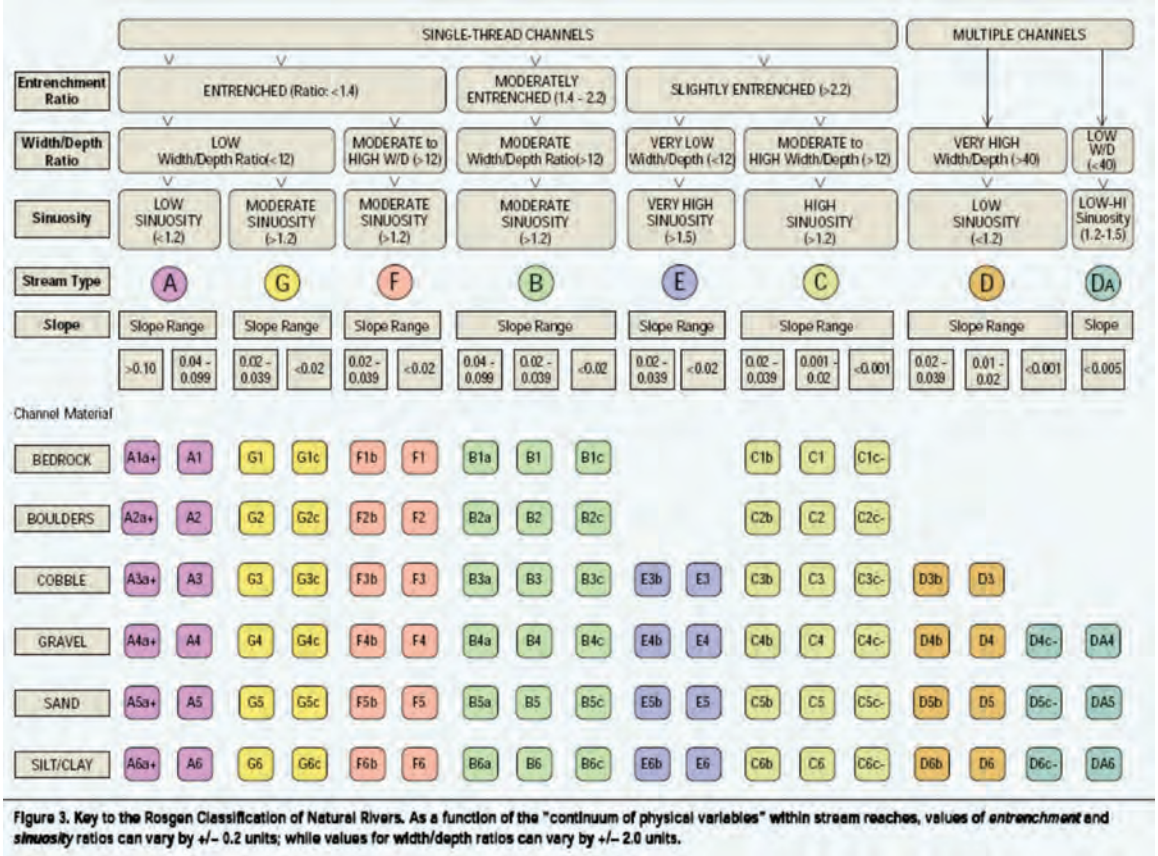


Figure 3. Key to the Rosgen Classification of Natural Rivers. As a function of the "continuum of physical variables" within stream reaches, values of *entrenchment* and *sinuosity* ratios can vary by +/– 0.2 units; while values for width/depth ratios can vary by +/– 2.0 units.

Source: Reproduced with permission from Wildland Hydrology

ing watershed health. Common BMP practices such as created wetlands, retention basins, bioretention areas, infiltration areas and restoration of riparian buffers are but a few of the practices that have been implemented to improve watershed health. These practices generally seek to reduce the amount of runoff delivered to streams (detention), reduce the rate at which runoff reaches streams (attenuation), increase the amount of water that percolates into the soil (infiltration), and/or promote physical and chemical processes that remove pollutants and sediment from runoff waters. Most of these practices are installed on smaller headwater catchments of a watershed, where such approaches are more feasible and cost effective, and where pollutants can be trapped near their sources.

River restoration is a technique that is applied at the stream reach scale and is generally used to complement the other techniques described above. BMP approaches can help to improve the quality and timing of water entering a receiving stream; river restoration approaches can address stability and water quality problems that are expressed or develop in the river itself, such as channel incision, streambank erosion and loss of aquatic habitat.

River Restoration

River or stream restoration has been defined in many different terms, but is generally considered to describe a set of activities that help improve the environmental health of a stream. Other terms commonly used for stream restoration include stream reclamation, stream stabilization, natural channel design and channel rehabilitation. Depending on the person using the term, stream restoration can have different meanings and associations, and can cover a wide range of practices and approaches to improving watercourses.

The practice of stream restoration began to achieve momentum in the 1980s, as interest grew in addressing stream stability problems in a way that was sustainable long-term and also improved recreational uses and ecological functions. Until that time, the primary approach used to stabilize streams was to harden the channel and/or streambanks with such materials as loose rock (rip-rap), gabion baskets, concrete, retaining walls, etc. Such practices addressed the stability problems with the stream, but often resulted in a dramatic loss of ecological function and aquatic life due to loss of aquatic cover, appropriate bed materials, shade and food sources. In addition, since these "hard" approaches did not address overall channel geometry issues, they often lead to downstream instability.

River or stream restoration has been defined in many different terms, but is generally considered to describe a set of activities that help improve the environmental health of a stream. Other terms commonly used for stream restoration include stream reclamation, stream stabilization, natural channel design and channel rehabilitation.

Practitioners began to develop techniques that would not only address stability issues, but also improve aquatic habitat functions and recreational uses, such as fishing. The movement began in the US in the Western states, where there was increasing concern over the degraded condition of trout and salmon rivers, and spread eastward across the country. The resulting designs, often referred to as *natural channel designs*, seek to replicate the channel forms seen in stable, natural rivers in order to restore stability and functions to degraded rivers.

Natural channel design can be defined as a stream restoration technique that seeks to create a stable stream channel that balances its flow of water and sediment over time, so that the channel does not aggrade or degrade. A variety of methods and tools are available to practitioners, but nearly all focus on several important design concepts:

- Providing connection between the channel and its floodplain (floodplain connectivity);
- Sizing low-flow channels to carry a given flow that over time carries the most sediment (channel-forming discharge concept);
- Designing channels to carry both their water and sediment loads; and
- Constructing channels to mimic the functions of natural channels to the extent possible.

For more information on specific design components commonly used in the practice of stream restoration, see the NRCS National Engineering Handbook Part 654 — Stream Restoration Design (USDA NRCS, 2007) *directives.sc.egov.usda.gov/viewerFS.aspx?id=3492*.

In 2008 the USACE and EPA issued regulations improving and standardizing mitigation policies, and increasing the emphasis placed on the restoration of functions. The rules specifically identify streams as a difficult-to-replace resource for which avoidance and minimization should be emphasized. Where compensatory mitigation for streams is needed, the rules emphasize in-kind rehabilitation, enhancement or preservation and outline stream specific considerations for site selection, providing design plans for review, monitoring requirements and ecological performance standards. This increased emphasis on the restoration of streams ensures that techniques such as natural channel design will continue to be the preferred methods for river restoration. For more information on natural channel design techniques for river restoration, see FISRWG (1998) and USDA NRCS (2007).

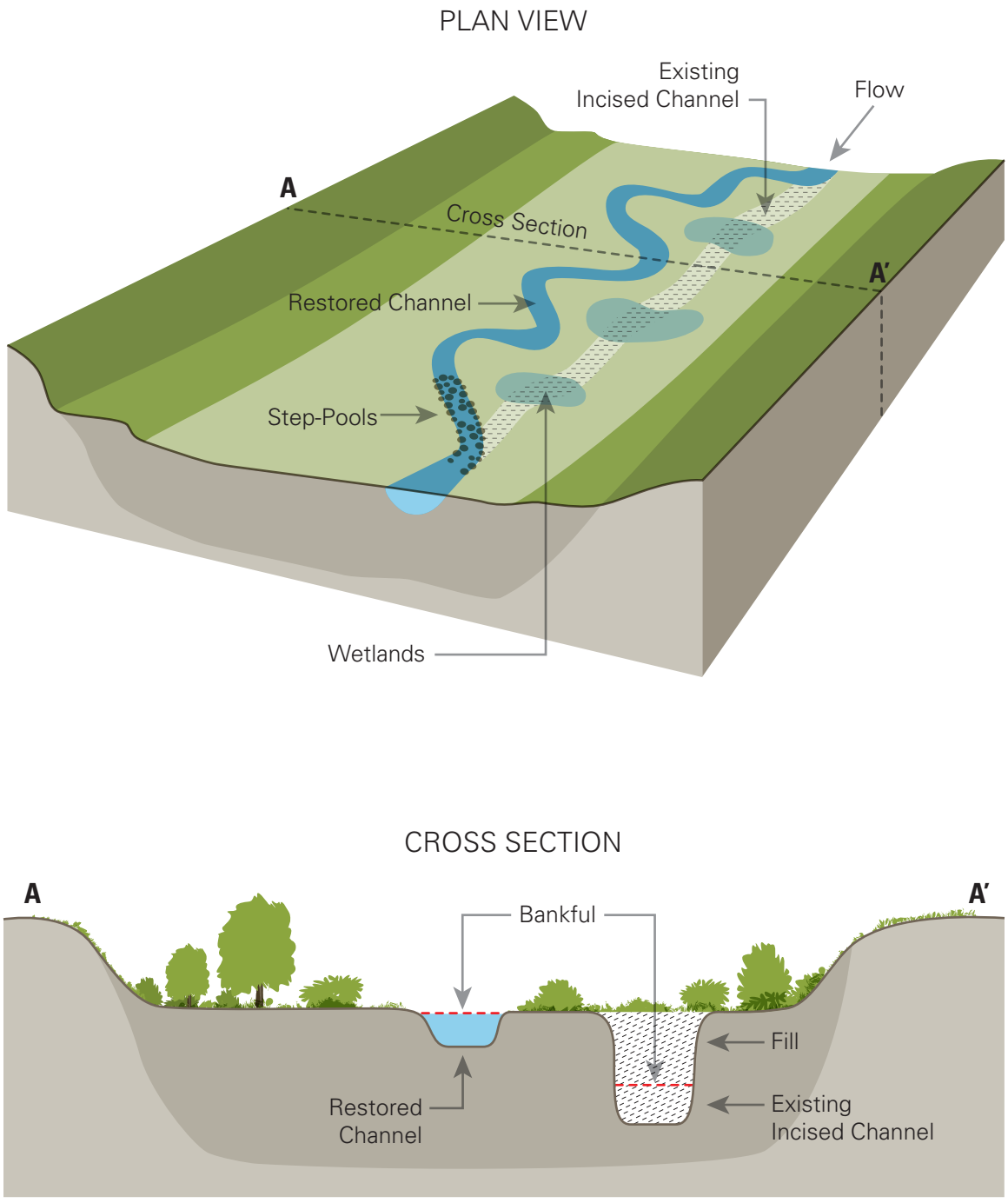
Natural channel design can be defined as a stream restoration technique that seeks to create a stable stream channel that balances its flow of water and sediment over time, so that the channel does not aggrade or degrade.

3.8 » PRIORITY LEVELS OF RESTORATION

Priority Levels for the restoration of incised streams were developed by Rosgen (1997). The "Rosgen Priority Levels" range from Priority Level 1 to Priority Level 4 and are chosen based on factors including both physical and economic constraints. These Priority Levels are often referred to in stream mitigation programs as restoration approaches (USACE Wilmington District et al., 2003; USACE Savannah District, 2004; and USACE Norfolk District and VDEQ, 2007). For example, a Priority Level 1 is often considered the highest level of restoration and receives the most credits per foot, while Priority Level 3 approaches often receive enhancement level credits. Chapter 11 and Appendix B of this document illustrate how select Priority Levels can be merged into a more function-based approach to developing stream credits. A brief description of the Priority Levels is provided below, and a more detailed description can be found in Rosgen (1997).

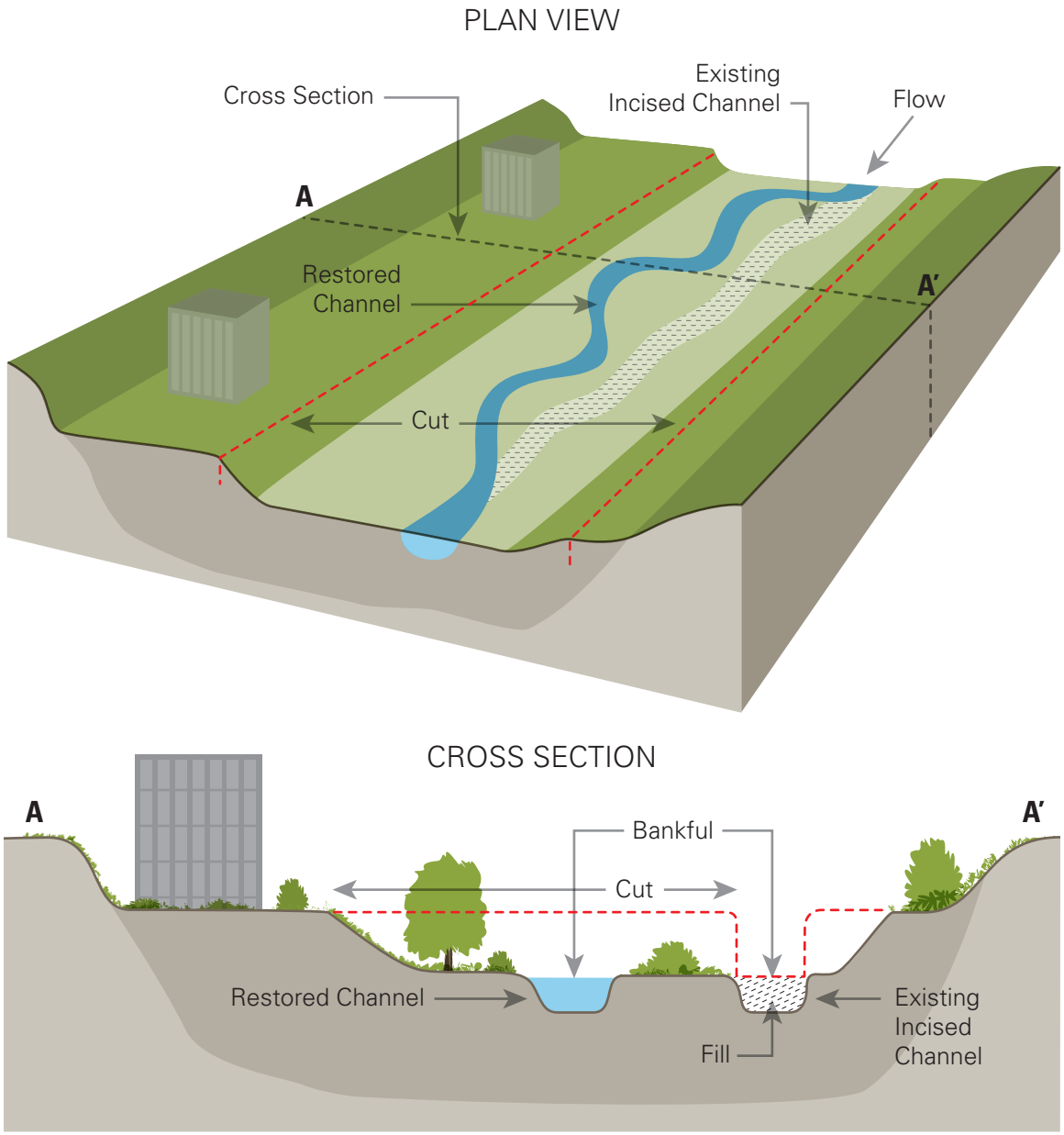
A Priority Level 1 restoration creates a new stable channel that is reconnected to the previous (higher in elevation) floodplain. A new stream channel is excavated on the original floodplain by raising the stream bed elevation. This approach requires an abrupt change in bed elevation at the upstream end of the project, e.g., culvert outfall or knickpoint. The former incised channel is filled, converting it to a floodplain feature. This approach is used in areas where there are few lateral constraints and where flooding on the adjacent land can be increased. An example of the plan form and dimension improvements created by a Rosgen Priority 1 is shown in Figure 3.8.

FIGURE 3.8 ROSGEN PRIORITY LEVEL 1 RESTORATION APPROACH



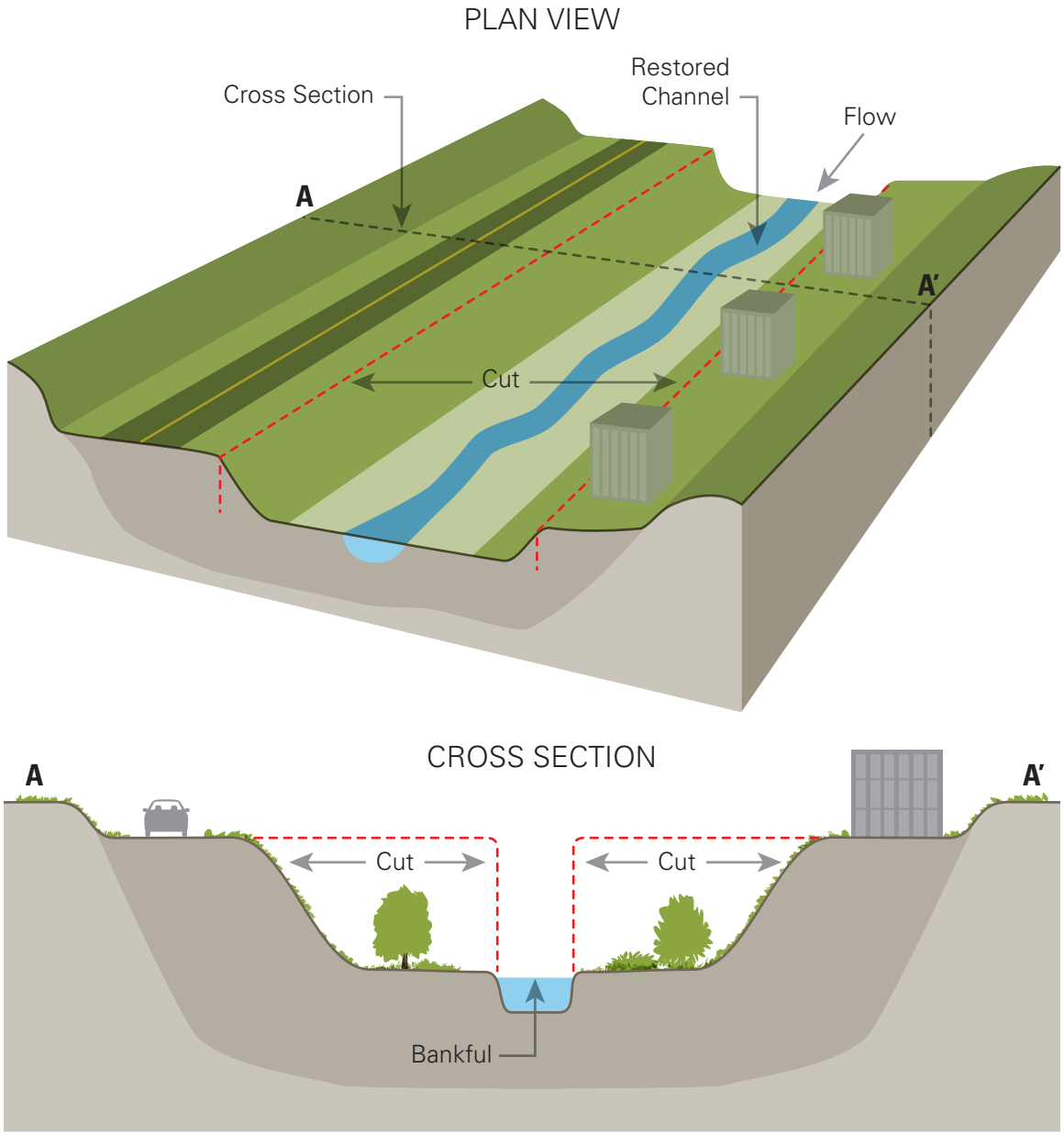
A Priority Level 2 restoration also creates a new stable channel that is connected to the floodplain, but the floodplain is excavated at the existing bankfull elevation, i.e., the bed elevation of the stream remains nearly the same. The formerly channelized and incised stream is re-meandered through the excavated floodplain. This approach is typically used if there is not a knickpoint or other abrupt change in grade upstream of the project, in larger streams, or in cases where flooding cannot be increased on adjacent property. A plan view and cross-section example is shown below in Figure 3.9.

FIGURE 3.9 ROSGEN PRIORITY LEVEL 2 RESTORATION APPROACH



A Priority Level 3 restoration converts a channelized and incised channel, often with poor bed form diversity, into a step-pool type of channel. The existing channel alignment stays nearly the same. Bankfull benches are excavated at the existing bankfull elevation to provide limited floodplain connectivity. In-stream structures are required to dissipate energy along the streambanks and to create step/pool bed forms. Priority Level 3 is often used where constraints inhibit meandering and flood elevations cannot be increased, e.g., urban environments. A plan view and cross-section example is shown below in Figure 3.10.

FIGURE 3.10 ROSGEN PRIORITY LEVEL 3 RESTORATION APPROACH



A Priority Level 4 stabilizes the channel in place, using in-stream structures and bioengineering to decrease stream bed and streambank erosion. This approach is typically used in highly constrained environments, such as backyards and highway right-of-ways. A Priority Level 4 is rarely used to create stream mitigation credits and is generally not considered restoration, only stabilization.

3.9 » IMPORTANCE OF SITE SELECTION IN RIVER RESTORATION

In the context of watershed health and the restoration of river functions, initial selection of river restoration sites is critically important. Sites that will provide the most functional lift are those that have few restoration constraints, have relatively healthy watersheds upstream, and have causes of impairment that are linked to the reach itself. An example would be a stream that is heavily degraded by direct cattle access, but has a relatively healthy watershed upstream and good water quality flowing into the site. In this situation, the primary causes of impairment are linked to the river restoration site itself, and include loss of riparian vegetation from grazing, eroding streambanks due to loss of vegetation and hoof-shear, elevated fine sediments in the river due to bank erosion and cattle crossings, and high bacterial loads due to cattle fecal matter. Assuming there are no constraints to the restoration work, such a project has a high probability of providing dramatic functional uplift because the primary sources of impairment can be addressed. Excluding cattle from the stream system, restoring a proper river form and restoring riparian vegetation will greatly decrease sediment and bacteria loads, provide improved aquatic habitat, provide shading and carbon sources, and improve overall channel stability and function.

In the context of watershed health and the restoration of river functions, initial selection of river restoration sites is critically important. Sites that will provide the most functional lift are those that have few restoration constraints, have relatively healthy watersheds upstream, and have causes of impairment that are linked to the reach itself.

In contrast, consider a proposed restoration site that is highly constrained by adjacent buildings and the streamflow entering the site is of poor quality. In this situation, the functional lift provided by stream restoration practices will be minimal, as the causes of watershed impairment are upstream of the project and restoration approaches are limited by the site constraints. Such a restoration site could address local instability, but will provide little in the way of water quality benefits.

The chapters that follow discuss the restoration of stream functions in depth; however, the practitioner should always be mindful that the degree to which functional lift can be provided is determined at the site selection phase of a project.

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Chapter 4

The Stream Functions Pyramid

The Stream Functions Pyramid, developed by Harman (2009), provides a framework that organizes stream functions in a pyramid form. The Stream Functions Pyramid illustrates that stream functions are supported by lower-level functions in a hierarchical structure. The Pyramid is a useful tool in goal setting, developing and reviewing stream assessment methodologies, and creating standard operating procedures (SOPs) for regulatory and non-regulatory stream restoration programs. This chapter provides a detailed overview of the Stream Functions Pyramid along with simple examples of how it can be applied. Detailed applications are provided in Chapter 11.

4.1 » FUNCTIONAL OBJECTIVES FOR STREAM RESTORATION

A stream functions framework was created by the US Army Corp of Engineers (USACE) for determining and evaluating objectives for stream restoration projects (Fischenich, 2006). This framework provided the foundation for development of the Stream Functions Pyramid. It identifies a suite of 15 functions critical to the health of stream and riparian ecosystems. These functions are summarized in Table 4.1. The USACE functional framework is appealing since it has a scientific basis in stream functions, is based on processes, and attempts to describe the interactions between identified functions.

TABLE 4.1 FUNCTIONS CRITICAL TO STREAM AND RIPARIAN ECOSYSTEM HEALTH (Fischenich 2006)

FUNCTION	DESCRIPTION
1. Maintain Stream Evolution Processes	Maintains appropriate energy levels; promotes diversity and variability of biotic communities.
2. Energy Management Processes	Allows for conversion between potential and kinetic energy through changes in the system.
3. Provide for Riparian Succession	Changes in vegetation structure promote diversity and ecological vigor, vegetation necessary for system stability and nutrient cycling.
4. Surface Water Storage Processes	Provides temporary water storage during high flows, regulates soil moisture, provides pathway for aquatic organism movement, and provides contact time for biogeochemical processes.

TABLE 4.1 FUNCTIONS CRITICAL TO STREAM AND RIPARIAN ECOSYSTEM HEALTH (Fischenich 2006)

FUNCTION	DESCRIPTION
5. Maintain Surface/ Subsurface Water Connections and Processes	Provides bi-directional exchange from open channel to subsurface soils; allows exchange of chemicals, nutrients and water.
6. General Hydrodynamic Balance	Provides proper flow conditions at the appropriate seasons for support of the biotic community.
7. Sediment Continuity	Provides for appropriate erosion, transport and deposition processes.
8. Maintain Substrate and Structural Processes	Provides substrate and structural architecture to support diverse habitats and biotic communities.
9. Quality and Quantity of Sediments	Determines the physical character of the system relative to the primary variables: sediment yield and character.
10. Support Biological Communities and Processes	Provides diverse assemblages of native species.
11. Provide Necessary Habitats	Produces and sustains habitats to support vigorous aquatic and riparian biotic communities.
12. Maintain Trophic Structures and Processes	Promotes growth and reproduction of biotic communities across trophic levels.
13. Maintain Water and Soil Quality	Promotes favorable conditions for riparian communities that trap, retain and remove particulate and dissolved constituents from surface and overland flow.
14. Maintain Chemical Processes and Nutrient Cycles	Provides for complex reactions to maintain equilibrium and supply required elements to biota.
15. Maintain Landscape Pathways	Maintains connectivity to allow for biotic and abiotic energy process pathways.

The functions characterized by Fischenich (2006) are ordered into a hierarchy of functions, where the relative significance of each function is inferred by assessing the interrelations among functions. Functions that affect the greatest number of other functions are ranked highest, while functions that have the least effect on other functions are ranked lower (Table 4.2). For example, the General Hydrodynamic Balance function (1), which describes a system's flow characteristics, supports directly or indirectly all other functions listed in the Framework, such as sediment transport, energy, biotic and chemical functions. In contrast, the Provide Necessary Habitats function (15) directly affects three other functions, which are all related to the biological systems that are supported by streams.

TABLE 4.2 RANKINGS OF FUNCTIONS PROPOSED BY FISCHENICH (2006)

FUNCTION	FUNCTIONS DIRECTLY AFFECTED	FUNCTIONS INDIRECTLY AFFECTED
1. General Hydrodynamic Balance	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15	13
2. Maintain Stream Evolution Processes	1, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15	9, 13
3. Surface Water Storage Processes	1, 4, 6, 10, 11, 12, 14, 15	2, 5, 7, 8, 9, 13
4. Sediment Continuity	3, 5, 6, 7, 8, 9, 11, 15	1, 13, 14
5. Provide for Riparian Succession	1, 2, 3, 4, 6, 12, 14, 15	9, 13
6. Energy Management Processes	1, 2, 3, 4, 5, 7, 8, 15	--
7. Maintain Substrate and Structural Processes	1, 2, 4, 6, 7, 10, 15	5, 9, 11, 13
8. Quality and Quantity of Sediments	2, 4, 5, 6, 7, 10, 15	1, 9, 11, 14
9. Support Biological Communities and Processes	5, 11, 13, 14, 15	1, 2, 3, 7, 8, 10, 12
10. Maintain Surface/Subsurface Water Connections and Processes	1, 5, 11, 15	3, 9, 12, 13
11. Maintain Water and Soil Quality	8, 9, 13, 14	5
12. Maintain Landscape Pathways	9, 13, 14, 15	6
13. Maintain Trophic Structures and Processes	9, 11, 14	8
14. Maintain Chemical Processes and Nutrient Cycles	8, 9, 13	6
15. Provide Necessary Habitats	9, 12, 13	–

Fischenich (2006) notes that efforts to restore streams are often ineffective because they fail to address the underlying processes that create and maintain the biological functions. The purpose of this hierarchy is to indicate the complex set of linkages that exists between functions of stream and riparian systems and to indicate which functions are most critical and interrelated to the restoration of stream and riparian functions.

Fischenich (2006) found that the most critical functions include those that address hydrodynamic processes (1, 3, 6), sediment transport processes (4, 7), stream stability (2) and riparian buffer restoration (5, 11). By addressing these fundamental functions and processes, a restored stream and riparian system are capable of supporting more dependent functions that typically require time to establish, such as diverse biological communities (9), chemical and nutrient processes (14), diverse habitats (15) and improved water and soil quality (11).

4.2 » THE STREAM FUNCTIONS PYRAMID

The Stream Functions Pyramid builds on the USACE work by placing stream functions in a hierarchy. However, the Pyramid uses parameters and measurement methods that are more often used in stream restoration approaches and assessment methodologies. It also provides a clear illustration of how physical functions support chemical and biological functions. This helps scientists, engineers and managers ensure that they are not only addressing the functions they are directly concerned about, but also the supporting functions that are required to achieve success.

The Stream Functions Pyramid Framework consists of four components that increase in detail. First, the broad-level view shows the five functional categories (Levels) with the underlying controlling variables of geology and climate. Second, function-based parameters are provided for each functional category. Third, measurement methods are provided for each function-based parameter. And fourth, where possible, performance standards are provided for the measurement methods. These terms can easily be confused with broader definitions of parameter, metric, tool and others. To help avoid confusion, definitions for these terms along with the criteria used to select function-based parameters, measurement methods and performance standards are provided below. See Appendix A for the entire Stream Functions Pyramid Framework. Also reference the Stream Functions Pyramid page at *www.stream-mechanics.com* for updates and examples of how the Pyramid is being used.

The Stream Functions Pyramid Framework consists of four components that increase in detail.

Typically, the Pyramid is applied at a reach scale even though some of the functions occur at a watershed scale, e.g., hydrology functions. Applications are discussed in detail in Chapter 11, including examples of how the Pyramid can be used in reach-scale function-based assessments and watershed management plans. However, even when used in watershed management plans, many of the measurement methods described below are conducted at a reach scale. The reach scale information can then be used in the broader context of watershed health, i.e., providing reaches that are functionally impaired or healthy, and as an aid in identifying potential restoration sites.

4.3 » STREAM FUNCTIONS PYRAMID: BROAD-LEVEL VIEW

The broad-level view is shown in Figure 4.1. The functional categories have been

modified from Fischenich (2006) to more closely match functions with parameters that are commonly used in the fields of hydrology, hydraulics, geomorphology, physicochemistry (called physicochemical on the Pyramid) and biology. The purpose of the broad-level Pyramid view is to show that the primary direction of cause-and-effect relationships flows from the bottom of the Pyramid to the top. In other words, functions higher on the Pyramid are more dependent on lower-level functions. This does not mean that cause-and-effect relationships can't or don't flow from higher levels to lower levels. The intention of the Pyramid is to show the dominant flow of cause-and-effect relationships. A dashed line is used to separate the functional categories to illustrate that the transition between categories is not a "hard" boundary. Cause-and-effect relationships can flow in both directions. For example, everything in the Pyramid is ultimately controlled by geology and the region's climate. If climate changes or there is a major geologic event, e.g., volcanic eruption, changes will occur throughout the Pyramid. Within the Pyramid, Hydrology and Hydraulic functions support Geomorphology functions like sediment transport, i.e., without water being contributed from the watershed and creating flow dynamics in the channel, sediment transport would not occur. Of course, channel form (geomorphology) does affect hydraulics through channel slope, sediment supply and boundary conditions. This is a downward example of cause and effect, but it is not as dominant as the requirement for water to be in the channel. Wohl (2004) alludes to these cause-and-effect relationships by stating, "We cannot save trout without saving their river and floodplain habitats. We cannot save river and floodplain habitats — and the plants and insects of the trout's food web — if we do not also maintain the processes controlling water and sediment entering the river corridor from the surrounding hillslopes and uplands." This concept exemplifies how the underlying physical functions support the biological functions.

The intention of the Pyramid is to show the dominant flow of cause-and-effect relationships. A dashed line is used to separate the functional categories to illustrate that the transition between categories is not a "hard" boundary.

This may seem obvious; however, many assessment methodologies address biological indicators without addressing the underlying controls provided by geomorphology, hydraulics and hydrology (Somerville, 2010). This concept also helps the practitioner match the project goal with the corresponding stream functions to avoid problems where practitioners design ineffective projects because they ignore the underlying hydrology, hydraulic and geomorphic functions (Fischenich, 2006).

Function Descriptions by Level

Function-based parameters and measurement methods are not shown on the broad-level Pyramid. Rather, a statement is provided to define the overall function of a given

FIGURE 4.1 STREAM FUNCTIONS PYRAMID — OVERVIEW
(See Appendix A for a full-size version.)

category. This information is based on Fischenich (2006), Somerville (2010), industry standards and professional experience. A description is provided below for each functional category. These statements are used to help select function-based parameters in the next Pyramid view.

Level 1: Hydrology

Hydrology functions transport water from the watershed to the channel. Hydrology is placed at the bottom of the Pyramid because water contributed from the watershed strongly affects the higher-level functions. Very simply put, without surface water flow, there would not be channel formation and the subsequent aquatic ecosystem. This definition of hydrology is most common in the engineering community and although it is related to hydraulics, the calculations are made separately, e.g., the USACE hydrologic model HEC-HMS (Scharffenberg and Fleming, 2010) and the USACE hydraulic model HEC-RAS (Brunner, 2010). Physical and life scientists tend to merge hydraulics into hydrology. However, from a stream assessment and restoration perspective, there are advantages to having both categories. The Pyramid keeps these functions separate for two reasons: 1) When conducting assessments or implementing a stream restoration project, it is important to distinguish between watershed scale functions of water transport (Hydrology) and reach scale relationships that describe how water interacts with the channel

(Hydraulics); and 2) The opportunity for functional lift is very different between the two.

Level 2: Hydraulics

Hydraulic functions transport water in the channel, on the floodplain and through sediments. Again, this is a broad statement — it defines how water behaves once it reaches a channel and how it interacts with the bed, banks, floodplain, hyporheic zone, etc. (Dingman, 2008). It is important to note that this function works in channels of all sizes, from valley bottom swales (ephemeral channels) to large rivers. It is also present in all forms of geology and climate zones (Knighton, 1998). The energy associated with moving water has the ability to do work, such as transporting sediment, which is a geomorphology function (Leopold et al., 1992). The Hydraulic functions are closely related to Geomorphology functions and many interrelationships exist between these two categories. For example, sinuosity (Level 3) affects channel slope, which in turn affects channel velocity (Level 2). However, the dominant cause-and-effect relationships involve Hydraulics supporting Geomorphology. At a basic level, water must be present in the channel before sediment can be moved, regardless of sinuosity and other measures of channel form. Hydraulic functions also affect many functions in Levels 4 and 5 because they determine the amount of force and power that is exerted by the water on aquatic habitats.

Level 3: Geomorphology

The function of geomorphology, as defined here, is the transport of wood and sediment to create diverse bed forms and dynamic equilibrium. The relative importance or even presence of certain Geomorphology functions varies greatly with changes in geology and climate. For example, wood transport and storage is extremely important to channel stability in headwater mountain streams but not important in low-gradient, grassland streams. In addition, some streams are naturally unstable and are not in a state of dynamic equilibrium, e.g., glacial outwash plains and some alluvial fans. However, the Hydrology and Hydraulic functions come together with the Geomorphology functions to create a channel form that is appropriate for the underlying geology and climate of the region. From a stream assessment and restoration perspective, we are most interested in these functions as they relate to the creation of diverse bed forms and channel stability (dynamic equilibrium) that has a dramatic effect on Level 4 and 5 functions, which are often the ultimate desire of a restoration project.

Level 4: Physicochemical

Physicochemical functions include temperature and oxygen regulation, and processing of organic matter and nutrients. These functions are generally more affected by the underlying functions than vice versa, even though some of these functions occur as soon as water is present in the channel, e.g., water temperature. However, the Physicochemical category was placed above Geomorphology because a restoration practitioner would typically address functions here (Level 3) in order to see improvements in Physicochemical functions. For example, fast riffles and deep pools (bed form diversity), along with

shade and a wide buffer help regulate stream temperature. It is true that some projects may only need to address water-quality stressors, e.g., a point-source discharge and animal waste inputs, rather than restore the underlying functions. However, even in these cases, an assessment should be made to ensure that the underlying, supporting functions are present so that the stream will naturally recover once the stressor is removed.

Level 5: Biology

Biology is located at the top of the Pyramid because these functions are dependent on all the underlying functions. These functions include the biodiversity and the life histories of aquatic and riparian organisms. Biology functions can affect lower-level functions, e.g., beaver activities; however, as with the other levels, the dominant cause-and-effect relationship is upward. A healthy aquatic ecosystem must have sufficient water contributed from the watershed, the right levels of hydraulic forces, proper bed form diversity and channel stability, suitable temperature and oxygen regimes, and so on. The value of the Pyramid at this level is that it helps regulators, scientists and engineers to identify the underlying functions that must be present in order to achieve functional improvements in biology. This is currently not happening. As Somerville (2010) points out, many assessment methods omit these underlying functions.

4.4 » STREAM FUNCTIONS PYRAMID: FUNCTION-BASED PARAMETERS

Figure 4.2 shows a more detailed view of the Pyramid with examples of function-based parameters that can be used to quantify or describe the *functional statement* provided in the broad-level view. The term "function-based" is used to acknowledge that the parameter may be a "structural" type of parameter or an actual function. Structural parameters describe a stream condition at a point in time, e.g., percent riffle and pool. A function parameter is expressed as a rate and directly relates to a stream process that helps create and maintain the character of the stream corridor (Allan, 1995). The Stream Functions Pyramid uses the term function-based parameter to take the emphasis off of structural measures versus actual functions. Rather, function-based parameters are used individually or in combination to quantify or describe a particular aspect of the functional statement provided in the broad-level view. For example, within the Hydrology category (Level 1), flood frequency is a function-based parameter that can be used to quantify the occurrence of a given discharge. It is not a function, but it does

The Stream Functions Pyramid uses the term function-based parameter to take the emphasis off of structural measures versus actual functions. Rather, function-based parameters are used individually or in combination to quantify or describe a particular aspect of the functional statement provided in the broad-level view.

provide critical information about the transport of water from the watershed to the channel, which is a function. Another example is bed form diversity, a function-based parameter in Geomorphology (Level 3). Bed form diversity is not a function, it is a structural measure. However, complex bed form diversity, e.g., gravel riffles with low embeddedness and slow-moving deep pools are an indication that sediment transport processes are working appropriately. Sediment transport is a function; however, it is much more difficult to measure than bed form diversity and may not be necessary for stream assessments that are focused on functionality. This does not mean that sediment transport should not be assessed for vertical stability or for a restoration design. In the end, stream assessments and designs may include a mix of structural measures and functions based on the complexity of the project and financial constraints. However, the combination of structural measures and functions can be considered function-based if they help describe or quantify a particular functional category, as expressed by the functional statement in Figure 4.1 (The Stream Functions Pyramid — Overview).

The function-based parameters shown on the Pyramid are fairly comprehensive and can be used in a wide range of settings. However, they should be considered as examples.

The function-based parameters shown on the Pyramid are fairly comprehensive and can be used in a wide range of settings. However, they should be considered as examples. Some parameters may be more important than others for a given region. In addition, some regions or unique projects within a region may need to add parameters. The criteria used to include function-based parameters within the Pyramid are provided below.

Criteria for Selecting Function-Based Parameters

For all Pyramid Levels

- Quantifies or describes (typically quantitative, but can be qualitative) a portion of the functional statement. The functional statements are provided above in Function Descriptions by Level.
- Has at least one measurement method that can be assigned. A function-based parameter can typically be measured in multiple ways, hence, it is broader than a measurement method.
- Can be a structural measure or a function.
- May or may not be applicable to all climate zones, geologic settings and eco-regions.

For Levels 1 through 3

- Must be a parameter that a practitioner can calculate or measure and use for restoration design and/or stream assessments.
- For restoration projects, typically include parameters that can be manipulated by the practitioner to create functional lift.

For Levels 4 through 5

- If adding a parameter to these Levels, consider if there are supporting lower-level parameters.

Ultimately, the suite of parameters selected will be dependent on the project's goals and budget, since some parameters can be measured quickly and inexpensively and others require long-term monitoring and expensive equipment. These issues can be addressed by selecting the appropriate measurement method. Chapter 11 provides examples of how to select parameters and measurement methods for various applications.

FIGURE 4.2 STREAM FUNCTIONS PYRAMID — FUNCTIONS & PARAMETERS
(See Appendix A for full-size version.)

4.5 » STREAM FUNCTIONS PYRAMID: MEASUREMENT METHODS

Table 4.3 shows examples of measurement methods associated with each parameter. Measurement methods are more specific than function-based parameters by including specific calculations, simple spreadsheet models, sophisticated computer models, rapid field-based assessments, and in some cases, assessment methods that influence more than one function-based parameter. However, unlike the function-based parameter, there is typically a well-defined approach for conducting the measurement method.

Most parameters have at least two measurement methods and some, like the Geomor-

phology category, have several for each parameter. Some measurement methods are rapid-based approaches (requiring a small amount of time and effort to make the measurement) and others require intensive monitoring and analysis. This provides the user with a wide selection of methods to quantify, describe, and understand stream functions. General descriptions about the individual measurement methods are provided in Chapters 6-10. These chapters correspond to a functional category (Hydrology, Hydraulics, etc) with the measurement methods under the function-based parameter sections. This document does not provide a lot of detail about how the measurement methods relate to each other. As real-world applications are developed, these relationships should become clearer. In the meantime, users will find links and references to additional resources that can be used to develop a more comprehensive understanding of how multiple measurement methods can be used together to quantify a function-based parameter.

Measurement methods are more specific than function-based parameters by including specific calculations, simple spreadsheet models, sophisticated computer models, rapid field-based assessments, and in some cases, assessment methods that influence more than one function-based parameter.

Ultimately, the suite of function-based parameters and measurement methods selected will depend on the purpose of the assessment and the funding level. Again, Chapter 11 provides examples of how to select parameters and measurement methods for various applications.

Table 4.3 provides a list of all the measurement methods associated with the function-based parameters that have been included in this document. These measurement methods should not be considered all-inclusive, but rather, represent examples that are frequently used in stream assessment and restoration. A more detailed table is provided in Appendix Ac that includes additional information about each measurement method, including: type, level of effort, level of complexity, and whether or not the measure is a direct versus indirect measurement of a function-based parameter. The criteria used to make these determinations are provided below and details for each parameter are provided in Chapters 6-10.

Type of Measurement Method

As discussed above, the measurement methods include a wide range of tools, techniques, metrics and even assessment approaches. Appendix Ac identifies each type of measurement method, using the following criteria/definitions:

- Tool: Includes spreadsheet and computer models, typically with predictive ability. Tools are more automated than a technique.
- Technique: Techniques are empirical equations, statistical approaches and field survey techniques/methods. Techniques are not part of a larger computer model/tool, e.g., HEC-RAS, which is a tool.

- Metric: A metric or parameter, which is more specific than a function-based parameter. It has a well-defined method for being measured. For example, flow dynamics is a function-based parameter and velocity is a measurement method of the metric type. This is a subtle, but important difference.
- Assessment Approach: Includes established assessment approaches, e.g., rapid bioassessment protocol. It often assesses more than the function-based parameter shown in the Pyramid, meaning that the Pyramid is only referring to a portion of the assessment methodology.

Level of Effort

Appendix Ac assigns a level of effort to each measurement method, including rapid, moderate and intensive. The overriding criteria is to determine how much effort is required to arrive at a final answer, so level of effort can include field and office/lab work. In general, rapid measurement methods require less than half a day in the field to assess a one-mile stream reach. Some rapid measurement methods use simple spreadsheets, maps or other office-based measurement methods that do not require field work. Other measurement methods, like regional curves, are simple to use if the curve has been developed, moderate if developing a watershed specific curve, and intensive for developing regional curves for a hydro-physiographic region. A moderate level of effort generally requires one day to one week of fieldwork for a one-mile stream assessment and another day or more to process and analyze the data. Some methods may not require field data, but still require time to collect existing data, e.g., from websites and databases. The results can be compared to existing performance standards and do not require monitoring over time, e.g., annual surveys to determine functionality. Intensive measurement methods require long-term (multi-year) monitoring efforts in order to develop trends that are often compared to reference conditions. The actual monitoring effort may be rapid, i.e., it takes less than half a day to assess one mile of stream; however, achieving results will take multiple measurements over time to develop a trend and is therefore intensive. The level of effort should not be confused with level of expertise, since some of the more qualitative and rapid measurement methods rely on professional judgment and, therefore, a high level of expertise.

Level of Complexity

Appendix Ac assigns a level of complexity to each measurement method, including simple, moderate and complex. Simple methods can be assessed after minimal training, e.g., on-the-job training and workshops. Simple can also mean that the sample is relatively easy to collect and analyze without the need of sophisticated equipment. Simple methods do not require elaborate or lengthy steps or processes to acquire the data. Moderately complex measurement methods require more effort and expertise than simple methods. These measurement methods often require someone with formal training and some experience. They may also require several steps to collect and analyze the data or to make calculations and estimates. Complex measurement methods should be completed by professionals with sufficient academic training and professional experience. These methods often require complex field and/or office procedures or complex modeling and analysis.

Direct Versus Indirect

Appendix Ac also shows if the measurement method is a direct or indirect measure of the function-based parameter. Direct measurement methods often do not require additional interpretation about the function-based parameter; they directly measure or assess the parameter. Indirect measures may require additional interpretation or only provide a partial, or incomplete, understanding of the function-based parameter. Assessment approaches typically include the additional interpretation needed for translating indirect measures to function-based parameters. Direct measures provide a more straightforward answer about a function-based parameter, whereas an indirect measure is more of an estimate.

TABLE 4.3 PARAMETERS AND MEASUREMENT METHODS

HYDROLOGY	
PARAMETER	MEASUREMENT METHOD
Channel-Forming Discharge	1. Regional Curves
Precipitation/Runoff Relationship	1. Rational Method 2. HEC-HMS 3. USGS Regional Regression Equations
Flood Frequency	1. Bulletin 17b
Flow Duration	1. Flow Duration Curve 2. Crest Gage 3. Monitoring Devices 4. Rapid Indicators
HYDRAULICS	
PARAMETER	MEASUREMENT METHOD
Floodplain Connectivity	1. Bank Height Ratio 2. Entrenchment Ratio 3. Stage Versus Discharge
Flow Dynamics	1. Stream Velocity 2. Shear Stress 3. Stream Power
Groundwater/Surface Water Exchange	1. Piezometers 2. Tracers 3. Seepage Meters
GEOMORPHOLOGY	
PARAMETER	MEASUREMENT METHOD
Sediment Transport Competency	1. Shear Stress Curve 2. Required Depth and Slope 3. Spreadsheets and Computer Models

TABLE 4.3 PARAMETERS AND MEASUREMENT METHODS (CONT.)

GEOMORPHOLOGY	
PARAMETER	MEASUREMENT METHOD
Sediment Transport Capacity	1. Computer Models 2. FLOWSED and POWERSED 3. BAGS
Large Woody Debris Transport and Storage	1. Wohl LWD Assessment 2. Large Woody Debris Index
Channel Evolution	1. Simon Channel Evolution Model 2. Rosgen Stream Type Succession Scenarios
Bank Migration/Lateral Stability	1. Meander Width Ratio 2. BEHI / NBS 3. Bank Pins 4. Bank Profiles 5. Cross-Sectional Surveys 6. Bank Stability and Toe Erosion Model
Riparian Vegetation	1. Buffer Width 2. Buffer Density 3. Buffer Composition 4. Buffer Age 5. Buffer Growth 6. Canopy Density 7. Proper Functioning Condition (PFC) 8. NRCS Visual Assessment Protocol 9. Rapid Bioassessment Protocol 10. Watershed Assessment of River Stability and Sediment Supply (WARSSS) 11. USFWS Stream Assessment Ranking Protocol (SAR)
Bed Form Diversity	1. Percent Riffle and Pool 2. Facet Slope 3. Pool-to-Pool Spacing 4. Depth Variability
Bed Material Characterization	1. Size Class Pebble Count Analyzer 2. Riffle Stability Index (RSI)

TABLE 4.3 PARAMETERS AND MEASUREMENT METHODS (CONT.)

PHYSICOCHEMICAL	
PARAMETER	MEASUREMENT METHOD
Water Quality	1. Temperature 2. Dissolved Oxygen 3. Conductivity 4. pH 5. Turbidity
Nutrients	1. Field test kits using reagents reactions 2. Laboratory analysis
Organic Carbon	1. Laboratory analysis
BIOLOGY	
PARAMETER	MEASUREMENT METHOD
Microbial Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices
Macrophyte Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices
Benthic Macroinvertebrate Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices
Fish Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices
Landscape Connectivity	1. Spatial Analysis 2. Species Tracking 3. Habitat Models

4.6 » FUNCTION-BASED PARAMETERS AND MEASUREMENT METHOD: DESCRIPTIONS BY CATEGORY

A more detailed description of the function-based parameters and measurement methods shown in Table 4.3 is provided below. These descriptions are stratified by functional category and discuss how the function-based parameters and measurement methods work together. In addition, information is provided about how the parameters and measurement methods relate to stream restoration.

Level 1: Hydrology

The function-based parameters shown on the Pyramid are used by practitioners to

determine how much water will reach the channel and how much water the channel should carry to maintain dynamic equilibrium. The parameters used to assess these functions include precipitation/runoff relationships, channel forming discharge, flood frequency and flow duration. Each parameter and its associated measurement method are discussed in detail in Chapter 6.

Hydrology parameters are typically independent parameters in a stream restoration project, meaning, for example, that a designer does not have the ability to influence or change the precipitation/runoff relationship or channel forming discharge. These parameters are simply quantified and then used as inputs for a more detailed hydraulic analysis. While this is common, it is not always the case. There are scenarios where a project may be able to "improve" the runoff relationship, such as by implementing stormwater best management practices. This can be a critical component of stream restoration projects in urban environments.

Level 2: Hydraulic

Results from Level 1 are used as input parameters in Level 2 to quantify two broad-level parameters: floodplain connectivity and flow dynamics. Floodplain connectivity is measured by the bank height ratio, entrenchment ratio and stage-versus-discharge relationships (rating curves). These measurement methods are used to determine if the channel can accommodate the targeted volume of water consistent with design goals and/or management objectives. The bank height ratio is a common method used to assess floodplain connectivity by comparing the bankfull depth to the total depth of the channel. Ideally, channels should not carry more than the bankfull discharge. For streams in alluvial valleys, flood flows should be spread across the floodplain. The entrenchment ratio, which describes the width of the floodprone area in relation to the bankfull width, is used to further describe floodplain connectivity (Rosgen 2009). In addition, estimates of the stage-versus-discharge relationship can be measured or estimated to directly assess floodplain connectivity. Flow dynamics is assessed through measures of velocity, shear stress and stream power, which change with increasing stage and discharge. Groundwater/surface water exchange is also included because this is an important process that supports physicochemical and biological processes that will be described later (Knighton, 1998). A detailed description of each Hydraulic parameter and its measurement method is described in Chapter 7.

Like Hydrology, Hydraulic parameters and measurement methods include structural measures and functions. Discharge and groundwater/surface water exchange are functions and can be quantified as rates-per-unit time, and they have a significant effect on the form of the channel and influence functions in Levels 3-5. Bank height and entrenchment ratios are structural measures, expressed as dimensionless ratios. However, they do relate to functions since the bank height ratio correlates to the stage that transports the bankfull discharge, and the entrenchment ratio describes the flow area inundated with the discharge at twice the stage of bankfull. In other words, they help to describe flow dynamics.

Stream restoration projects have the greatest effect on Level 2 and Level 3 functions

because projects occur at a reach scale and most of these functions can be modified as part of the design process. For example, the majority of stream restoration projects located in alluvial valleys and perennial streams include the goal of reconnecting the stream to a floodplain. Designers may accomplish this goal by raising the stream bed, lowering the floodplain or creating a bankfull bench. This approach often follows Rosgen's Priority Levels of restoring incised channels, as described in Chapter 3 (Rosgen 1997). To accomplish this goal, the designer calculates the bankfull discharge (Level 1) and then designs a cross section that will convey flows up to the bankfull discharge (Level 2). The degree of functional lift is determined by assessing the difference in pre- and post-restoration incision, which can easily be represented by the bank height ratio and entrenchment ratio. Re-establishing floodplain connectivity is one of the most important things that a restoration project can do at a reach scale because it affects so many of the upper-level functions.

Level 3: Geomorphology

The parameters used to assess Geomorphology functions include sediment transport competency, sediment transport capacity, large woody debris transport and storage, channel evolution, lateral stability, riparian vegetation, bed form diversity and bed material characterization. There are many different measurement methods provided for these parameters — more than any other category. Of these parameters, sediment transport, lateral stability and components of the riparian vegetation are quantified as rates and are considered functional measures. Channel evolution is not measured as a rate, but does imply a change in form over time and relates to channel-forming processes. However, the amount of time is not quantified. Bed form diversity is a structural measure, usually assessed as the percent of riffle and pool length per unit of channel length, depth variability and/or substrate distributions. Nevertheless, bed form diversity is an important structural measure that quantifies the effects of sediment transport and is much easier to assess. The transport of wood is also an important function in this category, although its degree of importance varies by stream type. For some stream types (Rosgen A and B), wood transport and storage is important for maintaining channel stability. For other stream types (Rosgen C and E) wood and organic matter transport and storage can be important for stability, but is more important in its role for supporting Level 4 and 5 functions. A detailed description of each parameter and measurement method is provided in Chapter 8.

Stream restoration designs often focus on Level 3 parameters. Like Level 2, a restoration project can affect these parameters at a reach scale, although the longer the reach the better with regard to functional lift. Restoration activities associated with Level 3 often include improving bed form diversity and reducing streambank erosion. Bed form diversity is often improved by designing the appropriate dimension, pattern and profile for the given valley type. Meandering perennial streams in alluvial valleys, for instance, create riffle-pool sequences. Large woody debris and in-stream rock and wood structures are used to further improve depth variability and channel stability and complexity. In addition, most stream restoration projects include planting vegetation on the streambanks and the riparian zone to provide bank stability and to support Level 4 and 5 functions.

Level 4: Physicochemical

Physicochemical functions include physical and chemical processes that create baseline water chemistry, breakdown organic matter and transform nutrients. It could be argued that once water reaches the channel (Hydrology and Hydraulic functions) chemical and biological processes begin to occur. However, from a stream restoration perspective, these functions are affected (and can be improved) by the presence of water and its interaction with bed forms, structures like woody debris, and the riparian vegetation. For example, dissolved oxygen can be increased by lowering the temperature through a robust riparian buffer and by the presence of steep, rocky riffles. These parameters are addressed in the lower levels.

Physicochemical water quality assessments include the following parameters: nutrients, organic carbon, dissolved oxygen, temperature, pH, specific conductivity and turbidity. Nutrients and organic carbon can be assessed rapidly in the field with test kits, but are more often measured in a laboratory. Organic matter and nutrient processing are always measured as rates and significantly contribute to the character of the stream system; therefore, these parameters are direct measures of function. Dissolved oxygen, temperature, pH and conductivity are typically measured at a point in time rather than a rate over time and are considered a structural measure. However, with continuous monitoring, parameters such as temperature can be considered a function. For example, the rate of change in water temperature as air temperature changes is a functional measure of thermal regulation. A detailed description of each parameter and measurement method is provided in Chapter 9.

It is difficult for stream restoration projects to directly affect Physicochemical parameters because they are affected by so many variables. They are supported by the lower-level functions, but they are also sensitive to weather and climate change, inputs from the upstream watershed and adjacent land uses, and even Level 5 functions. The relationship to Level 5 is discussed in more detail below. A reach scale stream restoration project often has very little control over these factors. Therefore, if a primary goal of a restoration project is to improve these functions, project site selection is as important (if not more important) than the reach scale activities associated with Levels 1-3, but especially Levels 2 and 3. The ideal situation for a restoration project that seeks to restore Level 4 functions is to have a healthy upstream watershed and reach scale impairments that can be improved by restoration activities. In this case, once the reach scale restoration activities have been completed, the project can benefit from a healthy watershed and not be limited by poor water quality. Common Level 2 and 3 restoration activities that support Level 4 functions include floodplain connectivity, bed form diversity, lateral stability, overhanging vegetation and a wide riparian buffer. This does not mean that Level 4 functions cannot be achieved in the future if the upstream health of the watershed improves. Watershed management plans are important tools that can combine reach scale restoration with preservation, stormwater BMP's, and other forms of water quality improvements to restore watersheds beyond individual stream reaches.

Level 5: Biology

Biology functions describe the processes that support the life histories of aquatic and riparian plants and animals. These life histories are dependent on all the lower-level functions, which is why Biology is at the top of the Pyramid. For instance, healthy fish populations cannot exist without the proper flow duration, velocity distributions, bed forms, temperature, water chemistry, etc. that are created through the interactions of all five levels. Parameters that describe Biology functions include microbial communities, macrophytes, macroinvertebrate communities, fish communities and landscape pathways. A detailed description of each parameter and various measurement methods is provided in Chapter 10.

Like Level 4, most reach scale restoration activities that support Level 5 occur at Levels 2 and 3. If a project goal is to have a healthy native fish population, the stream reach must have the proper flow duration, flow dynamics, bed form diversity, lateral stability, vegetative cover, temperature regulation, dissolved oxygen, pH and conductivity. As discussed in Level 4, site selection is just as critical as the reach scale restoration efforts because the quality of water and sediments entering the project reach are critical to the health of the aquatic life.

4.7 » STREAM FUNCTIONS PYRAMID: PERFORMANCE STANDARDS

The final layer to the Framework includes performance standards associated with the measurement methods. The performance standards are divided into functional capacity types, including: Functioning, Functioning-at-Risk, and Not Functioning, which are similar to the categories used in the Proper Functioning Condition method (Prichard et al., 1998). These categories are defined below:

- Functioning: A Functioning score means that the measurement method is quantifying or describing one or more aspects of a function-based parameter in a way that **does support** a healthy aquatic ecosystem. A single functioning measurement method may not mean that the function-based parameter or overall category (e.g., Geomorphology) is functioning.
- Functioning-at-Risk: A Functioning-at-Risk score means that the measurement method is quantifying or describing one or more aspects of a function-based parameter in a way that **can support** a healthy aquatic ecosystem. In many cases, this indicates the function-based parameter is adjusting in response to changes in the reach or the watershed. The trend may be towards lower or higher function. A Functioning-at-Risk score implies that the aspect of the function-based parameter, described by the measurement method, is between Functioning and Not Functioning.
- Not Functioning: A Not Functioning score means that the measurement method is quantifying or describing one or more aspects of a function-based parameter in a way that **does not support** a healthy aquatic ecosystem. A single functioning measurement method may not mean that the function-based parameter or overall category (e.g., Geomorphology) is not functioning.

Most published performance standards are not described in terms of Functioning, Functioning-at-Risk or Not Functioning, so professional judgment was required to distribute the values. Performance standards that are available for each measurement method are provided in Chapters 6-10, and a summary of all the performance standards is provided in Appendix Ad. Many of the performance standard values, especially the dimensionless ratios, should be considered as examples that can be modified based on regional variations in reference condition.

Many of the performance standard values, especially the dimensionless ratios, should be considered as examples that can be modified based on regional variations in reference condition.

Some measurement methods do not include performance standards because they either do not exist or the measurement method is more associated with design than the actual performance of a function-based parameter. An example is the bankfull discharge, a Level 1 measurement method for the channel-forming discharge parameter. The bankfull discharge is used in natural channel designs and geomorphic assessments and it drives many of the functions in Level 2 and 3, thereby supporting functions in Levels 4 and 5. It is a critically important measurement method; however, it is a result of the watershed characteristics and is unique to every stream. Therefore, it would be difficult to create a reliable performance standard for the bankfull discharge. There are other measurement methods, such as the bank height ratio used to measure floodplain connectivity, that are closely related to the bankfull discharge, can be much easier to measure, and have performance standards that can be used, irrespective of geology or climate.

The criteria used to select performance standards, in priority order, include:

- Provided in peer-reviewed journals;
- Provided in government documents;
- Provided in books or proceeding papers; and
- Professional judgment of the authors.

4.8 » STREAM FUNCTIONS PYRAMID AND RESTORATION ACTIVITIES

The above discussion provided an overview of the Stream Functions Pyramid Framework, describing the functions by category and listing the function-based parameters and measurement methods that can be used to describe the functions. A description of performance standards was also provided. In the following section, an example is provided to illustrate how restoration activities can improve stream functions using the Pyramid as a guide. This will help explain how a stream restoration project can improve stream functions at a reach scale or as part of a larger watershed improvement effort. However, not all types of stream restoration or water quality improvement projects fit neatly into the Pyramid.

Restoration of Channelized and Incised Channels

The restoration of channelized, incised streams is used as an example because it is a common approach in areas with well-established stream restoration and mitigation programs. Therefore, many stream mitigation programs appropriately discuss the importance of channel evolution and floodplain connectivity in their SOP (USACE Wilmington District et al., 2003; USACE Savannah District, 2004; USACE Norfolk District and VDEQ, 2007; and USACE Charleston District, 2010). Early stream mitigation programs were prevalent in the eastern United States, a region where channelized and incised streams are abundant. As mitigation programs continue to develop in the western regions, other types of impairments will increasingly be addressed by stream mitigation programs. However, incised channels are prevalent throughout the United States and will continue to be addressed by restoration and mitigation programs.

Background

Channelization is an engineering practice with a long history in the United States, starting in the 19th century. From 1820 to 1970, more than 200,000 miles of streams and rivers were channelized to reduce flooding, provide drainage for agriculture, and improve navigation (Wohl, 2004). Locally, channelization increases drainage and reduces flooding by increasing stream gradient (typically by straightening the channel), thereby increasing stream power, which typically leads to further incision (Darby and Thornes, 1992; Hupp, 1992). The increased width, depth and cross-sectional area following channelization and incision reduce floodplain inundation, decreasing water and sediment storage on the floodplain (Kroes and Hupp, 2010; Pizzuto, 1987). Shields et al. (2010) compared physical, chemical and biological functions between an incised channel and non-incised channel with a similar mix of agriculture and forested land uses in northern Mississippi. The results of this study showed that the incised channel had turbidity and suspended solids levels that were two to three times higher than the non-incised channel. Total phosphorus, total Kjeldahl nitrogen, and chlorophyll a concentrations were significantly higher in the incised channel; however, nitrate was significantly higher in the non-incised channel. There were twice as many fish species with four times the amount of biomass in the non-incised stream. Correlation analysis showed that hydrologic perturbations were associated with the water quality degradation, leading the authors to recommend that ecological engineering should provide as much attention on mediating hydrologic perturbations and habitat quality as on pollutant loading. The research cited above did not use the Stream Functions Pyramid or the Fischenich (2006) framework; however, it did show that negative changes to lower-level (physical) functions, like Hydrology, Hydraulics and Geomorphology (Levels 1-3) had negative impacts on Physicochemical and Biology functions (Levels 4-5). The research also showed that restoration efforts should address these lower-level functions in order to show changes in the higher-level functions. Examples of how to use the Pyramid to link restoration activities to functional improvement is provided below.

Linking Restoration Approach to Stream Functions Pyramid

Typically, restoration credits are based on restoration and enhancement definitions that include changes to dimension, pattern and profile (e.g., USACE Wilmington District et al., 2003). The Stream Functions Pyramid is a tool that can help change the definitions of restoration and enhancement to focus on functional lift rather than changes to dimension, pattern and profile. Consider the example in Table 4.4 showing restoration activities that are used to restore incised, channelized streams. The restoration activities are shown in the first column. The second column links a function-based parameter from the Pyramid that is *directly* improved as part of the design and implementation phase of the restoration activity. The third column shows *indirect* improvements of other function-based parameters within the same function category (level) or higher. This implies that the restoration activity and direct manipulation of function-based parameters in Pyramid Levels 2 and 3 will *support* the improvement of certain function-based parameters in Levels 2 through 5. The word support is stressed, because these restoration activities are implemented at a reach scale and cannot change the condition of the upstream watershed. It is possible that poor upstream conditions can prevent functional lift at the project reach, especially with Level 4 and 5 functions. Performance standards and subsequent monitoring are used to determine if the direct and indirect functional improvements are actually achieved.

The Stream Functions Pyramid is a tool that can help change the definitions of restoration and enhancement to focus on functional lift rather than changes to dimension, pattern and profile.

TABLE 4.4 LINK BETWEEN RESTORATION ACTIVITY AND FUNCTIONAL IMPROVEMENT

RESTORATION ACTIVITY	FUNCTION-BASED PARAMETER that is *directly* changed during the design and implementation phases	OTHER FUNCTION-BASED PARAMETERS that are *indirectly* supported
Re-connect the stream to the floodplain by raising the channel or excavating the floodplain	Level 2 – Floodplain connectivity	Level 2 – Groundwater/surface water exchange, flow dynamics Level 3 – Sediment transport competency and capacity, bank migration/lateral stability Level 4 – Nutrients Level 5 – Microbial Communities, Macrophyte Communities, benthic macroinvertebrates, fish communities

TABLE 4.4 LINK BETWEEN RESTORATION ACTIVITY AND FUNCTIONAL IMPROVEMENT (CONT.)

RESTORATION ACTIVITY	FUNCTION-BASED PARAMETER that is *directly* changed during the design and implementation phases	OTHER FUNCTION-BASED PARAMETERS that are *indirectly* supported
Re-meander the stream on the floodplain	Level 3 – Bed form diversity	Level 2 – flow dynamics, groundwater/surface water interaction Level 3 – Sediment transport competency and capacity, bank migration/lateral stability Level 4 – Water quality, Nutrients, Organic Carbon Level 5 – Microbial Communities, Macrophyte Communities, Benthic macroinvertebrates, fish communities
Add bed form structure and complexity, e.g. in-stream structures	Level 3 – Bed form diversity	Level 3 – Large woody debris transport and storage, bed material characterization Level 4 – Water quality, Nutrients, Organic Carbon Level 5 – Microbial Communities, Macrophyte Communities, Benthic macroinvertebrates, fish communities
Plant streambank and riparian vegetation	Level 3 – Riparian Vegetation	Level 3 – Bank migration/lateral stability Level 4 – Water quality, Nutrients, Organic Carbon Level 5 – Microbial Communities, Macrophyte Communities, Benthic macroinvertebrates, fish communities

Example Projects that May Not Need the Pyramid

The Stream Functions Pyramid Framework is more applicable to some types of projects and less to others. Stream restoration projects that involve physical manipulation to intermittent and perennial stream channels can benefit from the Stream Functions Pyramid. Stormwater Best Management Practices, regenerative design (Flores et al., 2011), Low Impact Development, and other practices that occur in ephemeral channels and uplands may benefit less from using the Pyramid. In addition, water quality solutions, like treat-

ing point source discharges and lime dosing, may not need the Pyramid to set project goals or develop assessment methods. However, even in these cases, it is always appropriate to ask, "What are the supporting functions that are required to meet the desired result?" This is important because other problems may exist in addition to the obvious impairment.

For example, low pH is a commonly known problem in many West Virginia streams. The state agencies have created a dosing program to add lime to the stream and increase pH. Results have been positive; however, in a presentation at the 2011 Mid-Atlantic Stream Restoration Conference, Anderson (2011) showed variable improvements in trout populations. The reasons are not known; however, very little additional information (other than water chemistry) was collected. The goal of this effort was to restore the trout fishery. Therefore, an understanding of key functions in all five levels is needed in order to find a solution. Reducing pH may be the most important part of the solution, but other function-based parameters may also need to be addressed, e.g., improved bed form diversity, to recover trout populations.

Implementation of upland stormwater BMPs probably does not need the Pyramid. The goals of these projects are typically to reduce flow energy, reduce nutrients and remove other inorganic and organic compounds. These projects would rely more on conventional approaches to stormwater treatment.

4.9 » APPLICATION OF THE STREAM FUNCTIONS PYRAMID FRAMEWORK

The Stream Functions Pyramid is a conceptual model, a broad-level view showing the supporting relationships between functions. It also provides *examples* of function-based parameters, measurement methods and performance standards. Together they create the Stream Functions Pyramid Framework. It is not an all-inclusive framework and other parameters, measurement methods and performance standards can be added. The Pyramid framework is more of a thought process than a set of guidelines, and it is definitely not a cookbook. As such, it can be challenging to figure out how to start applying the Pyramid or how to "enter" the Pyramid. This section provides general explanations and examples about how to think about and apply the Pyramid as it relates to goal setting, function-based assessments and developing Standard Operating Procedures (SOPs). Refer to Chapter 11 for more detailed information about how the Pyramid can be applied.

Setting Project Goals and Objectives

Fischenich (2006) reports that a common goal of stream restoration is to restore stream habitat. However, he points out that habitat has the least effect on the other functions and is affected by the most functions. The Stream Functions Pyramid can be used by practitioners to establish goals that are more specific than restoring habitat. It can also be used to identify and think through the underlying, supporting functions that would need to be addressed to achieve a desired result.

Restoring habitat as a goal is too broad. One could ask, "Habitat for whom?" Most of the planet provides habitat for something, so a goal like this does not communicate why the project is needed or what it hopes to accomplish. A better goal would be to restore

habitat for a specific species of concern, e.g., native, southern brook trout. Of course, this goal should come after some form of functional assessment has been completed to determine that brook trout habitat is in need of restoration and that the watershed can support brook trout if the reach is restored. The Pyramid framework can assist with this process by helping the restoration team think through the underlying functions that are needed to support brook trout. First, it must be acknowledged that restoring brook trout is a Level 5 function; it relates to the life history of an aquatic organism (brook trout). So the team would "enter" the Pyramid at Level 5. If they enter at Level 5, there must be supporting functions in Levels 1-4. Now the team must identify those functions and function-based parameters. Again, this is not a cookbook, and the Pyramid does not automatically prescribe the supporting functions. This is a thought process that requires qualified professionals to be able to identify the appropriate parameters. For example, the first question might be, "What are the Level 4 function-based parameters that are needed to support native brook trout?" The answer would include appropriate temperate and oxygen regulation, as trout need cool, highly oxygenated water. Water quality must also be sufficient to support native brook trout populations, which could be affected by lower-level functions at a reach scale, as well as the health of the upstream watershed. Using the temperature and oxygen regulation as an example to further explore how the Pyramid can be used, the team might ask, "How do we achieve the proper temperature and oxygen regulation? What are the supporting function-based parameters?" The answer is found in Level 3.

Geomorphology function-based parameters like bank migration/lateral stability, bed form diversity and riparian vegetation affect temperature and oxygen regulation. This is a critical understanding because these parameters can be manipulated as part of the design to change oxygen and temperature regulation. For example, the channel form can be changed to create riffles and deep pools, banks can be stabilized and the riparian corridor can be planted. The level 4 parameter of oxygen and temperature regulation cannot be directly manipulated; rather, changes at level 3 are made to affect changes at level 4.

The thought process continues. The team can now ask, "What Hydraulic (Level 2) function-based parameters are needed to support bank migration/lateral stability, bed form diversity and riparian vegetation?" In this case, all of the Level 2 function-based parameters (floodplain connectivity, flow dynamics and groundwater/surface water exchange) are important to support the identified Level 3 functions, as well as Level 4 functions. Floodplain connectivity minimizes the amount of energy and force within the channel banks by dissipating flood energy on a floodplain or floodprone area. However, the appropriate amount of energy is maintained in the channel to support the creation of appropriate bed forms, e.g., riffles and pools. Floodplain connectivity also affects flow dynamics and groundwater/surface water interaction, which helps create healthy hyporheic zones that can regulate water temperature and support macroinvertebrate populations, among other benefits. Floodplain connectivity is also a function-based parameter that can be directly modified by a restoration team and is often considered the most important restoration activity because it supports Levels 2-5 functions.

Finally, the team can ask, "What Level 1 function-based parameters are needed to support the higher-level function-based parameters listed above?" These function-based parameters support functions from Level 1 through Level 5. Level 1 function-based parameters, including channel-forming discharge, precipitation/runoff and flow duration, are important to restoring native brook trout. The channel-forming discharge is used to determine how large the channel should be and is directly used to determine floodplain connectivity. Runoff is a watershed calculation and may or may not be modified based on the size of the watershed, property control and condition. Flow duration is typically determined by watershed conditions, but can be moderately improved by some restoration activities. It is important to evaluate these Level 1 parameters to make sure that the Hydrology can support the project goals. And of course, if the underlying geology or climate regime does not support brook trout, the project should not be attempted.

This is a simple example of how the Pyramid can be used as a process for developing and thinking through reach scale project goals. Other function-based parameters could be identified, but questions about the supporting functions would be the same. And there are certainly many other goals that could be considered. For example, improving water quality is another common goal. Like habitat, this goal could be improved by being more specific. What water quality issues are being addressed (temperature and oxygen, nutrients, conductivity, pH, etc.)? The answer to this question will help the restoration team identify the supporting functions required to make this improvement and to determine if restoration activities that change function-based parameters are needed; or the team can determine if things outside of the Pyramid should be addressed, e.g., a treatment plant or lime dosing.

The last example discussed here relates to stream mitigation. Many stream mitigation SOPs (USACE Wilmington District et al., 2003; USACE Savannah District, 2004; USACE Norfolk District, 2007; USACE Charleston District, 2010) link restoration credits to changes in dimension, pattern and profile, based on the Rosgen (1996) definition of a stable channel. While this is an appropriate definition of channel stability, it does not explicitly relate to a stream function. This has resulted in numerous projects where the stated goal is to improve dimension, pattern and profile with no thought given to why these changes are being made, i.e., what functional improvements are desired. At worst, this has resulted in projects that have completely reconstructed channels that did not need reconstruction. At best, it resulted in projects where the improvements were misunderstood, e.g., the achievable goal was to reduce sediment supply from eroding streambanks, but assumptions were made that it should improve macroinvertebrates. If stream mitigation programs changed the definition to the restoration of function-based parameters identified on the Pyramid, then it could better clarify why the project was being completed. In addition, the mitigation program could then require the restoration team to identify the supporting function-based parameters and what restoration activities will be used to achieve the goal.

Developing Function-Based Stream Assessment Methods

The Stream Functions Pyramid Framework can be used as an aid to develop function-based assessments and to select or evaluate existing assessments. It can also be used as a way to organize watershed assessment plans. The term function-based is used instead of functional because the Pyramid includes a combination of functions and structural measures. However, this combination is considered function-based because the parameters and measurement methods are used to quantify or qualitatively describe the overall functional statement for a given Level. A detailed description of how the Pyramid Framework can be applied to function-based assessments, including developing, reviewing and organizing watershed management plans, is provided in Chapter 11. A general overview and example is provided below.

Stream assessments can be completed for a wide range of reasons, including but not limited to: fisheries management; threatened or endangered species recovery plans; drinking water source assessment; watershed/land use planning; compliance monitoring for State or Federal permits; documenting water quality trends (Somerville and Pruitt, 2004); before and after comparisons of stream restoration projects; and to determine the restoration potential for a degraded stream reach. Restoration potential is the highest level of restoration that can be achieved given the results of the function-based assessment, health of the upstream watershed and the project constraints.

The Pyramid Framework may help remedy this problem or at least improve predicative power by including those parameters that are known to support biological conditions. As Somerville (2010) illustrated, many of the current assessment methodologies do not include hydrologic parameters.

Somerville (2010) found that the eight most commonly assessed parameters for regulatory and non-regulatory programs were: discharge, channel habitat units (bed forms), sinuosity, substrate particle size, bank stability and dominant bank material, riparian canopy cover, water temperature, and benthic macroinvertebrates. These parameters were often included in categories like physical, chemical and biological to meet the Clean Water Act categorization of functions or some form of modification, like habitat. In his study, hydrologic parameters were the least represented; even though studies like Fischenich (2006) and Shields et al. (2010) show that hydrologic parameters are critically important to supporting other functions.

Hughes et al. (2010) completed an evaluation of four qualitative indexes of physical habitat to see if they yielded similar results when applied to streams with varying disturbance and ecoregion. They also compared the results with independent assessments of vertebrate and invertebrate assemblage condition. The results showed that there were varying meanings of the term "habitat"; however, the different methods did yield similar results. The results were not as favorable when the physical habitat index scores were compared to biological index scores. This led the authors to conclude that there is more to

learn about the factors that control biotic-assemblage structure across broad regional scales.

The Pyramid Framework may help remedy this problem or at least improve predicative power by including those parameters that are known to support biological conditions. As Somerville (2010) illustrated, many of the current assessment methodologies do not include hydrologic parameters. The Pyramid Framework takes this a step further by providing a structure for assessment developers to select biological parameters and then supporting parameters that are appropriate for their region. If the Pyramid Level 1-5 categories are used to organize the parameters, it will be easier to identify other supporting parameters that should be included.

In addition, since the Pyramid is a hierarchy, a framework is provided that can be used as a logical structure for creating functional assessment scores or indexes. For example, parameters lower in the Pyramid may be weighted differently than those higher in the Pyramid. For these applications, the assessments would likely have a method for summing values within a category to create an overall value, e.g., a Geomorphology score. Since measurement methods quantify a portion of a function-based parameter, and the function-based parameter describes the functional statement within a category, it is recommended that overall scores take place at the category level. There may be cases where the score could be made at the function-based parameter level; however, they should not be made at the measurement method level because a single measurement method rarely, if ever, fully describes the function-based parameter. Scoring based solely on an individual measurement method can lead to unintended consequences where the function-based parameter is not properly assessed, scored, or evaluated. For example, pool-to-pool spacing and pool depth variability are two measurement methods that quantify bed form diversity. Used together, they are appropriate indicators of the number of pools that are present in a study reach and the quality (depth) of those pools. However, if only one measurement method is used, the result is an inaccurate portrayal of bed form diversity. If pool depth alone is used, the result could be one deep pool out of a long stream length, e.g., one pool over a length of 2,000 feet. The score would show that bed form diversity is functioning when clearly it is not. Just using pool-to-pool spacing could yield a similar result. A reach could have the appropriate number of pools, but they may all be too shallow, perhaps from excessive sedimentation or an overly wide channel. Great care should be given to selecting measurement methods that fully describe the function-based parameter. And to avoid over emphasizing the measurement method, scoring should role up to the function-based parameter or category level.

Weighting will also apply to stream mitigation programs that ultimately need to link a score to debits and credits that relate to functional loss and lift, respectively. A step-wise approach for developing function-based assessments is provided in Chapter 11. However, weighting examples are not provided in this document. These examples will come from actual applications of the Framework and will be made available on the Stream Mechanics website (*www.stream-mechanics.com*).

Creating SOPs for Stream Mitigation Programs

The Pyramid can be used by Interagency Review Teams (IRTs) to develop debit and credit determination methods and performance standards for stream mitigation projects. This was discussed in the text above regarding stream restoration; and Chapter 11 provides templates that show how the Pyramid Framework can be used to develop debits and credits. Appendix B also provides some case studies for a variety of debit and credit scenarios.

Developing SOPs Beyond Stream Mitigation

The Stream Functions Pyramid can serve as an aid in creating SOPs for federal, state and local programs not associated with stream mitigation. These may include grant programs, impaired waters programs working on the development of Total Maximum Daily Loads (TMDLs), non-point source and stormwater management programs and others. Any program that deals with improving or preserving natural waterways can benefit from working through the thought process, questions and criteria that are outlined above.

4.10 » SUMMARY

The Stream Functions Pyramid is a simple, conceptual framework. It illustrates that stream functions should be addressed in a certain order while maintaining the concept that stream functions are interrelated. Many of the parameters support functions in their own level, upper levels and sometimes a lower level. It must be restated that the Pyramid was not developed to capture all the interrelationships between the parameters that are used to describe the functions. Fischenich (2006) is a better reference for showing specific interrelationships between functions.

The Pyramid can serve as a communication tool among the various disciplines that work in the fields of stream assessment, restoration and mitigation. There are very few individuals who are well versed in all five levels, so having a framework like the Pyramid makes it easier to communicate across disciplines and helps to ensure that future assessments do not make the same mistake illustrated by Fischenich (2006) and Somerville (2010), i.e., that most function-based assessments include habitat measures and rarely include hydrologic functions (split on the Pyramid into Hydrology and Hydraulic). This is critical because, as Fischenich (2006) and the Pyramid illustrate, these hydrologic functions must be working (at least to some level) in order to support Physicochemical and Biological functions. Existing assessments may be skewed towards Biological parameters because they are often prepared by biologists or ecologists who do not have a strong background in the hydrological sciences or geomorphology. Comparatively, there have been numerous "channel improvement" projects performed by hydraulic engineers that just deal with the Hydrology and Hydraulic functions and do not address Geomorphology, Physicochemical or Biology functions described by the Pyramid. This trend is changing and the Pyramid can be used as a guide to develop more comprehensive designs (and assessments) that address a wider range of stream corridor functions.

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Chapter 5
Reference Streams

5.1 » USE OF REFERENCE REACH DATA IN THIS DOCUMENT

The concepts of reference stream and reference condition are used throughout this document. They are used in various performance standards in Chapters 6-10, and tied to project goals and debit/credit determination methods in Chapter 11. The use of reference stream condition is most prevalent in the development of performance standards for the Physicochemical and Biology functions described in Chapters 9 and 10, respectively. The use of reference condition is also used to develop performance standards for several Geomorphology measurement methods, e.g., riparian vegetation and bed form diversity. The reason for this is due to the lack of data and knowledge about what constitutes healthy water chemistry, biology and geomorphology for every stream in the US. These parameters are simply too variable and dependent on all the supporting functions and weather/climate patterns to establish universal performance standards. For example, a bottomland hardwood forest is common to reference streams in the East, but certainly not the arid portions of the West. Some states and regions, however, have better reference condition databases than other places, and, in these cases, it may be possible to modify the performance standards to provide specific ranges. Hopefully over time, reference stream databases will be provided for a wide range of regions and the performance standards can be revised to include less subjective and more quantitative guidance.

The use of reference stream condition is most prevalent in the development of performance standards for the Physicochemical and Biology functions described in Chapters 9 and 10, respectively.

5.2 » BACKGROUND

There are many different views of what a reference stream is and how it should be used. The term “reference stream” or “reference reach” is used throughout the remainder of this document to develop measurement methods and performance standards for certain parameters. Therefore, it is important to have a clear understanding of what is meant by a reference stream, how it is used in the context of stream assessment and stream restoration design, how to select stream reference reaches, and how to collect and analyze the data. An ecosystem reference represents “some target, benchmark, standard, model or template from which or to which ecosystem biological integrity, structure,

function, condition or relative health are compared" (Miller et al., 2011). While a reference condition can be established for a single stream reach, whenever possible, the reference condition should come from several stream reaches that can more accurately reflect the range of natural variability.

Regulatory and non-regulatory stream assessment programs often use the term "reference condition" to describe the quality of a reference stream. The 2008 Mitigation Rule defines condition as "the relative ability of an aquatic resource to support and maintain a community of organisms having a species composition, diversity and functional organization comparable to reference aquatic resources in the region." The Rule goes on to define Functions as "the physical, chemical and biological processes that occur in ecosystems" and Functional Capacity as "the degree to which an area of aquatic resource performs a specific function." All of these regulatory definitions point to the need to demonstrate that a stream restoration project functions like some reference condition, at least within the constraints established through the project's goals and objectives. Stoddard et al. (2006) provides a discussion of the various ways that reference condition can be interpreted, along with definitions of reference condition types, including historical condition, least-disturbed condition, minimally disturbed condition and best-attainable condition. Miller et al. (2011) and Pruitt et al. (2012) prepared USACE technical notes that build on the Stoddard et al. (1996) concepts of reference condition. Reference condition is defined as "a contextual background against which the degree of degradation, range of condition, and benefits of restoration can be measured." The goal of these publications is to develop a common understanding of the reference condition concept to better interpret environmental regulations and to improve selection of reference ecosystems to meet restoration project objectives.

In stream ecosystems, the reference condition can be determined using information collected from reference streams that are used for comparison with both impaired and restored reaches, as well as development of a natural channel design for stream restoration. Rosgen (1998) developed the concept of a reference reach approach as a blueprint for developing a natural channel design. His definition of a reference reach is "a stream that can transport the flows and sediment produced by its watershed so that the dimension, pattern and profile are maintained without aggrading or degrading." In the Rosgen definition, the channel does not necessarily require a pristine condition without human disturbance; the stream simply needs to be in balance with watershed flow and sediment processes. Therefore, this concept of a reference stream focuses more on Hydrology, Hydraulic and Geomorphology functions (Levels 1-3) than Physicochemical and Biology functions (Levels 4 and 5). Historically, stream restoration practitioners have focused more on using reference reaches as defined by Rosgen to better understand Level 1-3 functions because they can directly manipulate, and thereby improve, these functions. However, with some adaptations to selecting and analyzing reference reach data, these reference streams can also be used to evaluate the condition and functional lift of Level 4 and 5 functions. Since the approaches are different for Levels 1-3 and Levels 4-5, the site selection and assessment method sections below are stratified accordingly.

Uses of Reference Streams in Restoration

Before moving into site selection and assessment methods, more information is needed on how reference stream data are used. These uses were introduced above and include the following:

1. As a blueprint for a natural channel design.
2. Structure and function comparison between an impaired stream and a reference condition, which can be determined using one or more reference streams. This assessment is often completed for:
   a. Establishing the baseline condition at a proposed restoration site;
   b. Determining functional loss at a site proposed for an impact; and
   c. Evaluating the success (functional lift) of a stream restoration project, i.e., establishment of performance standards.

Blueprint for Natural Channel Design

This document does not focus on stream restoration design, so a detailed overview of how reference reaches are used to develop natural channel designs is not provided. It is important to note, however, that reference reaches are commonly used by practitioners, especially those that use the Rosgen method for natural channel design (Rosgen 1998). A detailed description of how these reference reaches are used in natural channel design processes is included in the Natural Resources Conservation Service, National Engineering Handbook, Chapter 11. This handbook is available at *directives.sc.egov.usda.gov/viewerFS.aspx?id=3491*.

Comparison Between Impaired/Restored Streams and Reference Streams

Reference streams represent stable and highly functioning channels. Therefore, data collected from reference streams to determine the reference condition will provide a standard against which lower-functioning streams can be compared. Comparing a project reach to a reference stream(s) prior to restoration helps establish the level of impairment. This information can also help understand the potential to restore stream functions and to establish realistic project goals. This type of comparison can also be used to evaluate proposed impact sites. The project stream can be compared to a reference condition to determine the level of impairment that may occur from the impact, i.e., highly functioning streams would have more functional loss than streams that are already impaired.

Reference streams can also be used to evaluate the success of stream restoration projects. This comparison can be somewhat complicated because a stream restoration project must evolve for many years before it will function like a reference stream. The rate of this evolution varies by the functional category (categories shown on the Pyramid). Generally, improvements to Hydraulic functions (Level 2) quickly meet performance standards that resemble reference reach conditions. Re-establishing floodplain connectivity is a great example. The stream is either vertically connected to the floodplain or it is not, and connectivity can easily be measured by the bank height ratio at any riffle along the entire project reach. Functional improvements in Geomorphology (Level

3) take more time to achieve reference reach conditions, primarily because many of the processes are affected by the establishment of the riparian buffer. For this reason, most practitioners design a channel form that will evolve over time as the permanent vegetation matures. Physicochemical and Biology functions (Level 4 and 5) may take even longer to represent reference condition, and, depending on the health of the upstream watershed, they may never evolve to the reference condition. This is why site selection is so important in choosing a restoration project when the goal is to restore Level 4 and/or 5 functions.

5.3 » SITE SELECTION

Choosing a reference reach will depend on the purpose of the project established by the goals and objectives. For example, selecting a reference reach for stream restoration design purposes will require Hydrology, Hydraulic and Geomorphology functions more so than Physicochemical and Biology functions. The reference reach length may be shorter and have more water quality impairments than a reference reach selected to address Physicochemical or Biology functions. Therefore, the site selection criteria described below is divided into two sections, one for Levels 1-3 and the other for Levels 4-5.

Geomorphology Reference Reaches (Levels 1-3)

Identifying an appropriate site for a Geomorphology reference reach requires diligence and time spent in the field assessing potential sites. Reference reaches will be hardest to locate in areas that have been intensively modified for agriculture, forestry, mining and development. In these areas, most stream channels have been modified.

Hey (2006) shows that, unlike regional curves, reference reaches do not need to come from the same hydro-physiographic region as the project site. Therefore, it is important to look in different regions if a reference cannot be found near the project. In general, Geomorphology reference reaches should meet the criteria outlined below:

1. Stable dimension, pattern and profile.
2. Bank height ratio less than 1.2, preferably 1.0 (See Chapter 8, Floodplain Connectivity section for a description of the bank height ratio).
3. Stable banks — (See Chapter 8, Lateral Stability section for techniques to assess lateral stability).
4. Natural features such as point bars may be present, but without excessive bar development, like mid-channel or transverse bars.
5. Same stream type as the project reach after restoration (i.e., C4, E5, etc.).
6. Same valley type and approximate slope as study reach.
7. Same bed material as study reach (i.e., sand, gravel, cobble, bedrock, etc.).
8. Same type of bank vegetation as the project reach (e.g., do not use a mature bottom land hardwood forest reference reach for a restoration project that will only include a herbaceous buffer).

In order to select an appropriate reference reach, several tools are used in support of the identification process:

1. US Geological Survey Quadrangle Maps: Quadrangle maps can be used to identify streams of a particular watershed size, valley type and slope. Quadrangle maps also provide general information on watershed conditions and land use, although these data should be checked against other more recent data sources (such as aerial photographs), since quadrangle maps are not updated very frequently.
2. Aerial Photographs: Aerial photographs can be very useful in identifying potential reference reaches and further evaluating reference reaches identified by other maps, such as from a USGS quadrangle map. Evaluating multiple aerial photographs over time can provide additional support regarding stream stability by documenting stream dimension and pattern before and after flood events.
3. Windshield Surveys: Many reference reach sites have been identified by simply driving and looking at streams upstream or downstream of roadway crossings. Ensure that landowner permission to access the stream is obtained before entering private property.
4. Discussions with Local Residents: Landowners and local residents are often very familiar with their land and the land that is nearby. These resources can often be used to identify streams that are in good condition and may potentially serve as a reference reach.
5. Looking Upstream and Downstream of the Project Reach: When available, this is one of the best sources for reference reach data, because the reference reach and impaired reach targeted for restoration share the same climatic, topographic and watershed conditions. As with windshield surveys, ensure that landowner permission to access the stream is obtained before entering private property.
6. Existing Watershed and Stream Assessment Reports and Reference Reach Databases: Many agencies and organizations have produced assessment reports that identify stable and unstable stream reaches. These reports are an excellent source as an initial step in identifying potential reference reaches. Furthermore, some of these agencies and organizations have already developed reference reach databases that are available to the public.
7. Discussions with Environmental Professionals: There are many environmental professionals who, as part of the jobs, are required to walk many stream miles. These folks can provide expert opinions on the location of potential reference sites.

In urban and other highly altered environments, it is often difficult to identify true reference reach sites that meet the criteria above. Often, urban streams have been highly modified, either by direct manipulation or through modified hydrology from increased impervious surface runoff. While it is often difficult to identify a stable urban reference reach, it is not uncommon to find short segments of stable urban channel that can be used to evaluate stable bankfull dimensions. Such a stream segment is ideally located just upstream or downstream of the study reach, allowing for direct correlations to proper bankfull dimensions for the design. Finding an applicable reach can be a time-consuming process, and a thorough investigation should be completed to ensure a suitable reference reach is located.

Physicochemical and Biology Reference Reaches (Levels 4-5)

Selecting reference streams that represent high-quality Physicochemical and Biology functions is similar to selecting sites for Geomorphology functions (Levels 1-3) with one large exception. It is possible to have a stable channel with proper bed form diversity in a watershed with point and non-point sources of pollution. However, reference streams used to determine the reference condition for Physicochemical and Biology functions require a healthy upstream watershed with limited point and non-point sources of pollution. Therefore, additional site selection criteria are needed. Additional recommended criteria for reference streams used for Physicochemical and Biology functions are provided below:

1. Most of the watershed is at the natural climax vegetative community, e.g., forested, scrub shrub, grassland.
2. Adequate/comparable flow duration for species of interest.
3. No point sources of pollution (preferable) or point sources that have not impacted aquatic life.

In addition to the tools provided for the Geomorphology section above, the tools listed below may be helpful in identifying Physicochemical and Biology reference reach streams.

1. Choose from state designated sites. Most state water protection agencies have designated hundreds of reference sites based on robust region-specific reference site criteria for assessing aquatic-life use attainment.
2. Check water quality designations. Investigate state water quality designation lists and look for High Quality Waters (HQW), Outstanding Resources Waters (ORW) or similar designations.
3. Search on public land. Look for reference streams in national/state parks, national/state forests and designated wilderness areas.

Many of these streams will not be pristine due to historical impacts; however, they may represent the highest level of functionality that is achievable. This is an important consideration when selecting a site for Physicochemical and Biology functions. Some projects may strive to restore functions to a pre-disturbance, pre-European settlement condition — a worthy, but very difficult goal. Most projects try to restore functions to the highest level possible given the constraints of human development. If so, a reference stream should be selected that reflects this condition, i.e., healthy but not pristine. This is one of the most difficult and controversial issues related to determining the reference condition. Stoddard et al. (2006) and Miller et al. (2011) provide guidance for determining the reference condition type, e.g., historical condition, best attainable condition, and reference condition approach that may best fit with geographic constraints and legacy impacts.

5.4 » ASSESSING REFERENCE REACHES

There are dozens of ways to assess reference reaches, many of which can also be used to assess impaired reaches. However, assessment methods vary greatly in what and how they assess stream functions. Some methods are rapid and others are very time intensive

and costly. Some methods focus on physical functions and others focus on biological functions; few assess all functions. Therefore, it is critically important to know the reason for conducting a reference reach assessment prior to the assessment or survey. Having clear project goals and objectives will serve as an aid in selecting the proper type of reference reach.

Building on the discussion above about the uses of reference reach streams, the following list of assessment methods is provided for Hydrology, Hydraulic and Geomorphology references (Levels 1-3), and assessment methods that focus on Physicochemical and/or Biology conditions (Levels 4-5). The title of the assessment method, a brief description and Web link to the source document is provided. Refer to Somerville and Pruitt (2004) and Somerville (2010) for a description of additional assessment methodologies. These reports can be downloaded, respectively, from the EPA website at: *water.epa.gov/lawsregs/guidance/wetlands/upload/2004_09_01_wetlands_PhysicalStreamAssessmentSep2004Final.pdf* and *water.epa.gov/lawsregs/guidance/wetlands/upload/StreamProtocols_2010.pdf*. USACE is currently developing reference assessment approaches for reference stream condition built upon their Hydrogeomorphic (HGM) Approach that was initially applied to wetlands. The approach has been applied to intermittent streams in the Appalachian region (USACE, 2010), but not to perennial streams at this time. Pruitt et al. (2012) further describes a proposed Reference Condition Index (RCI) that could be used to guide the application of reference condition to an assessment of environmental benefits in aquatic ecosystems.

However, assessment methods vary greatly in what and how they assess stream functions. Some methods are rapid and others are very time intensive and costly. Some methods focus on physical functions and others focus on biological functions; few assess all functions. Therefore, it is critically important to know the reason for conducting a reference reach assessment prior to the assessment or survey. Having clear project goals and objectives will serve as an aid in selecting the proper type of reference reach.

Pyramid Level 1-3 Methods for Assessing Reference Stream Condition

The following list highlights assessment methods that focus on Pyramid Level 1-3 functions. Therefore, these methods are more physically based than biological. Some are used more for natural channel design and others for assessing sediment supply and channel stability.

Title: Stream Channel Reference Sites: An Illustrated Guide to Field Technique
Description: Provides basic overview of surveying procedures (differential leveling) for channel cross sections and profiles. Also provides methods for conducting pebble counts,

staff gauge installation, discharge measurements and pebble count procedures.
Link: *www.stream.fs.fed.us/publications/PDFs/RM245E.PDF*

Title: The Reference Reach — A Blueprint for Natural Channel Design
Description: A Proceeding paper that describes the Rosgen method for collecting and using reference reach survey data. Primarily used for natural channel design and comparing the geomorphology of reference streams to impaired streams.
Link: *www.wildlandhydrology.com/assets/The_Reference_Reach_II.pdf*

Title: Rosgen Geomorphic Channel Design
Description: Part 654, Chapter 11 in the NRCS Stream Restoration Design National Engineering Handbook. Provides a detailed description of how these reference reaches are used in natural channel design processes.
Link: *directives.sc.egov.usda.gov/viewerFS.aspx?id=3491*

Title: Proper Functioning Condition
Description: A rapid qualitative approach that uses a checklist to determine channel and riparian condition. Checklist includes questions about hydrology, vegetation and erosion/deposition. The final result places the stream into one of three categories: Proper Functioning Condition, Functional-at-Risk and Nonfunctional.
Link: *ftp.blm.gov/pub/nstc/techrefs/Final%20TR%201737-9.pdf*

Title: Watershed Assessment of River Stability and Sediment Supply
Description: A geomorphological approach for quantifying the effects of land uses on sediment supply and channel stability. Provides sub-watershed rankings and prioritizes stream reaches based on broad-level screening approaches, but also provides more detailed assessment procedures.
Link: *water.epa.gov/scitech/datait/tools/warsss/index.cfm*

Title: Size Class Pebble Count Analyzer
Description: A spreadsheet tool that is used to identify shifts in the fine gravel and smaller portions of the grain size distribution, rather than the median. It can be used to compare grain size distributions at an impaired site and determine if the distribution is statistically different than a reference site. It can also be used for before and after restoration comparisons.
Link: *www.stream.fs.fed.us/publications/software.html*

Title: Channel Evolution Models/Stream Type Succession Scenarios
Description: These two methodologies illustrate how streams evolve after a disturbance. They would rarely be used as a standalone assessment method, but are a valuable addition to most other assessment methodologies. A reference stream would typically function at an evolutionary endpoint; however, an impaired stream may be moving towards

or away from a reference condition.
Link: Simon Channel Evolution Model: *www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/alphabetical/water/restoration/?&cid=stelprdb1043448* (Chapter 7)
Link: Rosgen Stream Type Succession Scenarios: *water.epa.gov/scitech/datait/tools/warsss/successn.cfm*

Title: Regional Curves
Description: Many of the assessment methodologies used to evaluate Pyramid Level 1-3 functions require an estimate of the bankfull discharge and corresponding stage. Regional curves, while not an assessment methodology, are excellent tools for validating field estimates of the bankfull stage.
Link: *water.epa.gov/lawsregs/guidance/wetlands/upload/Appendix-A_Regional_Curves.pdf*

Pyramid Level 4-5 Methods for Assessing Reference Stream Condition

A wide variety of stream assessment protocols that focus on Physicochemical and Biology functions are available, probably more than for the Hydrology, Hydraulic and Geomorphology functions. Since both of these functions vary greatly across the country, most state water quality programs have developed their own assessment methods. However, many of these are based on the Rapid Bioassessment Protocol or Index of Biotic Integrity that are discussed below. Like the discussion above about assessing the reference condition of Pyramid Level 1-3 functions, selecting the correct reference reach assessment method for Pyramid Levels 4-5 will depend on the project goals and objectives. Some of the more common assessment methods are listed below; however, many projects may require a tailored approach.

Title: EPA Rapid Bio-assessment Protocol (RBP)
Description: A rapid assessment method that provides basic aquatic life data for water quality management purposes such as problem screening, site ranking and trend monitoring. The RBPs are a synthesis of existing methods from state water resource agencies and include three aquatic assemblages (periphyton, benthic macroinvertebrates, fish) and habitat assessment methodologies.
Link: *water.epa.gov/scitech/monitoring/rsl/bioassessment/index.cfm*

Title: Index of Biotic Integrity (IBI)
Description: The original version included 12 metrics that were used to evaluate stream health based on fish data. The metrics and scoring have been modified over time and expanded to include an IBI for macroinvertebrates.
Link: *www.epa.gov/bioiweb1/html/ibi_history.html*

Title: NRCS Stream Visual Assessment Protocol
Description: A simple assessment of stream condition that includes qualitative observations of Pyramid Level 1-5 parameters. It is intended to be a first approximation of stream

condition rather than an intensive assessment of stream function.
Link: *www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/alphabetical/water/restoration/?&cid=stelprdb1043249*

Title: Monitoring Wilderness Stream Ecosystems
Description: This document is a manual that presents a protocol for monitoring a variety of Pyramid Level 1-5 parameters and includes measures of structure and function. The document also includes guidance on setting monitoring goals and objectives, selecting sampling location and analyzing data.
Link: *www.fs.fed.us/rm/pubs/rmrs_gtr70.pdf*

Title: US 301 Environmental Stewardship Study
Description: The US 301 Environmental Stewardship Study is a green infrastructure study that included a stream assessment component. The stream assessment component consists of a GIS-based course stream stability assessment and a rapid stream habitat and stability assessment and restoration feasibility methods. The rapid assessment methods provide a numerical score which can be used for ranking and prioritization purposes.
Link: *www.fws.gov/chesapeakebay/streampub.html*

5.5 » MONITORING APPROACHES

The above methodologies can be used to assess reference streams that can then be used as a comparison against an impaired stream. However, it is important that reference streams are in the same hydro-physiographic region and ecoregion as the project site for Physicochemical and Biology function assessments. In addition, some reference reach and project reach assessments may need to focus on a few select parameters, rather than an overall assessment of channel condition or function that is typically provided by "canned" methodologies. For example, one project may have a goal to increase the grain size distribution in a gravel bed stream to reference conditions. Another project may want to improve dissolved oxygen, temperature and nutrient levels to reference conditions. There are two common monitoring approaches that can be used to help show statistical differences in a project reach versus a reference reach: upstream/downstream and paired watershed monitoring. However, determining the correct statistical approach to use within these two sampling regimes is critical and should often be provided by a trained statistician. The EPA provides a statistical primer with a variety of examples at *http://www.epa.gov/bioindica-*

The above methodologies can be used to assess reference streams that can then be used as a comparison against an impaired stream. However, it is important that reference streams are in the same hydro-physiographic region and ecoregion as the project site for Physicochemical and Biology function assessments.

tors/statprimer/statistical_testing.html. USEPA (1997a) also provides instruction on how to statistically evaluate the effectiveness of best management practices, like stream restoration, on improving water quality.

Upstream/Downstream Monitoring

The ideal scenario for performance standards that use reference reach data is for the reference reach to be located upstream of the project reach. This makes it much easier to have a goal of restoring a project reach to a reference condition. The parameters and measurement methods are selected, again based on project goals and the potential to restore those functions. The monitoring must occur upstream of the project reach and downstream of the project reach and before and after restoration, lasting long enough to complete the statistical analysis. The purpose in this approach is to show that, over time, the downstream monitoring station becomes statistically similar to the upstream monitoring station. Upstream/downstream monitoring can also be used if the reach upstream of the project is not of reference condition. However, in this case, it is more likely that the project will show improvements to Pyramid Level 3 parameters like lateral stability (sediment supply from bank erosion) than to Pyramid Level 5 parameters like macroinvertebrate communities.

Paired Watershed Monitoring

If a reference stream cannot be found upstream of the project reach, a paired watershed approach may be practical, especially for small headwater catchments. This monitoring approach compares monitoring/assessment results from a stable watershed to the impaired watershed. However, for this approach to work, the stable watershed must remain stable throughout the life of the project. Both sites must be monitored before and after restoration for a long enough time to show statistical differences. The Size Class Pebble Count Analyzer discussed above under Pyramid Level 1-3 Method for Assessing Reference Condition provides an example of using a paired watershed approach.

Monitoring Guidance for Determining the Effectiveness of Nonpoint Source Controls (USEPA, 1997a) is a good resource for designing monitoring plans that use statistical techniques to show that stream improvements were caused by a best management practice, in this case stream restoration.

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Chapter 6
Hydrology

The study of hydrology, especially by engineers, quantifies the transport of water that is contributed from the watershed and delivered to a stream channel. Hydrology functions are the base of the Stream Functions Pyramid (Level 1) and therefore support all other functions. Common ways to assess and quantify this hydrologic function include channel-forming discharge, precipitation/runoff relationships, flood frequency and flow duration. Table 6.1 provides a list of parameters discussed in this chapter along with the measurement methods. There are other measures of Hydrology; however, the ones provided here are most closely associated with stream assessment and restoration techniques. Appendix Ac includes a list of all the Hydrology measurement methods along with information about the method's type, level of effort, level of complexity, and whether it is a direct or indirect measure of the function-based parameter. The criteria used to make these determinations are provided in Chapter 4.

TABLE 6.1 HYDROLOGY PARAMETERS, MEASUREMENT METHODS AND AVAILABILITY OF PERFORMANCE STANDARDS

PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD
Channel-Forming Discharge	1. Regional Curves	No
Precipitation/Runoff Relationship	1. Rational Method 2. HEC-HMS 3. USGS Regional Regression Equations	No No No
Flood Frequency	1. Bulletin 17b	No
Flow Duration	1. Flow Duration Curve 2. Crest Gage 3. Monitoring Devices 4. Rapid Indicators	No No No No

For most stream restoration projects, Hydrology parameters are independent variables, meaning that the restoration practitioner cannot change them as part of the design process. They are primarily used to characterize the watershed and as input parameters for Hydraulic assessments; therefore, the Hydraulics Chapter in this document discusses their importance and associated performance standards. There can be exceptions, how-

ever, especially if the stream restoration project is part of a larger watershed management plan. It may be possible to use stormwater BMPs, or other practices to reduce runoff. In these cases, a performance standard could be established for the reduction in runoff. Other scenarios include highly modified headwater systems, such as impacts associated with mining through springs and headwater streams. Here, restoring flow duration is a critical component of the restoration project and should include the development of performance standards. Hydrology parameters are included even without performance standards because of their importance in supporting the higher-level functions. Without an assessment of these parameters, many of the higher-level computations cannot be completed; therefore, it would be remiss to not include them.

6.1 » PARAMETER: CHANNEL-FORMING DISCHARGE

Description

Channel-forming discharge theory suggests that a unique flow over an extended period of time would yield the same channel morphology that is shaped by the natural sequence of flows. Inglis (1947) stated that at this discharge, equilibrium is most closely approached and the tendency to change is least. This condition may be regarded as the integrated effect of all varying conditions over a long period of time. Channel-forming discharge theory is often described as dominant discharge, effective discharge and the bankfull discharge (Knighton, 1998). Dominant discharge is simply a synonym for channel-forming discharge theory. Effective discharge is the product of the flow duration curve and the sediment transport rating curve; therefore, it is the discharge that moves the most sediment over time and is a key parameter in determining channel size (Wolman and Miller, 1960). Bankfull discharge fills a stream channel to the elevation of the active floodplain, thereby delineating the break between erosional (channel forming) and depositional features in a floodplain (Dunne and Leopold, 1978; FISRWG, 1998). Since this discharge leaves a geomorphic indicator, it has become the method used most often to describe channel-forming discharge theory. It is also the design discharge for natural channel designs.

Measurement Method

1. Regional Curves

The identification of bankfull stage and its associated dimensions and discharge are often used in stream assessment and restoration projects using natural channel design techniques. The identification of the bankfull stage is one of the first measurements made during a geomorphic assessment because the Rosgen stream classification system and stability assessments (vertical and lateral) are all dependent on knowing the bankfull stage. In addition, many of the Hydraulic and Geomorphic parameters, such as floodplain connectivity, are dependent on being able to identify and verify the bankfull stage and its corresponding dimensions (especially cross-sectional area). There are several documents that discuss how to field identify and verify bankfull. Rosgen (2006), as part of the Watershed Assessment of River Stability and Sediment Supply (WARSSS), provides a

detailed description of field methods for identifying and calibrating the bankfull stage. (WARSSS is available on the EPA website at *www.epa.gov/warsss*.) Harrelson et al. (1994) provides a more concise summary of field methods for identifying bankfull (*www.stream.fs.fed.us/publications/PDFs/RM245E.PDF*). Harman (2000) provides methods for identifying bankfull in North Carolina streams, which also include a detailed description of how to measure and calculate the bankfull cross-sectional area (*www.bae.ncsu.edu/programs/extension/wqg/srp/rv-crs-3.pdf*).

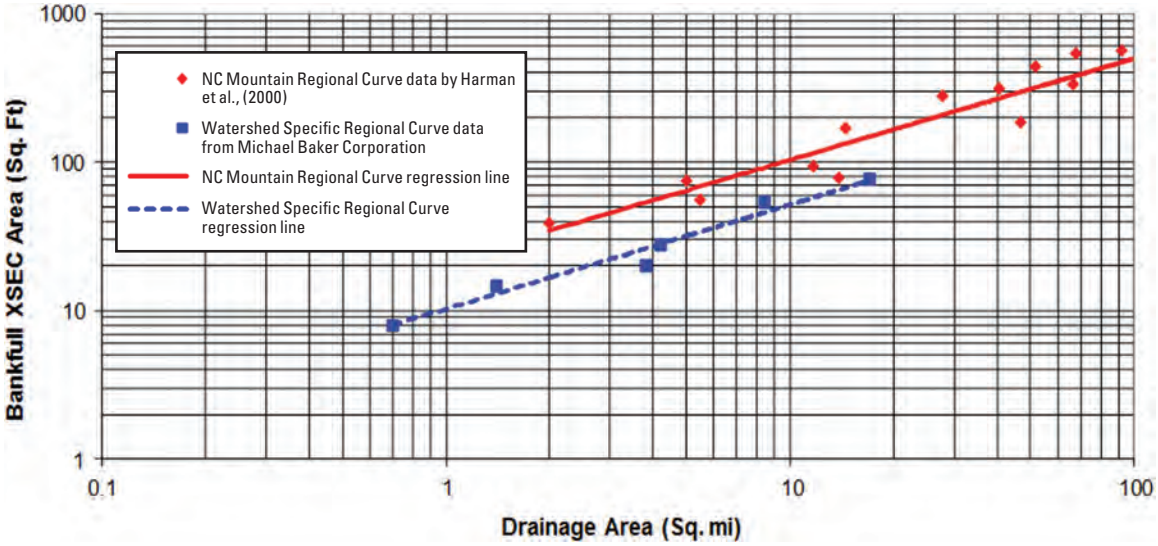
All of these references rely on regional curves as the primary method for verifying the bankfull stage. These curves are tools that can be used to verify the bankfull stage in projects prior to restoration, as a design aid and as a tool for assessing performance. Regional curves relate bankfull discharge and channel dimensions (i.e., width, depth and cross-sectional area) to drainage area. (See Figure 6.1 for an example regional curve.) Regional curves are empirically derived, primarily from USGS gauge stations, and can be developed for a single watershed or multiple watersheds in the same hydro-physiographic region (FISRWG, 1998). Developing watershed-specific regional curves requires a moderate level of effort; however, developing regional curves for an entire physiographic region is an intensive level of effort. If existing regional curves are used, then the level of effort required to use the curve is considered rapid. Likewise, using an existing regional curve is not complex and is categorized as simple in Appendix Ac; however, developing a regional curve is complex, requiring experience and expertise.

Regional curves were first developed by Dunne and Leopold (1978). In recent years, regional curves have been developed across many regions to assist in geomorphic assessments and natural channel design (Cinotto, 2003; Keaton et al., 2005; Miller and Davis, 2003; Harman et al., 1999; Harman et al., 2000; McCandless and Everett, 2002; McCandless, 2003a and 2003b; Sweet and Geratz, 2003; Castro and Jackson, 2001; Chaplin, 2005; Doll et al., 2002; Dudley, 2004; Dutnell, 2000; Mulvihill et al., 2005; and Metcalf, 2004). Somerville (2010) provides a comprehensive list of regional curves published throughout the United States.

When using existing regional curves, care should be taken to determine that the regional curves are appropriate for the project site, i.e., that they are in the same hydro-physiographic region and that the curves were created through unbiased surveys of bankfull indicators. The dimensions (area, width and depth) should come from cross-sectional surveys taken at stable riffles. There have been cases where the 1.5-year return interval was used as bankfull, rather than a physical assessment of the geomorphic indicator. There are other cases where the terrace was used as the bankfull stage, which often results in a return interval that is greater than two.

FIGURE 6.1 REGIONAL CURVE EXAMPLE

North Carolina Mountain Regional Curve (Harman et al.*, 2000) overlaid with a watershed specific curve within the same region. The blue line is lower because it is in a region of the mountains with lower rainfall. The red line represents the entire mountain region of NC, including high and low rainfall areas. Note that while the magnitude of the cross-sectional area is different between the two curves, the slope of the two lines is similar.*



Source: Reproduced with permission from Michael Baker Corporation

Design Standard

As mentioned above, the bankfull discharge is the design flow for a natural channel design project. The design review process should be used to determine that the appropriate bankfull discharge was selected. The easiest way to determine if the bankfull discharge was used in the design is to compare the design value with the results from a regional curve. However, this does not ensure that the project was constructed properly, i.e., that the design bankfull cross-sectional area was constructed. Therefore, performance standards should be developed to determine that the as-built and subsequent monitoring results prove that the appropriate bankfull cross-sectional area was constructed. This will require a field determination of the bankfull stage, as discussed above. The bankfull cross-sectional area from the as-built survey or monitoring report should show that the channel is not incised (too deep), or that it is not too small. Therefore, the best performance measure for determining this is the bank-height ratio, which is discussed in detail in the Hydraulics Chapter under Floodplain Connectivity.

It should be noted, however, that in some cases the design may include a design discharge that is less than the bankfull discharge. If the sediment supply is low, this could result in a stream with greater functionality due to better floodplain connectivity and more riparian wetlands. But if sediment supply is high, it could result in channel aggradation and bank erosion. Therefore, caution should be used when assigning functional

performance standards based solely on the bankfull discharge. An example of a project that used a design discharge that was less than the bankfull discharge is shown below in Figure 6.2. The result is a channel that is much smaller than a typical channel size designed using the bankfull discharge (Art Parola, 2011, personal communication).

FIGURE 6.2

Photos of a project near Lexington, KY that was sized using a discharge smaller than the bankfull discharge. The channel has remained stable after numerous floods. Flow duration has significantly improved due to improved groundwater/surface water interaction, converting an intermittent channel into a perennial channel. This approach works because, among other things, the sediment supply is fairly low, grade control is used in the channel and beneath the floodplain, and vegetation is allowed to establish before the stream flow is moved to the new channel. This approach should not be used in streams with a large sediment load that must be transported through the reach.

Photo by Will Harman

6.2 » PARAMETER: PRECIPITATION/RUNOFF RELATIONSHIP

Description

The amount of precipitation that does not soak into the ground and instead "runs off" the ground surface is a critical component in determining the size of a stream channel. Regions that have high precipitation and runoff (precipitation/runoff) rates often have larger channels than areas with lower precipitation/runoff rates. In humid areas like the Southeastern United States, perennial channels form in watersheds with drainage areas considerably less than one-half of a square mile. In arid regions, however, ephemeral channels exist in watersheds with drainage areas that are hundreds of square miles. This has a major effect on functions in Pyramid Levels 4 and 5.

The effect of precipitation/runoff variability can be seen in comparisons of regional curves of bankfull discharge and cross-sectional area versus drainage area. Regional curves are power function regression equations. Regions with higher precipitation/runoff rates have higher y-intercept values than regions with lower precipitation/runoff relation-

ships; however, the slope of the regression line for all these curves is remarkably consistent. In other words, while the processes that create channel shape and size are similar across regions, variations in the precipitation/runoff relationship create different size channels. An example of this is shown above in Figure 6.1.

Measurement Method

1. Rational Method

The most rapid and simplest method for calculating runoff is the Rational Method or Rational Equation, which is used to estimate peak runoff in small drainage basins. This equation uses a runoff coefficient (C) that is taken from a table, like the one published by the American Society of Civil Engineers (1970) and is most suited for watersheds with a drainage area less than 250 acres. The Rational Equation shows that if it rains long enough, the peak discharge from the drainage area will be the average rate of rainfall times the drainage basin area, which is then reduced by multiplying by the runoff coefficient. The time of concentration is the length of time that it takes water to flow from the beginning of the watershed to the point where runoff (discharge) occurs (Fetter, 1994). The Rational equation is:

Qp = CiA, where

Qp = the peak runoff rate in cubic feet per second.

C = the runoff coefficient

i = the average rainfall intensity in inches/hour, and

A = the size of the drainage in acres.

The Rational Method has evolved through time with the use of computer models. The Natural Resources Conservation Service (NRCS) has developed two computer models that are based on the Rational Method: WinTR55 and WinTR20 (USDA, 2009a and 2009b). These models have been used extensively to design small farm ponds and even large flood control reservoirs. Since it is better to build a dam that is slightly too large rather than one that is too small, these models often give conservatively high estimates of runoff.

2. HEC-HMS

The USACE Hydrologic Engineering Center has developed a more sophisticated and complex model called the Hydrologic Modeling System (HEC-HMS). This model simulates precipitation and runoff processes from a wide range of dendritic watersheds, including small and large watersheds, as well as rural and urban conditions. More information and a free download of the software can be found at the HEC-HMS website (*www.hec.usace.army.mil/software/hec-hms*). However, only experienced hydrologists should use the model.

3. USGS Regional Regression Equations

The United States Geological Survey (USGS) uses their network of gauging stations to provide "regional regression equations" that typically estimate discharge for the 2-, 5-,

10-, 25-, 50- and 100-year flood events. These empirical relationships are often developed for each physiographic region and stratified by rural and urban basins. The results are published in reports, often by state, that can be obtained from the USGS website (*water.usgs.gov/software/NFF*). Since the return interval for the bankfull discharge is less than the 2-year return interval, regional regression equations from the 1-to 2-year range are needed for stream restoration applications. The USGS in West Virginia has prepared regional regression equations from the 1.0- to 3.0-year range. In addition, they created equations in 0.1-year increments, from the 1.0- to 2-year return interval, e.g., 1.1, 1.2, etc. (Wiley et al., 2002). Ideally, more curves for these lower return intervals will be developed for other regions.

Design Standard

The precipitation/runoff relationship is an important variable in determining channel size and is a vital part of the design process. It was mentioned that the discharge produced by the watershed is often an independent variable in the natural channel design, with the exception of watershed scale projects that might reduce runoff through stormwater BMPs. Therefore, there isn't a performance standard associated with this parameter. A natural channel should carry the appropriate amount of water to maintain dynamic equilibrium and appropriate streambed formations. However, channels that are designed to carry larger storm events, such as the 100-year event, would not function as a natural channel. This type of performance can be assessed below in the Hydraulic Chapter under Floodplain Connectivity.

6.3 » PARAMETER: FLOOD FREQUENCY

Description

Flooding is the periodic, natural occurrence of high flows that exceed the depth of the channel. Flood frequency defines the magnitude and frequency of a given flood and is often analyzed as part of the precipitation/runoff analysis described above. However, these parameters are sometimes assessed for different reasons because "flooding" is defined differently by different disciplines. For example, the geomorphologist defines flooding as the flow that leaves the channel and spreads onto a floodplain that was built by a meandering river, sometimes called a geomorphic floodplain. A traditional water resources engineer might define flooding as the flow that would impact personal property, such as a home. In both cases, flood frequency can be used to predict the probability that a flow will reach a certain elevation (active floodplain or house) within a given timeframe. The geomorphologist typically associates the flood frequency of the active floodplain as the discharge with a 1.5-year return interval (on average). The water resources engineer typically delineates floodplains by the elevation of the 100-year return interval discharge. These two return intervals can also be expressed as an exceedence probability, which is simply the reciprocal of the return interval. Therefore, in the case of the 1.5- and 100-year return intervals, the exceedence probabilities are 67% and 1%, respectively.

While the smaller floods are important for channel formation and maintenance, large

floods are important geomorphic agents as well. They are important in developed areas because large floods can damage homes, roads and other structures. For stream restoration projects, it is typically most important to know the flood frequency of the bankfull discharge and the 100-year flood event. It is important to know the frequency of bankfull to help ensure that the channel is not carrying more water than is necessary to maintain dynamic equilibrium. In addition, many stream restoration projects are located in Federal Emergency Management Agency (FEMA) regulated floodplains. In these cases, a no-rise certification is required to show that the project is not increasing the 100-year flood elevation. If the project is designed to increase flooding, and it is acceptable to the landowner, a Letter of Map Revision will be required. More information about working in FEMA regulated floodplains can be found at: *www.msc.fema.gov*.

Measurement Method

1. Bulletin 17b

The standard for estimating flood frequency in the United States is published by USGS (1981) in Bulletin 17b (*water.usgs.gov/osw/bulletin17b/bulletin_17B.html*). The most common method for estimating flood frequency is the Log-Pearson Type III distribution, which is also described in the bulletin. This method uses the annual peak discharge over many years to calculate the probability of occurrence. The technique is complex and should be performed by experienced hydrologists. However, for most regions of the United States, flood frequency analysis has already been completed and can be downloaded by state from the USGS website.

Some areas of the country are starting to use partial duration analysis to determine the flood frequency of bankfull. This technique is often preferred over Log Pearson because it uses more data points per year than the single peak discharge used by Log Pearson. Partial duration analysis sets a discharge of interest and then includes all the discharges that exceed that value. Therefore, gauge stations with continuous data are required for this analysis.

Design Standard

Flood frequency analysis is often performed in conjunction with the precipitation/runoff analysis. For flood control projects, a flood discharge with a certain return interval, e.g., the 100-year or 1% probability storm event, is used as the design discharge. A channel size is then designed to carry the 100-year discharge. In natural channel design, however, the channel is sized to carry the bankfull discharge. Methods to determine the bankfull discharge are described above, but the return interval for bankfull is only used as a guide. As mentioned before, the average is 1.5 years and the range is from 1 to 2 years. This range can be used as a guide to develop performance standards, along with other parameters like floodplain connectivity. Therefore, the specific performance ranges for Functioning, Functioning-at-Risk and Not Functioning are described in the Hydraulics Chapter.

6.4 » PARAMETER: FLOW DURATION

Description

Flow duration is the percentage of time that a discharge is above or below a given value. It is often expressed as a flow duration curve that plots discharge on the y-axis and probability (percent of time) on the x-axis. In some parts of the country, especially the West, improving flow duration is an important stream restoration goal. It is also an important functional goal for stream restoration after landscape alterations, such as surface mining through streams.

When flows are critical to maintain a particular species of fish, mussel or macroinvertebrate, flow duration curves can allow one to denote the percent of time a river will exceed that critical value. Alternatively, flow duration curves can be used to determine the discharge that occurs a certain percentage of time. Flow duration can also be generalized to focus on the simple presence versus absence of flow over time — in other words, perennial, intermittent or ephemeral streams. For most projects perennial, intermittent or ephemeral flow will be an independent variable. For more specific information on the importance of flow duration, see Dahm et al. (2003), Humphries and Baldwin (2003), and Stromberg et al. (2007).

Measurement Method

1. Flow Duration Curve

Long-term records from gauge stations are needed in order to develop flow duration curves. From the historical records, the data are ranked in order from highest to lowest. The probability that a discharge can be equaled or exceeded can be calculated as follows:

$P = 100\ M / (n+1)$, where

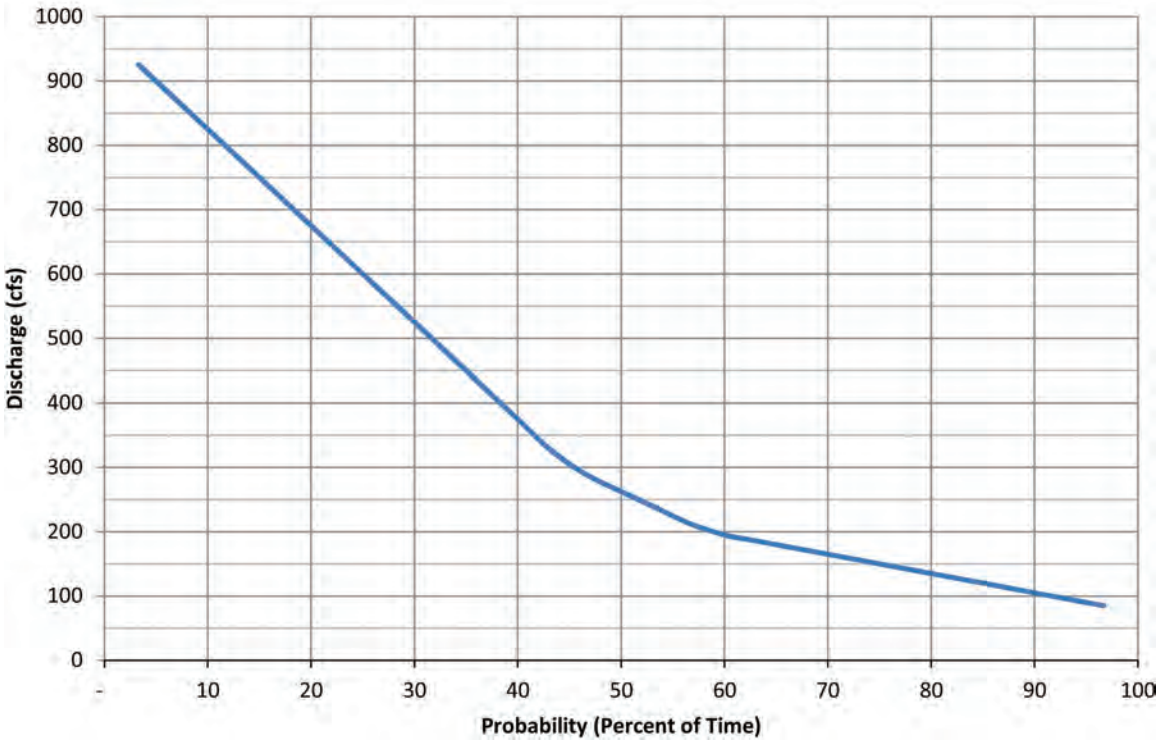
P = the probability that a flow will be equaled or exceeded (% of time)

M = the ranked position of the peak discharge values (dimensionless)

n = the number of peak discharge values in the record (dimensionless).

The discharge and corresponding probability are then plotted on probability paper. A step-by-step example of how to create a flow duration curve is provided by Watson and Burnett (1993). An example of a flow duration curve is shown in Figure 6.3. If gauge data are not available, computer models like HEC-HMS can be used to predict a flow duration curve using information from the closest gauge.

FIGURE 6.3 FLOW DURATION CURVE EXAMPLE



Source: Adapted from original graph by Michael Baker Corporation

Flow duration can also be directly measured at the project site. For perennial streams and large intermittent and ephemeral channels, a gauge station can be established with an automatic stage recorder. These recorders will measure stage and time. A stage/discharge relationship would have to be developed in order to plot discharge. Dingman (2008) provides instructions on how to establish a stream gauge for short-term studies. For this reason, the level of effort can range from moderate (for modeling) to intensive (for measuring flow over time). The level of complexity can also vary; however, it is often more complex to model flow duration than to measure flow duration. A measured flow duration curve is a direct measure of the flow duration function-based parameter; whereas, a modeled curve is an indirect measure (Appendix Ac).

2. Crest Gauge

A simpler and more common approach is to establish a crest gauge at the project site. A crest gauge records the highest elevation of the peak flow, usually without electronic instrumentation. A crest gauge does not provide information about the duration of the peak flow; however, it will provide information about flow occurring between site visits. Crest gauges are most often used in stream restoration projects to determine if bankfull

events occurred between monitoring surveys. Harrelson et al. (1994) provides a simple description of how to build a crest gauge.

3. Monitoring Devices

A monitoring device developed by Flowline Products is being used on small ephemeral and intermittent drainages in the Coastal Plain of North Carolina to document the duration and relative magnitude of flow events. The device is based on the principles of a variable area flow measurement, and consists of a vertical baffle mounted on an axis inside a protective housing. Flow passing through the housing causes the baffle to tilt on its axis, and the degree of tilt is recorded by the internal electronics and logging device. The device is capable of recording flows as low as 0.5 gal/min (Tweedy, 2010, personal communication). Other monitoring devices are also available and can be used for a variety of conditions (Blasch et al., 2002; Adams et al., 2004; Goulsbra et al., 2009; Fritz et al., 2006).

4. Rapid Indicators

Measuring general flow duration rapidly in the field on a non-gauged stream, whether the stream is perennial, intermittent or ephemeral, can be done using indicators of flow duration. Specific indicator-based methods have been developed by the North Carolina Department of the Environment and Natural Resources; EPA Region 10, Oregon Department of State Lands and the Portland Corps District; New Mexico Environment Department; and others that are currently under consideration. Links to select manuals are provided below.

North Carolina Department of Environment and Natural Resources, Division of Water Quality. Raleigh, NC. V.4. *portal.ncdenr.org/web/wq/swp/ws/401/waterresources/streamdeterminations*)

Oregon Streamflow Duration Assessment Method Interim Version, Public Notice release date, 6 March 2009. *www.oregonstatelands.us/DSL/PERMITS/docs/osdam_march_2009.pdf?ga=t*

New Mexico Environment Department/Surface of Water Quality Bureau (NMED/SWQB) Hydrology Protocol for the Determination of Ephemeral, Intermittent, and Perennial Waters — DRAFT. Released August 2009. *ftp.nmenv.state.nm.us/www/swqb/MAS/Hydrology/NMHydroProtocol-PublicCommentDraft08-2009.pdf*

Performance Standards

Performance standards for flow duration will be unique to every stream. Therefore, functional categories are not assigned to this parameter. However, local practitioners can develop performance standards based on flow needs of fish, mussels or other needs. For stream restoration projects on highly manipulated sites, such as surface mining, restoring the general flow duration may be used as a performance standard to help ensure that the suite of functions lost is being replaced.

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Chapter 7
Hydraulics

Hydraulic functions transport water in the channel, on the floodplain and through sediments. Fischenich (2006) describes these functions as surface water storage processes, maintenance of surface and subsurface connections and processes, and the general hydrodynamic balance, which describes the flow conditions in the channel and on the floodplain throughout the year. Here, three broad-level parameters are used to describe the Hydraulic functions. These include floodplain connectivity, flow dynamics and groundwater/surface water exchange. A variety of measurement methods are provided for each parameter, and performance standards are provided when available, as shown in Table 7.1. Appendix Ac includes a list of all the Hydraulic measurement methods along with information about the method's type, level of effort, level of complexity, and whether it is a direct or indirect measure of the function-based parameter. The criteria used to make these determinations are provided in Chapter 4.

Three different methods are provided for measuring floodplain connectivity and respective performance standards. Performance standards are not provided for shear stress and stream power; however, these are important measures of flow dynamics that are used in the sediment transport competency and capacity discussion in Geomorphology (Level 3). Performance standards are also not provided for groundwater/surface water exchange. This parameter and methods for measuring it are included because of its importance to Physicochemical (Level 4) functions and Biology (Level 5) functions. A discussion is provided under Design Standards that illustrates how this parameter can be used in a stream restoration design. Ultimately, as more reference research and project surveys are completed, a better understanding of this parameter will emerge that may allow for development of performance standards.

7.1 » PARAMETER: FLOODPLAIN CONNECTIVITY

Description

Floodplain connectivity describes how often streamflows access the adjacent floodplain. Fischenich (2006) included floodplain connectivity as part of the hydrodynamic character function, which was considered the most important of the 15 functions addressed. In high-functioning alluvial valleys, all flows greater than the bankfull discharge spread across a wide floodplain. In humid environments, streams that are well connected to the floodplain also have relatively high water tables, encouraging the development of riparian wetlands. In these systems, the channel is just deep enough to maintain sediment transport equilibrium and to create diverse bed forms and habitats.

Channelization is the primary impact that has directly disconnected streams from

their adjacent floodplain. Schoof (1980) defines channelization as the widening, deepening and straightening of channels to increase their capacity for transporting flood flows and to decrease flooding on adjacent land. Schoof (1980) estimates that over 200,000 miles of stream channels in the US have been modified over the past 150 years. He also estimates that the primary effects of channelization have included draining of wetlands; reduction in stream length through straightening; clearing of floodplain hardwoods; lowering of groundwater levels; reduction of groundwater recharge from stream flow; increase in erosion and sedimentation; and increase of downstream flooding. In a more recent study, Kroes and Hupp (2010) evaluated the effect of channelization on floodplain deposition and subsidence in a Maryland watershed. They found that the sediment storage function of the river had been dramatically altered by channelization. Finally, channelization has been found to reduce the size, number and species diversity in streams (Schoof, 1980). Indirect impacts, like urbanization and increases to impervious cover, also contribute to channel enlargement and incision through increased runoff. The extra runoff often causes an increase in stream power, which leads to headcuts and incision. The combination of increased runoff and channelization can lead to rapid destabilization and adjustment of stream channels.

TABLE 7.1 HYDRAULIC PARAMETERS, MEASUREMENT METHODS AND AVAILABILITY OF PERFORMANCE STANDARDS

PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD
Floodplain Connectivity	1. Bank Height Ratio 2. Entrenchment Ratio 3. Stage Versus Discharge	Yes Yes Yes
Flow Dynamics	1. Stream Velocity 2. Shear Stress 3. Stream Power	Yes No No
Groundwater/Surface Water Exchange	1. Piezometers 2. Tracers 3. Seepage Meters	No No No

Therefore, reconnecting streams to the floodplain is a major goal when working in watersheds that have channelized/incised streams. Floodplain connectivity is a driving force for many of the geomorphic and ecologic functions (Wohl, 2004; Shields et al., 2010). It is also a parameter that can easily be assessed, modified as part of a design and evaluated through monitoring, making it an excellent parameter for including a performance standard.

Floodplain Connectivity by Stream Type

Floodplains are associated with streams in alluvial valleys. Alluvial valleys are typi-

cally many times wider than the stream channel with longitudinal valley slopes less than 2%. Floodplain material is mostly comprised of alluvium (sand, silt and clay) that is deposited from frequent overbank flooding and long-term channel migration (Bridge, 2003). Rosgen C, E and DA stream types are common in these alluvial valleys, with the C and E stream types common as natural channel design targets. The DA stream type is associated with wetland/swamp systems in coastal plain settings where flows are often braided and diffuse. Restoring DA stream types in coastal plain settings has become a more common restoration approach in recent years (USACE Wilmington District and NCDENR, 2005).

Therefore, reconnecting streams to the floodplain is a major goal when working in watersheds that have channelized/incised streams. Floodplain connectivity is a driving force for many of the geomorphic and ecologic functions (Wohl, 2004; Shields et al., 2010). It is also a parameter that can easily be assessed, modified as part of a design and evaluated through monitoring, making it an excellent parameter for including a performance standard.

Colluvial valleys do not have wide, well-developed floodplains and are naturally confined between hillslopes. Colluvial valleys have bowl-shaped cross sections and typically have valley slopes greater than 2%. Colluvium is angular and poorly sorted material that eroded from adjacent hill slopes and then deposited on the valley floor or even the channel (Easterbrook, 1999; Leopold et al., 1992). The Rosgen B stream type is often found in colluvial valleys. However, colluvial/confined valleys do exist with valley slopes that are less than 2%. The Rosgen Bc stream type is found in these low-gradient, but confined valleys. Floodplain connectivity, therefore, is limited to a bankfull bench or flood-prone area because the true definition of a floodplain is not relevant for these settings. These features are much narrower than a fully developed floodplain; however, they do dissipate flood energy and provide a flat depositional feature, which allows riparian vegetation to become established.

Rosgen stream types A, G and F do not have floodplains. The A stream type is associated with v-shaped valleys, which typically have longitudinal slopes greater than 4%. They are rarely associated with stream restoration projects; however, they are often impacted by surface mining activities in the Appalachian Mountains. The A stream types do not have a floodplain, but can have small bankfull benches like the B stream type (Rosgen, 1996). When the drainage area for these stream types becomes very small and the channel is ephemeral, there may not be a bankfull discharge that represents channel formation.

The F and G stream types can exist in natural, stable environments like gorges. However, they are most often associated with unstable environments due to channelization and urbanization (Rosgen, 1996). These stream types are very common targets for

stream restoration because they are disconnected from the floodplain and have often evolved from C or E stream types through degradation and lateral erosion processes. Therefore, the functional lift of reconnecting the stream to a floodplain is greatest in these scenarios.

D stream types are associated with glacial outwash plains, alluvial fans and other environments where sediment supply exceeds sediment transport capacity (Rosgen, 1996). D stream types in alluvial valleys are sometimes caused by land use changes and can be restored to single-thread channels, often to a C stream type. This is more common in the arid West. However, in many other cases, D stream types are natural (glacial outwash plains and alluvial fans) and should not be altered. Regardless, D stream types are not incised and have access to a very active floodplain.

The descriptions above offer a general discussion of the three most common valley types and their associated stream types. There are many subtle differences and changes to valley morphology based on climate and geology, and a good description of the various valley types can be found in Bridge (2003), Easterbrook (1999) and Rosgen (1996).

Measurement Method

There are simple to moderately complex methods for measuring floodplain connectivity. Simple methods include the bank height ratio and entrenchment ratio, both of which require that the bankfull stage be determined. A more complex method is the use of HEC-RAS, which can show the stage versus discharge relationship for a wide range of return intervals, e.g., from base flow through the 100-year flood event. A brief description of each method is given below.

1. Bank Height Ratio

The bank height ratio (BHR) is a direct measure of channel incision. This ratio is calculated as follows:

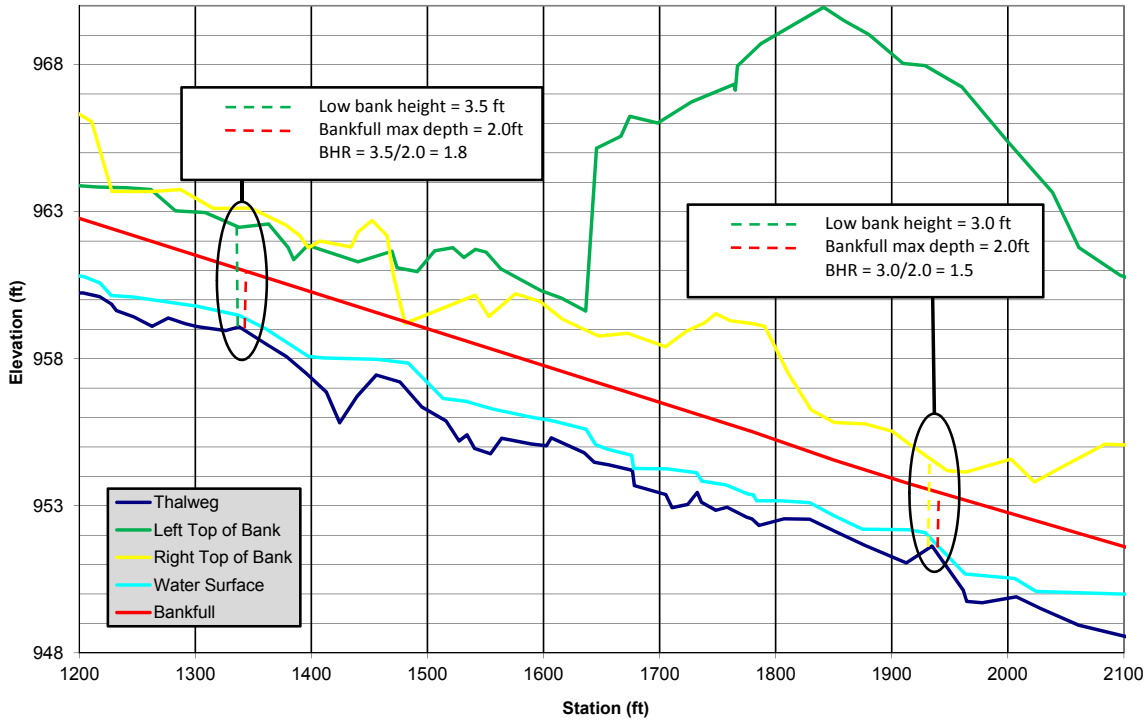
BHR = Dtob /Dbf, where

Dtob = the depth from the top of the lowest bank to the thalweg

Dbf = the depth from the bankfull elevation to the thalweg.

A BHR of 1.0 means that all flows greater than bankfull are spreading onto a floodplain (C and E stream types) or bankfull bench/floodprone area (A and B stream types). A BHR of 2.0 means that it takes a stage of two times the bankfull stage to access the floodplain and the stream is highly incised. The bank height ratio can be measured from a cross section or longitudinal profile if the profile includes the stream bed and both banks (left and right) or the lowest profile of the two banks. Generally, it is preferable to measure BHR from riffles along the profile because riffles represent the natural grade control feature for a river. In this application, the BHR is not measured in the pool. An example of measuring the BHR from a longitudinal profile and cross section is shown in Figures 7.1 and 7.2, respectively.

FIGURE 7.1 MEASUREMENT OF BANK HEIGHT RATIO FROM A LONGITUDINAL PROFILE



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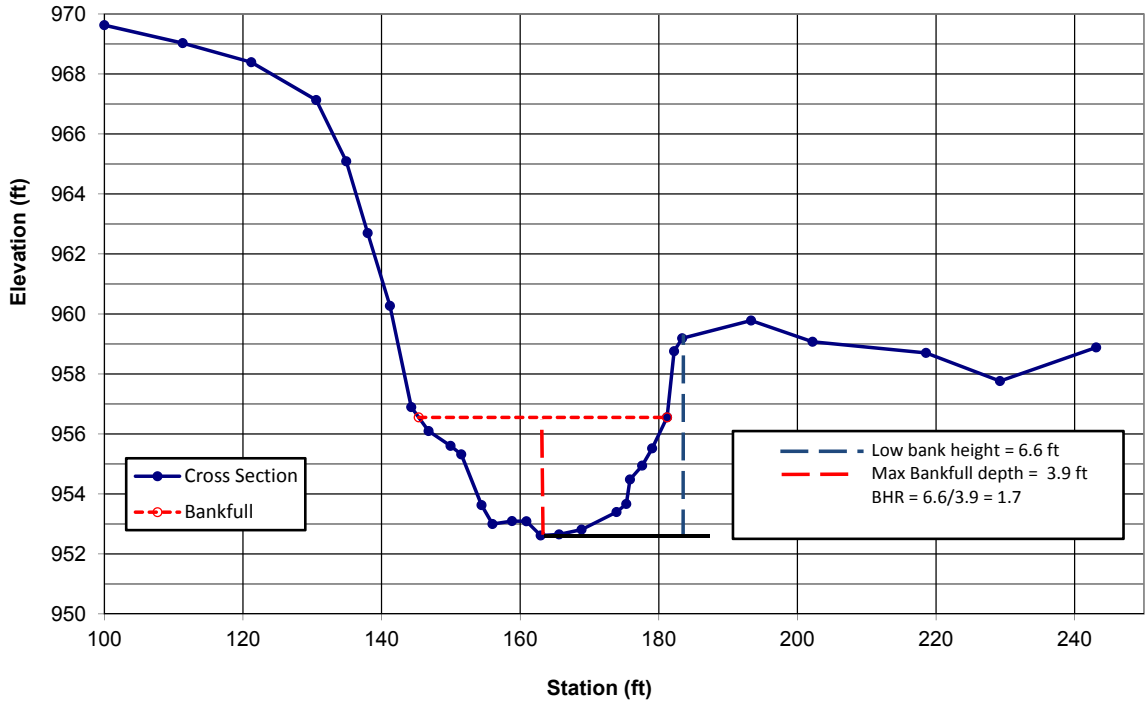
It should be noted that the BHR can be measured differently for other purposes. For example, the Bank Erosion Hazard Index, developed by Rosgen (2001), calculates the BHR by measuring the depth near the study bank, rather than the thalweg, and may include measurements from a pool feature.

Measuring the bank height ratio from a profile or cross section is considered a moderate level of effort and moderate level of complexity (see Appendix Ac) because of the time and skill required to make the survey measurements. A rapid and simpler approach is available for assessing the bank height ratio, which is often preferred by regulatory agencies or others who quickly want to determine if a stream (pre- or post-restoration) is incised. A rapid approach is best used if a regional curve is available. If it is, the riffle mean depth from the curve can be used as an estimate for the bankfull max depth. Next, measurements are made along the stream reach from the top of the bank to the bottom edge of the channel, along riffle sections. This measurement is typically made with a pocket rod or standard survey rod. The measurement can quickly be divided by the bankfull depth to get the bank height ratio. If a regional curve is not available, at least one measurement from a bankfull indicator is required, measuring from the indicator to the edge of the water surface.

FIGURE 7.2 MEASUREMENT OF BANK HEIGHT RATIO FROM A CROSS SECTION



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2. Entrenchment Ratio

The entrenchment ratio (ER) is a measure of the floodprone area width in relation to the bankfull width (Rosgen 1994). The floodprone area width is measured at a stage of 2 times the bankfull max depth. Therefore, it is possible to have a stream that is incised, e.g., BHR of 1.8, but not entrenched if the floodplain is wide. The ER is calculated in a riffle cross section as follows:

ER = FW / BW, where

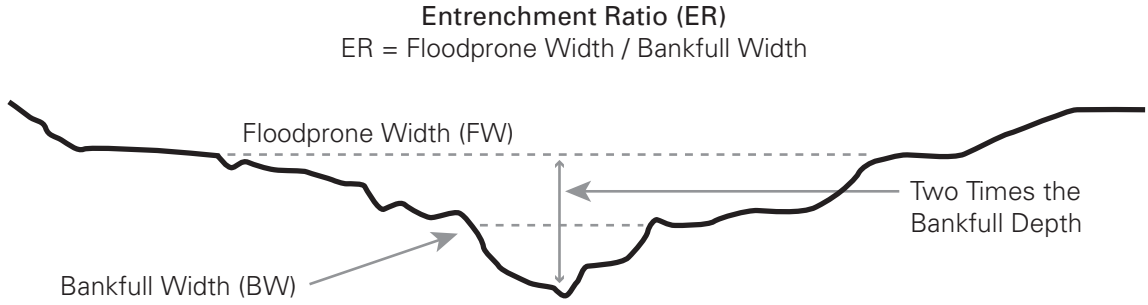
FW = floodprone width, measured at a stage of 2 times the bankfull max depth

BW = bankfull riffle width.

The BHR and ER work well together to quantify floodplain connectivity. For all stream types, a BHR of 1.0 indicates that the stream is not incised and has access to a floodplain or floodprone area. However, the ER will naturally vary by stream type. Streams in v-shaped valleys (A stream types) and colluvial valleys (B stream types) will have lower entrenchment ratios than streams in alluvial valleys (C, E and DA stream types). Therefore a C or E stream type with a bank height ratio of 1.0 and an entrenchment ratio of 10 is not incised and has a wide floodplain that will minimize flood depths, thereby encouraging flood storage, floodplain accretion and other floodplain processes. C or E stream types that have a BHR of 1.0 and an ER of 2.5 are also not incised, but are

more entrenched than the previous example, meaning that flood flows do not have as large a floodplain to dissipate energy and provide wetlands.

FIGURE 7.3 MEASUREMENT OF ENTRENCHMENT RATIO



3. Stage Versus Discharge

HEC-RAS (Hydrologic Engineering Center, River Analysis System) is a one-dimensional stream flow model developed by the USACE and is the most common analytical tool for completing hydraulic analysis associated with stream assessment and restoration projects. Regarding floodplain connectivity, HEC-RAS can be used to predict the stage of various flood return intervals, e.g., bankfull, 2-year, 10-year, etc. A separate analysis of Hydrology is used to determine the discharge for bankfull and the various return interval floods (See Hydrology Chapter). Therefore, HEC-RAS can be used to show if the channel carries the bankfull discharge, the 100-year discharge, or something in between. Obviously, if the channel carries the 100-year discharge, it is very incised; if it carries the bankfull discharge, it is not incised. An example of using HEC-RAS to determine how much water the channel will carry is shown in Figure 7.4. In this example, the channel will carry the 5-year discharge. The bankfull discharge is shown as a dashed line and is between the 1.1- and 1.5-year discharge. The bankfull stage came from the Geomorphic assessment and was entered into HEC-RAS.

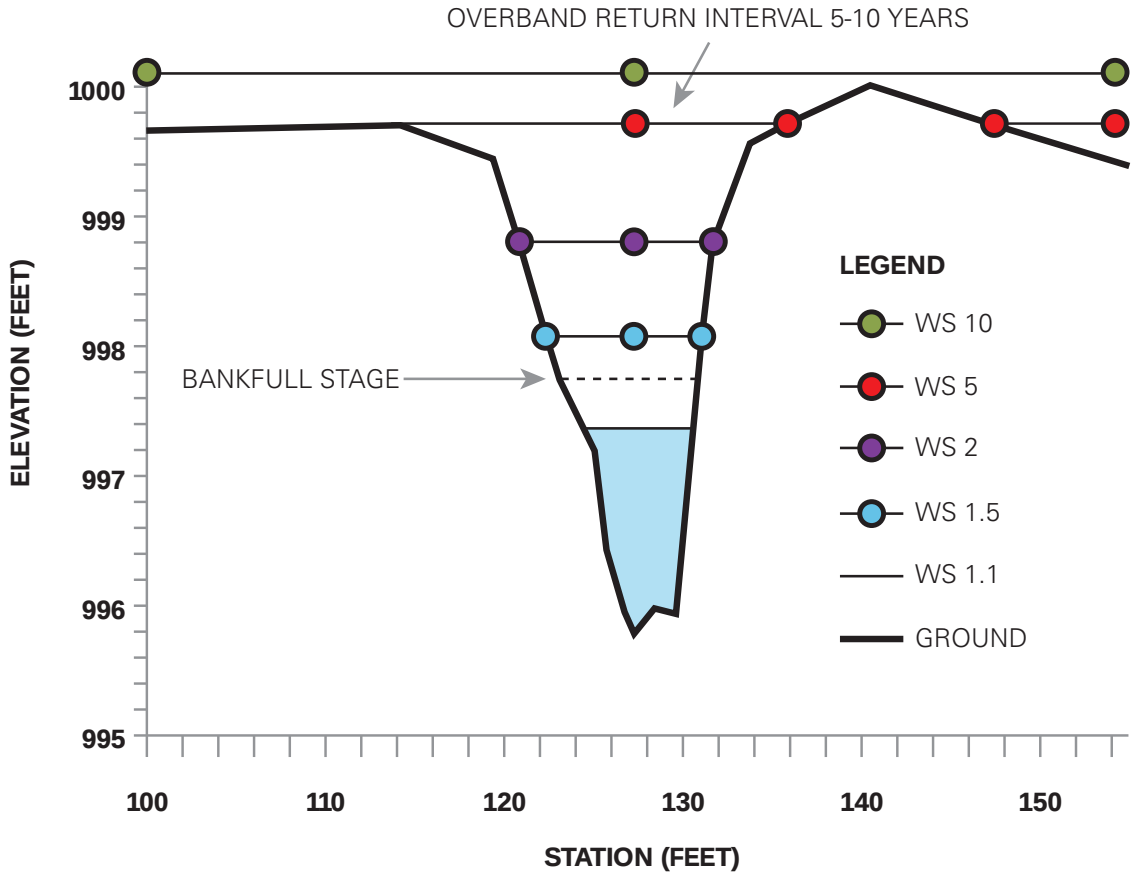
Dunne and Leopold (1978) created a dimensionless rating curve for gauge stations in the Eastern US by plotting the measured flood depth divided by the bankfull depth (d/dbkf), versus the measured flood discharge divided by the bankfull discharge (Q/Qbkf). This relationship is shown below in Figure 7.5 and includes data from streams with alluvial valleys. Relationships like this can be used to determine if stream restoration projects have channels that are connected to an active floodplain. It does, however, require an estimate of the bankfull discharge and knowledge that the curve represents the hydro-physiographic region of the project. If the bankfull discharge is unknown, then a return interval discharge of 1.5 can be used (as an estimate only) in the denominator. Rosgen (1996) created similar curves by stream type. The G stream type is shown on Figure 7.5 representing streams that are not connected to a floodplain. In the absence of

bank height ratios and entrenchment ratios, these two curves can be used to assess floodplain connectivity. Performance standards related to the use of these curves is provided in the section below.

Performance Standard

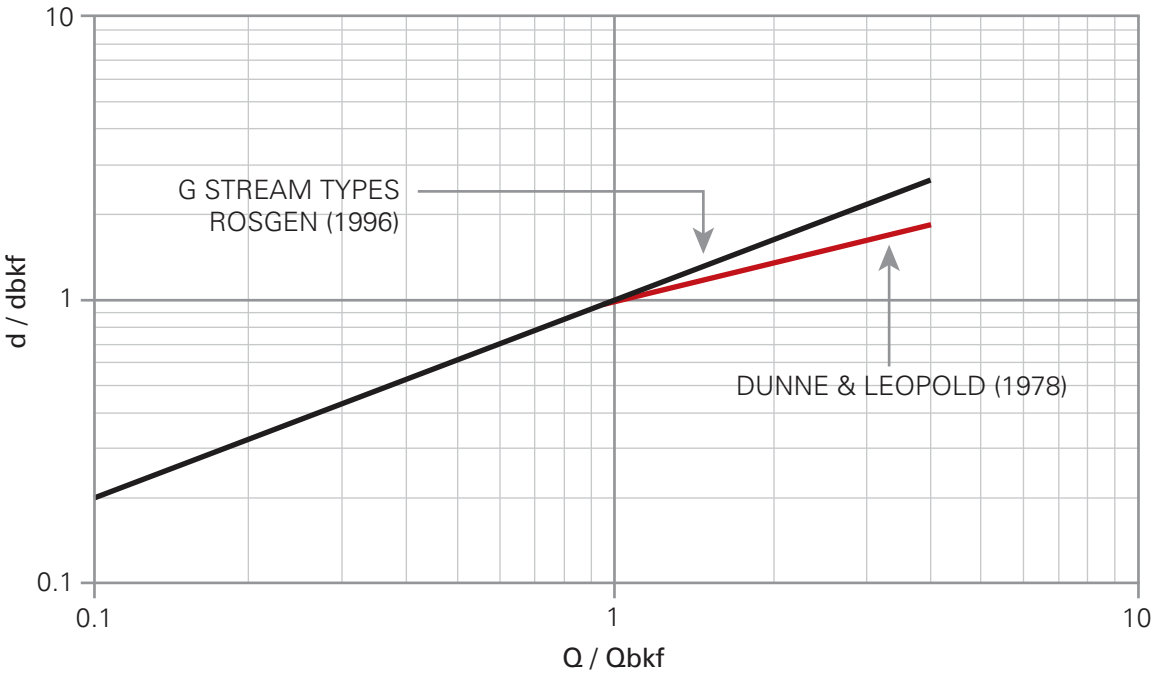
Performance standards for floodplain connectivity metrics are shown in Table 7.2. The BHR performance standards are adapted from Rosgen (2006), which include a graph showing the relationship between BHR and a qualitative stream stability rating using the following categories: stable, slightly incised, moderately incised and deeply incised. These values relate to channel stability; however, to assess floodplain connectivity the values were recategorized as Functioning, Functioning-at-Risk or Not Functioning.

FIGURE 7.4 HYDRAULIC ANALYSIS BY THE HEC-RAS STREAM FLOW MODEL



Source: Adapted from original graph by Michael Baker Corporation

FIGURE 7.5 DIMENSIONLESS RATING CURVE FOR GAUGE STATIONS IN THE EASTERN UNITED STATES



Souce: Adapted from Dunne and Leopold (1978), Leopold (1994), and Rosgen (1996)

TABLE 7.2 FLOODPLAIN CONNECTIVITY PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Bank Height Ratio (BHR)	1.0 to 1.2	1.3 to 1.5	> 1.5
Entrenchment Ratio (ER) for C and E Stream Types	> 2.2	2.0 to 2.2	< 2.0
Entrenchment Ratio (ER) for B and Bc Stream Types	> 1.4	1.2 to 1.4	< 1.2
Dimensionless rating curve*	Project site Q/Q_{bkf} plots on the curve	Project site Q/Q_{bkf} plots above the curve	Project site Q/Q_{bkf} of 2.0 plots above 1.6 for d/d_{bkf}

** See Figure 7.5 for dimensionless rating curve from Dunne and Leopold (1978).*

The entrenchment ratio performance standards are also based on Rosgen (2006). The Functioning category represents the minimum value for that stream type, e.g., a 2.2 for C and E stream types. The Functioning-at-Risk category represents the amount that the

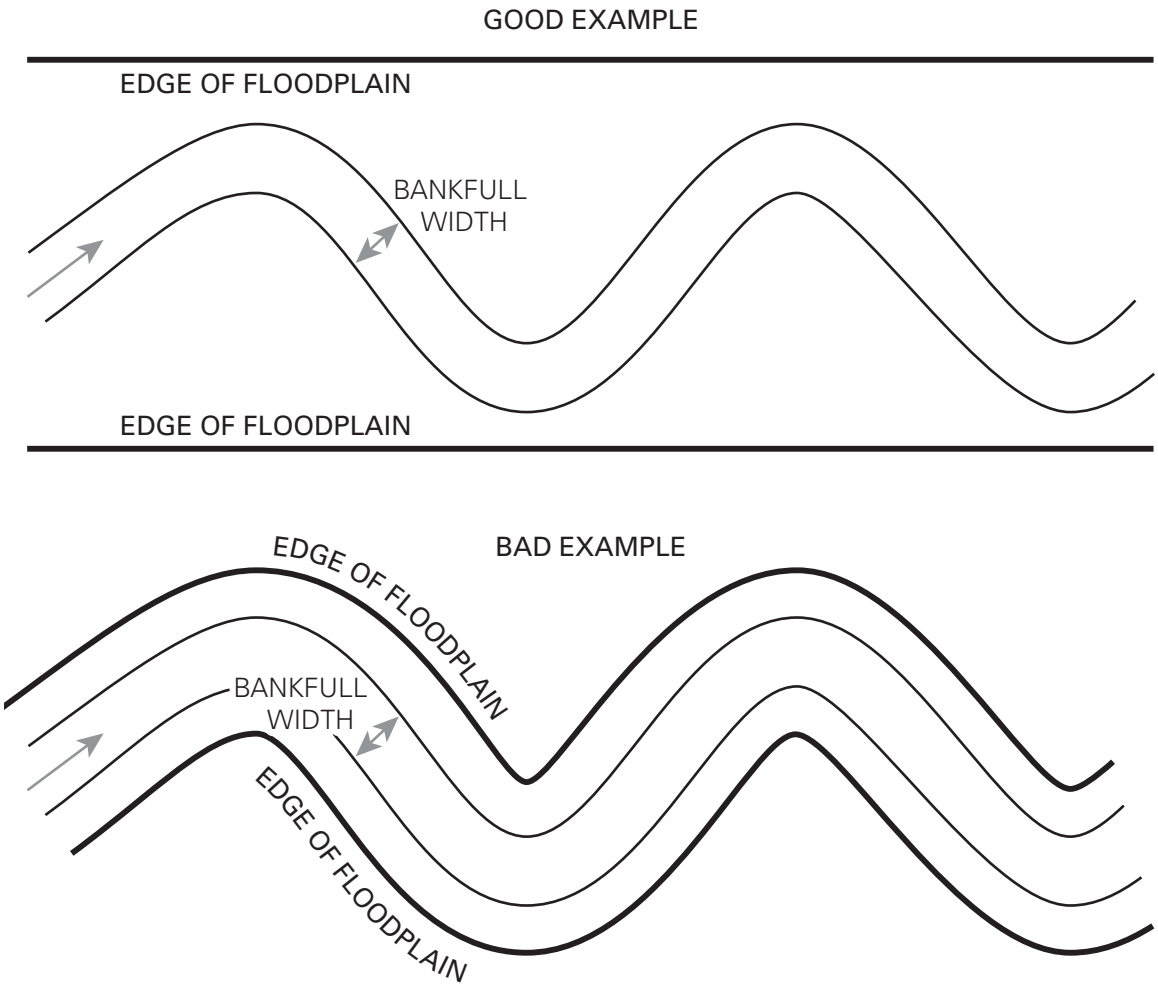
ratio can vary and remain in the same stream type. For example, a C and E stream can have an entrenchment ratio of 2.0 and still be a C or E stream type based on what Rosgen calls the "continuum of physical variables". However, a decreasing entrenchment ratio is a negative trend because it indicates that the valley is becoming more confined and floodplain processes are diminishing.

Between the BHR and ER, the BHR is the most important for achieving functional lift because it is a direct measure of incision and, therefore, floodplain connectivity. It does not, however, provide information about how far water can spread onto the floodplain. The ER is a nice complement to the BHR because it accounts for the width of the floodplain/valley once floodwaters leave the channel. The ER becomes more critical for restoration projects that include floodplain excavation. It would be extremely rare for this type of project to have an ER of 10, for example. Instead, minimum ER values will be used to lower construction cost and meet landowner constraints. These minimums should not exceed the values listed in 7.2. In addition, an excavated floodplain should be relatively straight with the fall line of the valley and should not simply follow the pattern of the channel using a constant floodplain width to achieve the targeted ER. An example is shown below in Figure 7.6.

It is more difficult to use discharge as a performance standard because the discharge rating curve varies by the shape of the channel (Leopold, 1994) and the degree of incision. However, rating curves from different gauge stations become quite similar when the values are converted to a dimensionless form (Leopold, 1994). If the d/d_{bkf} versus Q/Q_{bkf} plots on the curve, then the stream is connected to the floodplain. If data from the project site plot above the curve, it means that stage is increasing at a higher rate than the non-incised streams used to create the curve. This is likely caused by a deeper channel, and the additional discharge is not spreading onto an active floodplain as quickly. If the project site plots near the curve, it may still be functioning similar to reference reach streams, but it is Functioning-at-Risk. As the project site plots further from the curve, the risk of channel incision increases.

Rosgen (1996) shows a dimensionless discharge rating curve stratified by stream type. This relationship shows that the G stream type at a Q/Qbkf of 2.0 has a d/dbkf of 1.6. The breakpoint for Not Functioning floodplain connectivity was therefore set at a d/dbkf of 1.6 for a Q ratio of 2.0, indicating a potential stream type change of a C or E to a G. Again, it would be easier to use the BHR and ER (and then stream type) to make this determination. However, a practitioner or reviewer could use gauge station data or published dimensionless discharge rating curves and the 1.5-year Q for bankfull to make an estimate of floodplain connectivity performance.

FIGURE 7.6 PROPER VERSUS IMPROPER FLOODPLAIN EXCAVATION DESIGN



7.2 » PARAMETER: FLOW DYNAMICS

Description

The water flowing in a stream channel moves downhill because of gravity and slope. The flow is then retarded by resistance applied by the stream bed and banks. The interaction of flowing water against the stream bed and banks creates dynamic flow conditions, termed here as flow dynamics. The morphology of natural channels is dependent on these flow dynamics. In intermittent and perennial streams, the discharge of groundwater and the overall surface/subsurface interaction creates additional functions, especially as they relate to and support Physicochemical and Biology functions.

There are many resources that describe flow dynamics in stream channels and floodplains. A few include Knighton (1998), Leopold et al. (1992), Fetter (1994) and Bridge

(2003). Flow dynamics have a major role in shaping the geometry of the channel. Therefore, restoration practitioners spend a considerable amount of time determining the proper flow dynamics for a restoration project. Assessing flow dynamics for establishing a baseline functional capacity or determining functional lift could include a wide range of measurements, ranging from surface/subsurface interactions, stage versus discharge relationships, velocity distributions, shear stress or tractive force, and stream power. Many of these metrics relate to the ability of the stream to "do work" by transporting sediment that is delivered to the channel from upstream sources, the stream bed, and streambanks. Sediment transport parameters (sediment transport capacity and competency) are discussed in the Geomorphology Chapter because they describe the Geomorphology function of transporting sediment.

Three important measures of flow dynamics are described here: stream velocity, shear stress and stream power. However, they are also applied in the Geomorphology Chapter for assessing channel stability and sediment transport. These Hydraulic parameters influence channel stability and sediment transport by providing the force and power needed for Geomorphic functions to occur, e.g., transport of organic material and sediment to create diverse bed forms and dynamic equilibrium.

Measurement Method

1. Stream Velocity

Stream velocity is a vector that has magnitude and direction. Knighton (1998) describes stream velocity as one of the most sensitive and variable properties of open-channel flow because it is dependent on a wide range of factors. Knighton (1998) describes the variability in four different ways, including distance from the stream bed, across the stream channel and downstream, as well as with time. It is the character of this variation that is important because of its influence on erosion, sediment transport and deposition. Stream velocity is also important at baseflow and flood flow conditions. Baseflow velocities that are too high prevent upstream fish movement, and high stream velocities during flood flows can cause stream bed and bank erosion if the flow force exceeds the resisting forces. Therefore, stream velocity is a widely used parameter to help assess channel stability, create stable channel designs and help support aquatic life.

The bankfull discharge and other flow magnitudes, e.g., the 100-year discharge, are determined as part of the Hydrology assessment discussed in Chapter 6. The average bankfull velocity is calculated as the bankfull discharge divided by the cross-sectional area, which can be measured during an assessment of the pre- or post-restoration condition. In other words, the bankfull discharge is a design element and will not change after restoration construction, but the cross-sectional area may change after construction, and this change can be positive or negative. Dunne and Leopold (1978) noted that the average bankfull velocity is approximately 4 feet/sec. Published regional curves, however, show bankfull velocities varying by stream type.

Velocity can also be measured in the field; this is easier to do during baseflow conditions than bankfull or flood conditions. Velocity may be measured in the field to assure that

baseflow velocities will allow for fish passage and to measure discharge (discharge = velocity x the cross-sectional area). This may be important for stream restoration projects that include culvert removal or other barriers to fish passage. Dingman (2008) and Harrelson et al. (1994) provide detailed methods on a variety of ways to measure stream velocity and discharge. A single velocity measurement as described above is considered a rapid level of effort with moderate complexity. However, taking velocity measurements for a range of flow conditions to develop a stage versus discharge rating curve requires multiple trips and more expertise and is considered an intensive level of effort and complex (Appendix Ac).

2. Shear Stress

Shear stress is a hydraulic force that is often used to predict sediment entrainment (sediment transport competency). Regarding the Pyramid, shear stress is a Hydraulic parameter (Level 2) that is used to quantify a Geomorphology function (Level 3), the entrainment and transport of bed material. Most stream beds consist of unconsolidated, cohesionless grains of sand and gravel. As flow increases, the force of the water over these particles increases. At some threshold, the particles begin to move. This initial movement is commonly defined as the critical shear stress (τ_{cr}) or mean boundary shear stress (τ_0) (Knighton, 1998). The mean boundary shear stress is calculated as:

$\tau_0 = \gamma Rs$, where

τ_0 = mean boundary shear stress in lbs/ft^2

γ = the specific weight of water (typically 62.4 lbs/ft^3)

R = hydraulic radius in ft

S = average channel slope in ft/ft.

There are many ways to calculate critical shear stress, and it is beyond the scope of this document to review them all here. However, Knighton (1998) and Wilcock et al. (2009) provides a description of the different ways to calculate critical shear stress, including a variety of graphs and equations that can be used to predict erosion, transport and deposition. Moreover, Rosgen (2006) provides an application of Andrews (1983 and 1984) equations for estimating the depth needed to maintain bed equilibrium during a bankfull event, and Wohl (2000) provides a description of entrainment processes in mountain rivers. Rosgen (2006) also created a relationship between particles transported at near bankfull flows versus the boundary shear stress. These procedures are described in more detail in the Geomorphology Chapter. Simple calculations of shear stress and its use with existing graphs is considered a moderate level of effort and moderate complexity because sufficient expertise is required to know when to use this method over other methods. The level of effort and complexity becomes intensive if shear stress curves are developed for a certain region, which requires bedload/material samples for a range of flow conditions (Appendix Ac).

3. Stream Power

Stream power is the ability of the stream to do work, where work is defined as the

conversion of potential energy (elevation change) to kinetic energy. Most of the kinetic energy is dissipated through friction from the bed and banks. However, a small portion is available to accomplish geomorphic work like the entrainment and transport of sediment (Bagnold, 1960). Phillips (1989) provides a cross-sectional stream power calculation, which is a physically based measure of sediment transport capacity. Thus, cross-sectional stream power can be written as:

$\Omega = \gamma QS$, where
Ω = stream power per unit length (Watts/meter)
γ = specific weight of water (1 g/m^3)
Q = discharge (m^3/s)
S = slope (m/m).

Mean stream power is related to competence and can be expressed as:

$\omega = \gamma RSV = \Omega/W = \tau V$ (Lecce, 1997)
ω = unit or mean stream power (W/m2)
R = hydraulic radius (m)
V = velocity (m/s)
W = width (m).

As a functional assessment tool for stream restoration projects, mean stream power is more useful than cross-sectional stream power. This is because mean stream power is normalized by channel width and can be compared across various streams of different size. Mean stream power is also the product of shear stress and velocity, which were each discussed above. In this regard, mean stream power is probably the most important parameter for describing flow dynamics. It is also a vital input parameter for sediment transport functions, as described in the Geomorphology Chapter. Similar to shear stress, if stream power is calculated and compared to literature values or existing graphs, the level of effort and complexity is moderate. However, if stream power curves (sediment transport rate versus stream power) are developed the level of effort and complexity is complex (Appendix Ac).

Nanson and Croke (1992) used stream power to classify floodplains into three classes: High-energy non-cohesive floodplains with bankfull ω greater than 300 W/m^2; medium-energy non-cohesive floodplains with bankfull ω between 10 and 300 W/m^2; and low-energy cohesive floodplains with bankfull ω below 10 W/m2. To further divide the classes into orders and suborders, nine discriminatory fluvial geomorphic factors are added. These factors include: (1) Valley Confinement, (2) Channel Cutting and Filling, (3) Braid-channel Accretion, (4) Lateral Point Bar Accretion, (5) Overbank Vertical-accretion, (6) Annabranching, (7) Scroll-bar Formation, (8) Counterpoint Accretion and (9) Organic Accumulation. The first six factors are used to divide the classes into orders, and the remaining three are used to divide the floodplains into suborders.

This is one example of how stream power can be used to assess the functional capacity of a potential steam restoration site. For example, there are many low energy floodplains

(ω less than 10 W/m^2) in the Piedmont and Coastal Plain regions of the eastern United States. But these floodplains lack many of the processes (factors) described above due to channelization, floodplain aggradation, deforestation and other direct and indirect disturbances. The Nanson and Croke (1992) floodplain classification provides restoration practitioners with a framework of processes that can be incorporated into restoration goals and then quantified during design and monitoring as functional lift. It also provides guidance to help ensure that the right type of stream channel is designed given the valley morphology.

Performance Standard

The measurement methods used to describe flow dynamics include stream velocity, shear stress and stream power. Shear stress and stream power are important input parameters for assessing sediment transport; however, there are other Geomorphology parameters and measurement methods that are better for developing performance standards. Stream velocity can be used as a flow dynamics performance standard, especially for evaluating the appropriate bankfull discharge (and flow area) and for fish passage. Bankfull velocity performance standards should be based on local regional curves stratified by stream type and the bankfull cross-sectional area measured in the field. Example performance standards by stream type are provided below in Table 7.3.

TABLE 7.3 FLOW DYNAMICS PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Bankfull Velocity for C and E stream types (ft/s)	3 to 6	6 to 7	> 7
Bankfull Velocity for Cc- (ft/s)	< 3	3 to 4	> 5
Bankfull Velocity for B stream types (ft/s)	4 to 6	6 to 7	> 7

Bankfull velocities typically should not exceed the range of velocities provided by gauge sites used to develop regional curves. For C and E stream types with slopes between 0.005 and 0.02 ft/ft, the average bankfull velocity is 4 ft/s (Dunne and Leopold, 1978). However, these values only provide general guidance and are not the best performance standard for stream restoration projects. Values outside of the range shown can indicate a potential problem (usually with stability), but the bank height ratio parameter and other parameters in the Geomorphology Chapter are probably better suited for stream restoration performance standards.

A wide range of velocity performance standards may be applied to projects with fish passage issues and should be based on the fish species and site conditions, e.g., open channel or culvert crossing. Stream assessments and restoration projects often deal with culvert crossings and associated fish passage issues. The FishXing (pronounced “fish crossing”)

software is a free tool that can be used to design culvert crossings for passage. The FishXing website includes references and supporting materials that could be used for assessing velocity thresholds for a variety of fish species (*www.stream.fs.fed.us/fishxing/index.html*).

7.3 » PARAMETER: GROUNDWATER AND SURFACE WATER EXCHANGE

Description

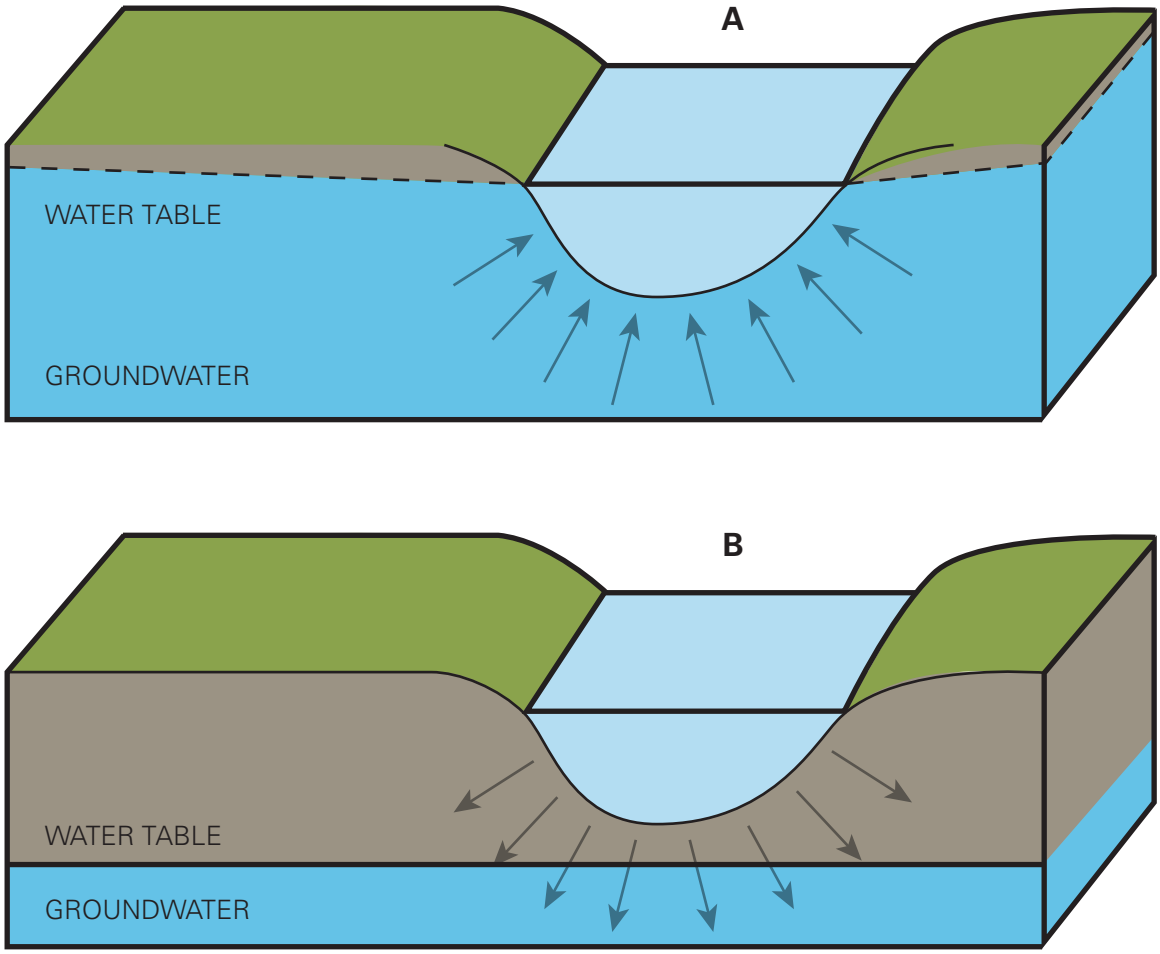
Surface water in streams interacts with groundwater in three basic ways: groundwater discharging into the stream through the stream bed (gaining stream), surface water flowing through the bed and into groundwater (losing stream), or a combination of both (Winter et al., 1998). This document describes the processes of groundwater and surface water exchange as it relates to stream assessments and restoration. An overview of groundwater hydrology is not provided; however, Fetter (1994) and Winter et al. (1998) are good sources for background information.

Figure 7.7 shows examples of a gaining and losing stream. Gaining streams are characterized as zones where the water table is higher than the stream bed. Losing streams are the opposite — areas where the water table is below the elevation of the stream bed. Losing streams can be connected to the water table by a continuous zone of saturation or by an unsaturated zone (Fetter, 1994; Winter et al., 1998).

In some environments, stream reaches are almost always gaining or losing. However, in other environments, surface and groundwater exchange is more variable, e.g., headwater streams. Flow direction toward or away from the stream bed can change quickly, based on flood events that cause recharge near the streambank, short-term flood peaks or transpiration of groundwater by riparian vegetation. A very common type of groundwater and surface water interaction during storms is called bank storage, which occurs during a rapid rise in stream stage (depth). As the stage increases, water flows from the channel into the unsaturated portion of the streambank. If the storm does not overtop the streambank and spread onto the floodplain, water stored in the banks (bank storage) typically returns to the channel within a few days or weeks. If the storm does overtop the bank and spread onto the adjacent floodplain, widespread recharge to the water table occurs as water seeps through the unsaturated zone (Winter et al., 1998). The timeframe for this water to return to the channel through groundwater flow may take weeks, months or even years. Depending on the frequency, magnitude and intensity of storms in a given region, the stream and adjacent aquifer may be continuously readjusted based on these processes (Winter et al., 1998). This is another reason that floodplain connectivity is so important. Streams that overtop the streambank frequently (all flows greater than bankfull) have more opportunity to store and slowly return flood flows to the channel. Figure 7.8 illustrates these two processes (bank storage and recharge) as stream stage increases.

The processes described above occur during storm events; however, many gaining streams have reaches that lose water to the aquifer during baseflow conditions. The direction and rate of seepage through the bed is often related to abrupt changes in bed slope and meander bends. This subsurface zone where stream water flows through short segments of the bed and banks is called the hyporheic zone. The hyporheic zone is a

FIGURE 7.7 GAINING AND LOSING STREAM EXAMPLES
(In the illustration, **A** shows gaining stream and **B** shows a losing stream with an unsaturated zone.)

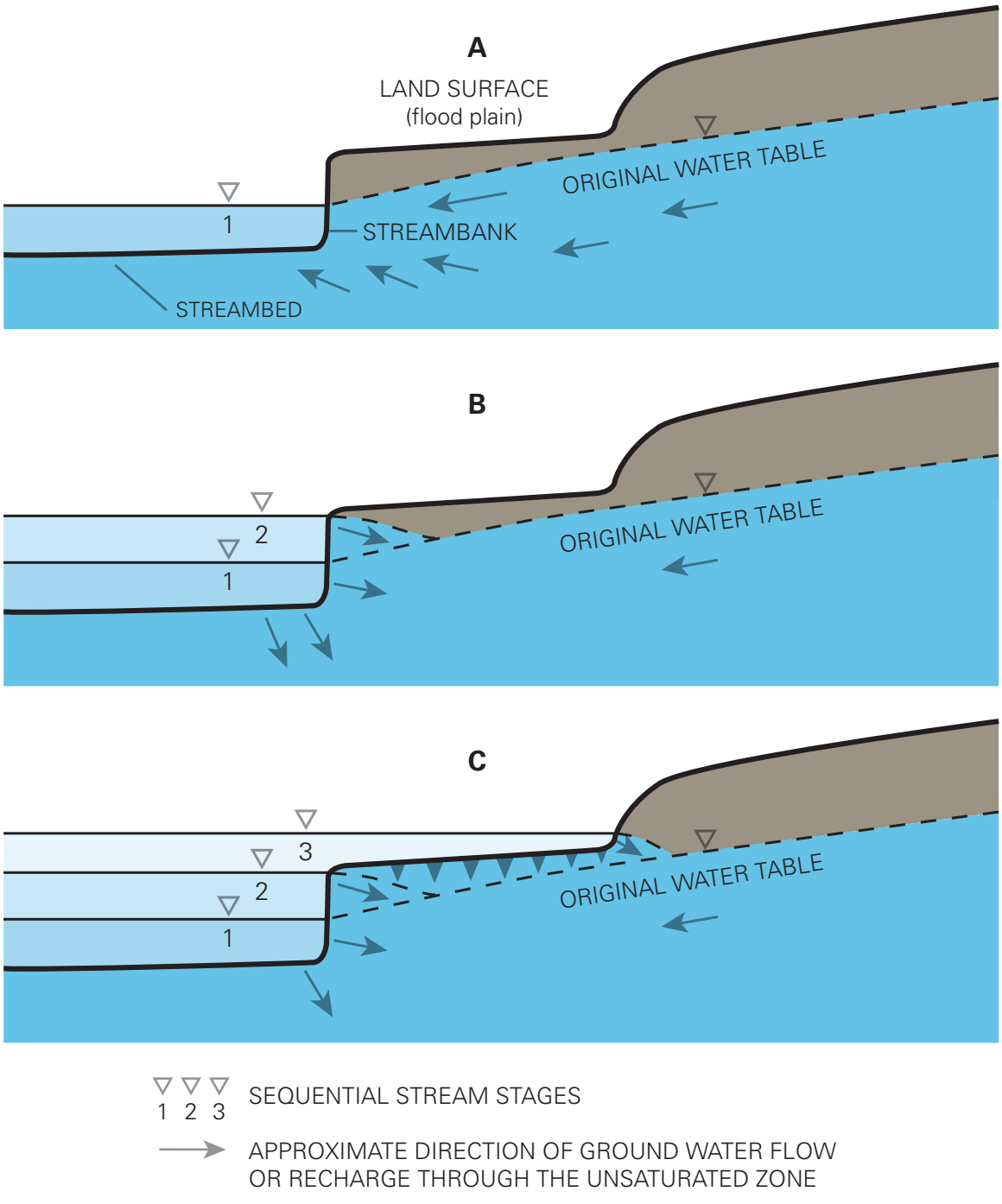


Source: Adapted from Winter et al. (1998)

subsurface area of porous sediments where surface water and groundwater mix, thereby creating an environment that is different from the stream or the groundwater (Figure 7.9).

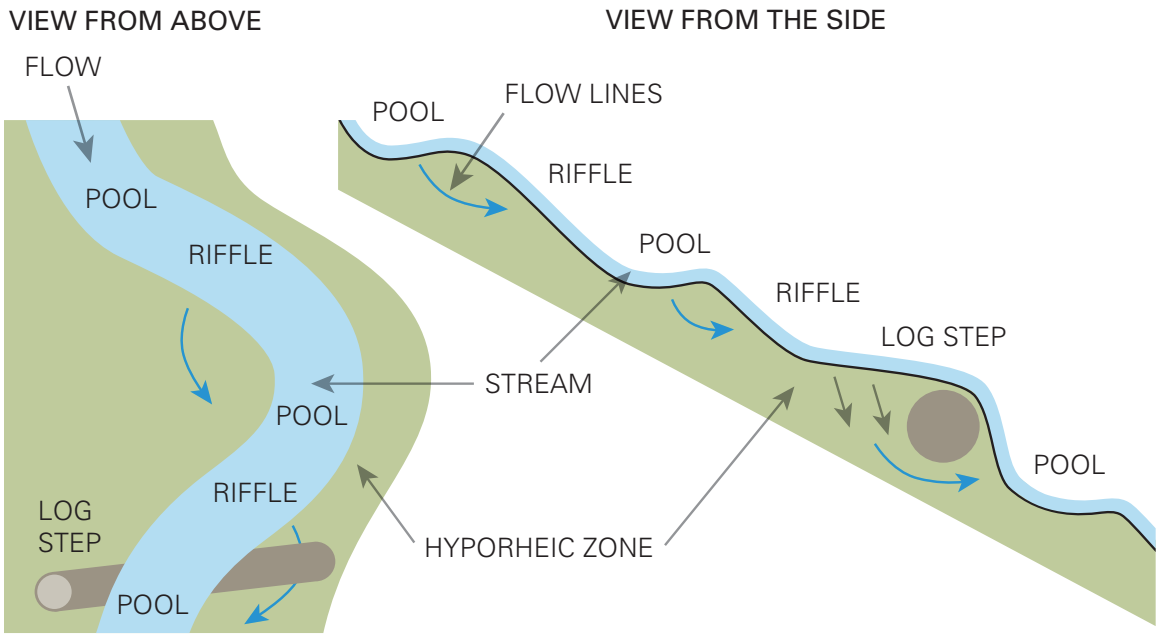
This unique environment can have a large effect on the types and numbers of organisms (Level 5 – Biology) found in the stream. The importance of the hyporheic zone is increasingly being recognized in stream and watershed assessments. As such, restoration approaches that help to encourage the development of a hyporheic zone are being identified and implemented. These restoration techniques include adding meanders, creating bed form diversity (steep riffles and flat pools), adding gravel layers beneath the ground surface of the floodplain and sometimes step structures like cross vanes. Since these design elements must be included as part of a sediment transport analysis and overall stable geometry, it is included in Pyramid Level 3 (Geomorphology) rather than Level 2 (Hydraulic).

FIGURE 7.8
(In the figure, A shows gaining stream, B shows bank storage and C shows groundwater recharge associated with overbank flooding.)



Source: Adapted from Winter et al. (1998)

FIGURE 7.9 HYPORHEIC ZONE



Source: Adapted from Waterencyclopedia.com

Measurement Method

There are many ways to measure groundwater/surface water interactions; however, mapping the extent of the hyporheic zone is challenging. Kalbus et al. (2006) provides a thorough review of methods to measure groundwater discharge into streams, stream recharge of groundwater and the interactions between the two. This document only highlights three methods described by Kalbus et al. (2006), piezometers, tracers and seepage meters, because they are the most likely methods to be used by stream professionals. However, refer to Kalbus et al. (2006) for a more thorough review of methods.

1. Piezometers

A piezometer is a small diameter well with a short screen or section of slotted pipe at the bottom end. It is used to measure hydraulic head (Fetter, 1994) and can usually be installed by hand. As such, it is probably the most common method for measuring the hyporheic zone. Piezometers are typically installed in the stream bed. This type of installation shows if the stream is gaining or losing by comparing the water elevation in the piezometer to the adjacent water elevation of the stream. If the water elevation in the piezometer is lower than the adjacent stream elevation, the stream is losing water to the hyporheic zone and vice versa. Transects of piezometers are installed throughout the stream reach to delineate gaining and losing areas. Additionally, water samples can be collected and the chemistry compared between the stream and the piezometer. This can be compared to results from piezometers installed in the floodplain to delineate the

lateral extent of the hyporheic zone, thus providing the depth and lateral extent.

2. Tracers

Tracers, or dye, can also be used to measure flow velocity in the hyporheic zone. A known concentration of the tracer is injected into the sediments below the stream bed. Water samples are then collected downstream to determine the concentration of the dye. Tracer studies are often used in combination with computer models to estimate the flow dynamics in the stream channel and hyporheic zone.

3. Seepage Meters

Bag-type or automatic seepage meters are also used to measure groundwater/surface water interaction. There have been problems with using the bag-type meter in stream systems, many of which have been overcome by the automatic seepage meter. The automatic meter records velocities using a heat pulse, an ultrasonic device or an electromagnetic flow meter.

Design Standard

The development of a hyporheic zone is critically important to support Physicochemical and Biological processes. There are stream restoration techniques that can be used to support the development of a hyporheic zone. Some examples include adding meanders, creating step-pools or steep gradient riffles, adding bed form complexity, and creating porous subsurface sediments. As stream restoration technologies advance, there is an increase in working with bed sediments, and even loosening sediments that have been previously compacted in the floodplain. However, developing performance standards for groundwater/surface water exchange is difficult. The science is emerging, but currently there are no quantitative standards to say that a hyporheic zone is Functioning, Functioning-at-Risk or Not Functioning. The best opportunity for developing a performance standard would be cases where a reference reach is upstream or downstream of the project. In this case, the design goal could be to have a hyporheic zone that is similar in depth and width to the reference reach, which could be assessed using piezometers. Another option is to use Level 5 parameters like macroinvertebrate communities, since many of these organisms rely on the hyporheic zone as a critical habitat.

Chapter 8
Geomorphology

Level 3 on the Pyramid represents the Geomorphology functions, which transport and store organic matter (wood) and sediment to create diverse bed forms and dynamic equilibrium. These functions include the interaction of flowing water with the stream bed, streambanks and upstream sediment supply. Therefore, the assessment and restoration of Geomorphology functions come after an assessment of the Hydrology (Level 1) and Hydraulic (Level 2) functions, as the Geomorphology functions integrate both of these preceding functions.

The interaction between flowing water and sediment transport creates bed forms like riffles, runs, pools and glides, which provide the critical habitats for macroinvertebrates, fish and other organisms. Streams that are in balance with Hydraulic and Geomorphology functions are said to be in *dynamic equilibrium*. This means that the stream bed is not aggrading nor degrading over time, and that lateral adjustments do not change the cross-sectional area, even though its position on the landscape may change (Hack, 1960).

Table 8.1 provides a list of the parameters included in Level 3, along with methods for measuring the parameters. An indication of whether or not a measurement method includes a performance standard is also provided. A description of each parameter, measurement method and performance standards are provided below. Appendix Ac includes a list of all the Geomorphology measurement methods along with information about the method's type, level of effort, level of complexity, and whether it is a direct or indirect measure of the function-based parameter. The criteria used to make these determinations are provided in Chapter 4.

8.1 » PARAMETER: SEDIMENT TRANSPORT COMPETENCY

Description

The ability of the stream to transport its sediment load can be determined through sediment transport competency and capacity analyses. Sediment transport competency is the ability of a stream to move particles of a given size and is a measurement of force, often expressed in units of pounds per square foot (lbs/ft^2). A description of shear stress is provided in the Hydraulics Chapter. Sediment transport competency is a common parameter used to determine the vertical stability of a gravel bed stream. Competency analysis is typically not completed in sand bed channels because all particle sizes are mobile.

Sediment transport competency is used more during the stream restoration design phase than for evaluating performance during the post-restoration monitoring phase. Other parameters, such as bed form diversity, are easier to measure during the monitor-

TABLE 8.1 GEOMORPHOLOGY PARAMETERS, MEASUREMENT METHODS AND AVAILABILITY OF PERFORMANCE STANDARDS (CONT.)

PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD
Channel Evolution	1. Simon Channel Evolution Model 2. Rosgen Stream Type Succession Scenarios	Yes Yes
Bank Migration/Lateral Stability	1. Meander Width Ratio 2. BEHI / NBS 3. Bank Pins 4. Bank Profiles 5. Cross-Sectional Surveys 6. Bank Stability and Toe Erosion Model	Yes Yes Yes Yes Yes Yes
Riparian Vegetation	1. Buffer Width 2. Buffer Density 3. Buffer Composition 4. Buffer Age 5. Buffer Growth 6. Canopy Density 7. Proper Functioning Condition (PFC) 8. NRCS Stream Visual Assessment Protocol 9. Rapid Bioassessment Protocol 10. Watershed Assessment of River Stability and Sediment Supply (WARSSS) 11. USFWS Stream Assessment Ranking Protocol (SAR)	Yes Yes Yes Yes Yes Yes Yes Yes Yes No Yes
Bed Form Diversity	1. Percent Riffle and Pool 2. Facet Slope 3. Pool-to-Pool Spacing 4. Depth Variability	Yes Yes Yes Yes
Bed Material Characterization	1. Bevenger and King (1995) 2. Riffle Stability Index (RSI)	Yes Yes
Sediment Transport Competency	1. Shear Stress Curve 2. Required Depth and Slope 3. Spreadsheets and Computer Models	No No No
Sediment Transport Capacity	1. Computer Models 2. FLOWSED and POWERSED 3. BAGS	No No No
Large Woody Debris Transport and Storage	1. Wohl et al. (2009) 2. Large Woody Debris Index	No Yes

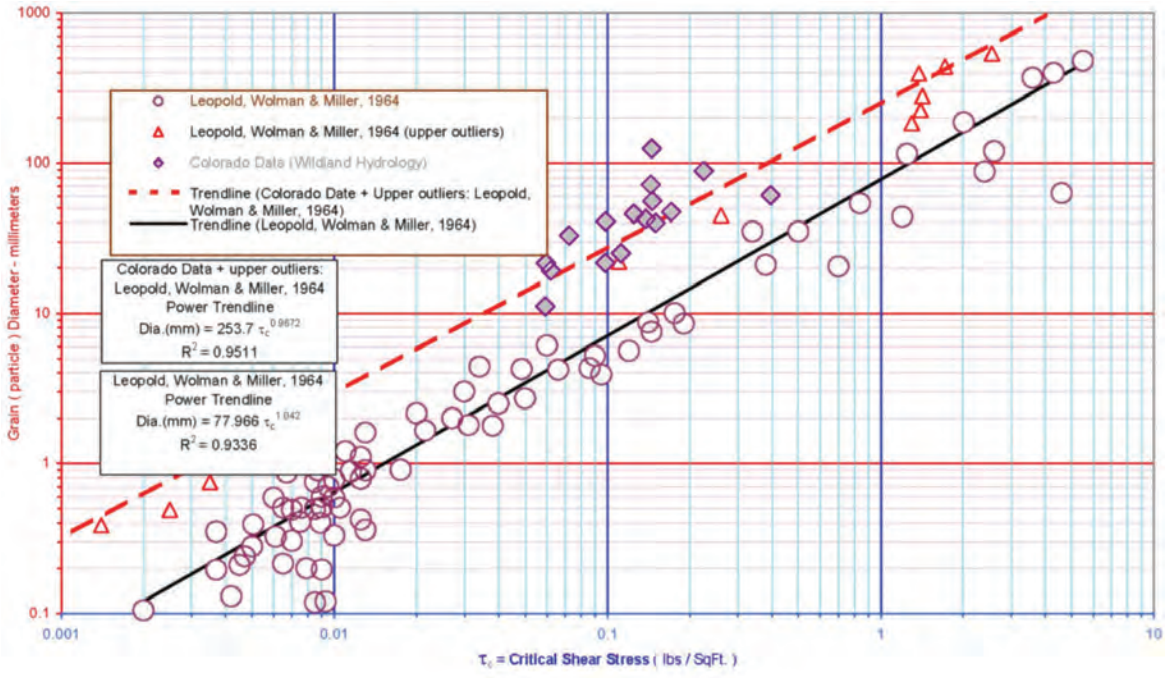
ing phase to determine if sediment transport processes are working properly. For example, if the stream is aggrading, excessive bar development, e.g., mid channel bars, will be obvious. If the stream is degrading, headcuts and the lack of pool features will be obvious. Therefore, the measurement methods described below are typically used to assess reference reach and project reach streams. Design standards are discussed after the measurement methods; however, performance standards are not included for this parameter.

Measurement Methods

1. Shear Stress Curve

There are a variety of methods for assessing sediment transport competency in gravel bed streams, most of which are based on tractive force or shear stress calculations. Rosgen (2006) measured bedload from Colorado Rivers and combined this data set with the high outliers from a Leopold, Wolman and Miller (1964) data set. This form of boundary shear stress is used by Rosgen (2006) to predict particle sizes that may be transported during a bankfull event. It is therefore a rapid assessment tool that does not require detailed modeling or intensive field work, only a cross section, average slope measurement and grain size distribution of the bed material. The result is shown below in Figure 8.1.

FIGURE 8.1 GRAIN SIZE ENTRAINED AS A FUNCTION OF SHEAR STRESS



Source: US EPA Watershed Assessment of River Stability and Sediment Supply (WARSSS) v1.0

The upper line represents data measured in natural rivers at or near the bankfull discharge, along with upper outliers from the Leopold, Wolman and Miller (1964) curve. The upper curve is used more often to assess sediment transport competency in stream restoration projects. However, it is an empirical tool and data from the project reach should be representative of the data used to create the curve (Rosgen, 2009). If it is not, then local curves should be developed in order to use the curve for design or assessment purposes. The development of a local curve requires an intensive level of effort and should only be developed by qualified scientists or engineers (Appendix Ac).

2. Required Depth and Slope

Rosgen (2006) also describes a much more detailed procedure that involves sampling bed material from the riffle pavement (surface layer) and the riffle subpavement, or material from the point bar. The material is sieved and a grain size distribution for the pavement and subpavement or point bar is developed. A series of calculations are then made using equations from Andrews (1984) and Andrews and Erman (1986) to determine the depth and slope required to move the largest particle from the subpavement or bar. From past monitoring, Rosgen has determined that the largest particle from the subpavement or point bar closely matches the largest particle sampled during a bankfull event. The required depth and slope can then be compared to the project reach depth and slope (could be a pre- or post-restoration condition as well). If the required depth and slope is greater than the project depth and slope, then there is a potential for stream bed aggradation because more shear stress is needed to move the bed. If the required depth and slope is less than the project depth and slope, then there is risk of bed degradation because there is more shear stress than is necessary to move the bed, e.g., all particle sizes may be transported rather than the largest size from the sub-pavement or bar sample.

3. Spreadsheets and Computer Models

Several computer models can be used to assess vertical stability, including those ranging from rapid/simple spreadsheet programs like BAGS to one-dimensional models like HEC-RAS, as well as the more sophisticated two-dimensional models. These models typically compute competency and capacity with more emphasis placed on capacity. A description of these techniques is provided below.

Design Standard

Sediment transport competency and capacity are often assessed together. Therefore, design standards for both parameters are discussed in the following section (Parameter: Sediment Transport Capacity).

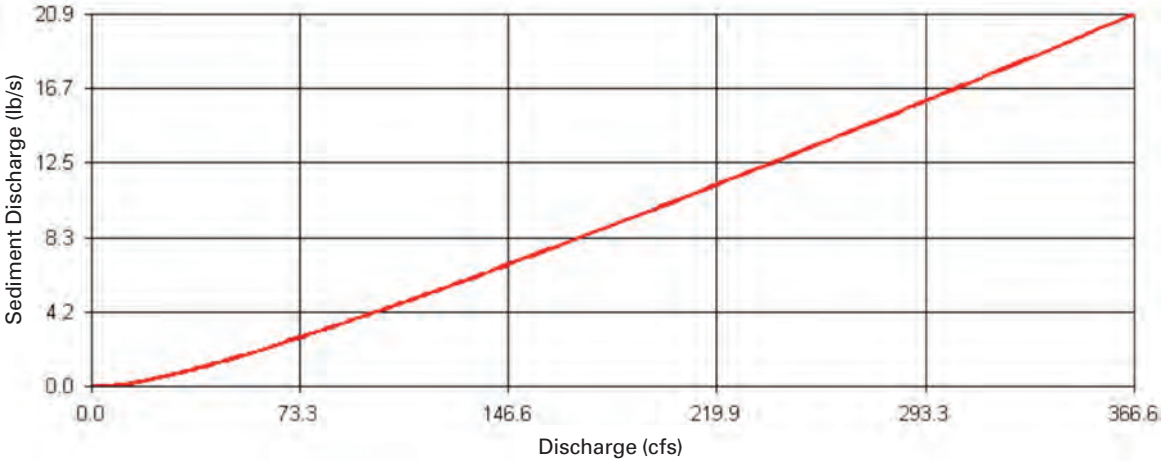
8.2 » PARAMETER: SEDIMENT TRANSPORT CAPACITY

Description

Sediment transport capacity is the ability of a stream to move a quantity of sediment through a riffle cross section. It is typically assessed using stream power, and is often

expressed as units of watts/square meter (W/m^2). A description of stream power is provided in the Hydraulics Chapter. Sediment transport capacity is often shown as a sediment transport rating curve, which provides an estimate of the quantity of total sediment (load) transported through a cross section per unit time. The curve is provided as a sediment transport rate versus discharge or stream power. An example of a sediment transport rating curve is shown below in Figure 8.2.

FIGURE 8.2 A MODELED SEDIMENT RATING CURVE FOR A PROJECT IN NC



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The total sediment load transported through a cross section can be divided by type of movement into bedload and suspended load fractions. Bedload is generally composed of larger particles, such as course sand, gravel and even cobbles or boulders, which are transported by rolling, sliding or hopping (saltating) along the bed. Suspended load is normally composed of fine sand, silt and clay particles transported in the water column.

Measurement Method

As mentioned previously, sediment transport capacity is often characterized by calculating stream power and developing rating curves, such as sediment transport in lbs/sec versus discharge or stream power. A common approach is to calculate the sediment transport capacity of a reach immediately upstream of the project, called the supply reach. Sediment transport capacity is also calculated for the project reach. The two are compared, and if the project reach has a similar transport rate as the supply reach, the project reach is assumed to be in equilibrium. If the project reach is transporting more sediment than the supply reach, there is a risk of bed degradation. Conversely, if the project reach is transporting less sediment than the supply reach, then there is a risk of aggradation. It is preferable that the upstream supply reach is stable, i.e., not aggrading or degrading. However, this approach can be used even if the upstream reach is unstable, as the goal is to transport the load of sediment that is delivered to the project reach, whatever that value may be. The problem is that an unstable supply reach will likely change

significantly with time and, therefore, the sediment supply to the project reach will change. This is one reason that it is preferable to select restoration reaches downstream of stable reaches. Another complicating factor is that a restoration design may have a goal to store sediment rather than have a transport reach. Furthermore, projects with a low sediment supply may not need a quantitative sediment transport analysis. Innovative design approaches like those shown on Figure 6.2 are redefining approaches for assessing sediment transport.

1. Computer Models

There are several computer models that can be used to quantify sediment transport capacity. HEC-RAS Version 4.1 has a sediment transport feature that can easily be run if a hydraulic model has already been developed for the project and bed material data are available. Another option is SAMWin, which is a single cross-section analyzer using a variety of sediment transport capacity equations. The software then predicts a stable cross-sectional geometry based on a Copeland stability curve and other methods (Thomas et al., 2002). More information about SAMWin, as well as a free download of the software and supporting documents, can be found at *chl.erdc.usace.army.mil/chl.aspx?p=s&a=SOFTWARE;2*.

Two-dimensional models are also becoming more prevalent for assessing channel hydraulics and sediment transport capacity. Two examples of commercially available 2-D models with hydraulic and sediment transport modeling capabilities are provided below.

RiverFLO-2D *www.flo-2d.com/products*

Mike 21 *www.mikebydhi.com*

2. FLOWSED and POWERSED

Rosgen (2006) developed an empirical approach to assessing sediment transport capacity. This approach is used to develop dimensionless bedload and suspended rating curves by normalizing the measured transport rates by the bankfull value. Dimensionless rating curves are developed for the project reach and as a reference reach for comparison. Sediment supply often increases in unstable streams, which will cause the curve to shift toward finer sediment sizes. This shift can then be compared to the reference curve to determine if the shift is significantly different.

This approach has been automated and further advanced through the FLOWSED and POWERSED models (Rosgen, 2006). FLOWSED is a model that is used to estimate annual sediment supply/loading, and it is often used to determine functional capacity by comparing results of a project reach to a reference reach, or pre-restoration conditions to post-restoration conditions. FLOWSED is also used to input sediment supply into POWERSED, which is used in conjunction with FLOWSED to determine channel stability. POWERSED includes a hydraulic analysis in order to calculate sediment transport capacity. FLOWSED and POWERSED are included in the RIVERMorph software program (*www.rivermorph.com*).

3. Bedload Assessment in Gravel-bedded Streams (BAGS)

A simpler spreadsheet-based program called Bedload Assessment in Gravel-bedded Streams (BAGS) was developed by Pitlick et al. (2009). BAGS predicts sediment transport using six different bedload transport equations developed for gravel bed streams. A sediment transport primer by Wilcock et al. (2009), a user manual, and the BAGS program is available from *www.stream.fs.fed.us/publications/bags.html*. The primer is a good document for those who want to learn more about the fundamentals of sediment transport processes.

Design Standard

Sediment transport competency and capacity are two of the most important design elements for stream restoration projects located in *transport zones*. Transport zones are stream reaches that receive significant sediment supply from upstream and adjacent sources. The project reach must be able to transport this load in order to maintain equilibrium. If a project is located in a reach where there is not significant sediment supply, like a small headwater stream or perhaps an urban channel, sediment transport competency and capacity analyses are less important.

In either case, sediment transport calculations are probably more useful as a design and assessment parameter than for determining post-restoration performance. If sediment transport calculations are wrong and the design is flawed as a result, stability problems will be obvious without the need for recalculating competency and capacity (although calculations may help to understand why a project is not properly transporting the sediment load). Indicators of sediment transport problems include excessive bar development (aggradation) and head-cutting (degradation), among others. Harman and Starr (2011) provide a checklist that can be used to help assess whether a natural channel design included the appropriate sediment transport analyses. The checklist is available for free download at *http://water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm* under Technical Resources for Mitigation or *www.stream-mechanics.com*.

In addition, Rosgen (2006) provides a comprehensive method for assessing vertical stability using a wide range of quantitative and qualitative methods. Other parameters from the Pyramid, like depth variability, percent riffle and pool, and lateral stability provide better performance standards because they represent the *result* of proper sediment transport. If the channel is in equilibrium, there is a greater probability that the appropriate bed features will form and the streambanks will have low erosion rates (rates that are comparable to reference reaches).

8.3 » PARAMETER: LARGE WOODY DEBRIS TRANSPORT AND STORAGE

Description

In addition to sediment, streams also transport, store and breakdown organic matter. Of course the type of organic matter and the rates of transport, storage and breakdown or decomposition vary greatly across the US, with the greatest rates being in forested headwater streams. A forested riparian buffer delivers many types of organic matter to the

stream, including leaves, large woody debris (LWD), dissolved organic compounds, feces and even dead animals (Richardson et al., 2005). LWD includes logs, limbs and whole trees that are sometimes transported or stored in the channel and oftentimes stored on the floodplain and floodprone area (Wohl, 2000).

The minimum size for organic matter to be classified as LWD is often reported as 10 cm in diameter (Wohl, 2000). Davis et al. (2001) defines LWD as having a 10-cm diameter at one end and is over 1 m in length. There is no maximum size for LWD, and it can include parts of trees (limbs), entire trees or groups of trees. Particulate organic matter (POM — leaves, needles and small pieces of wood) transport can be considered a Geomorphology (Level 3) parameter, at least in terms of recruitment and transport; however, since POM breaks down much faster than LWD, it fits better under organic processing, which is a Physicochemical (Level 4) parameter. The distinction made here is that LWD is a structural control and often included in geomorphology assessments, whereas, the transport and processing of POM is often part of ecological assessments. For this reason, LWD measurements are included in this section and methods for measuring organic processing are included in the Physicochemical Chapter (Level 4).

Large woody debris is most prevalent in mountain streams (Rosgen stream types A and B) and provides an important form of boundary roughness and flow resistance. Additionally, LWD can increase localized bank erosion and, therefore, sediment supply; produce a stepped channel profile where large pieces span the channel width; create sediment and organic matter storage areas; provide cover for fish; and increase substrate diversity (Wohl, 2000). In this role, LWD has a major influence on bed forms, sediment transport and channel stability — clearly a Pyramid Level 3 parameter. It also provides structure that is important for the processing of organic matter (Level 4 – Physicochemical) and supporting macroinvertebrate and fish health (Level 5 – Biology).

Measurement Method

There is an increasing amount of literature about the role and importance of LWD in rivers. Montgomery et al. (2003) provides a good overview of the geomorphic effects of wood in rivers with a global and historical overview. Abbe and Montgomery (1996) describe the role of LWD jams on channel hydraulics and habitat formations in large rivers of the Pacific Northwest. Webster et al. (1999) describes the transport and breakdown of allochthonous material at the Coweeta research forest, a Southeastern US watershed.

1. Wohl LWD Assessment

Wohl et al. (2009) published a recommended list of parameters and methods of measurement to create a more standardized approach to measuring LWD. This list may be more suited for stream assessments that are associated with research projects than those for stream restoration. However, as noted in this document, many of these parameters can be measured rapidly. Unfortunately, there have not been enough studies or assessments completed using this method, and especially on high-quality streams, to create a reference reach database and, therefore, a basis for developing performance standards.

Hopefully, that information will be available in the near future. A list of parameters and measurement methods from Wohl et al. (2009) are provided at *stream.fs.fed.us/publications/documentsStream.html*. Level I lists metrics that the authors propose should be included in all studies; Level II lists those metrics that are more applicable to a research project.

2. Large Woody Debris Index (LWDI)

While the research continues to evolve, Davis et al. (2001) provides a moderately rapid and simple method of measuring LWD that includes a Large Woody Debris Index (LWDI), making it a useful technique for comparing LWD functionality at a project reach to a reference reach. Two stages of assessment of LWD and debris dams are described by Davis et al. (2001). Stage 1 involves simply counting all LWD pieces and debris dams within a reach and standardizing the count, based on reach length or sample area. In addition to total counts of LWD and debris jams, stage 2 includes the single LWD piece and debris dam size, compared to stream size, its position in the channel and the overall stability of the LWD. The data collected in stages 1 and 2 are used to compute the LWDI. Davis et al. (2001) also provide guidance on how to set up a monitoring program to collect and evaluate the data, which generally include multiple samples that are statistically compared to a reference stream.

Performance Standard

Many restoration projects are beginning to incorporate LWD into their designs. This is most prevalent in the Pacific Northwest, where practitioners are using engineered log jams to restore floodplain connectivity, pool habitat and substrate diversity, as well as reduce streambank erosion (Abbe et al., 2003). Rosgen (2010) is also incorporating more wood into natural channel designs through the use of a toe-wood structure. Harman (2004) shows techniques for using root wads and cover logs to increase wood in the outside of meander bends. In these cases, performance may be measured based on the stability of the structures post-restoration and flows that exceed the bankfull discharge.

To determine the overall performance of LWD on creating bed form diversity, organic matter and nutrient retention, and channel stability, the LWDI index can be used. A Functioning stream would have a LWDI that statistically has the same score as the reference reach. A Not Functioning stream would have statistically significant lower value than the reference stream with no evidence that the stream is trending towards a Functioning condition, e.g., no buffer along the study reach or upstream. A Functioning-at-Risk stream would also be statistically lower than the reference condition; however, the trend is toward a Functioning condition, e.g., a buffer has been planted or is already established and/or a wood supply exists upstream (Table 8.2).

TABLE 8.2 LARGE WOODY DEBRIS PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Large Woody Debris Index (LWDI)	LWDI of project reach equals LWDI of reference reach	LWDI of project reach does not equal reference reach, but is trending in that direction.	LWDI of project reach does not equal LWDI of reference reach and is not trending in that direction.

8.4 » PARAMETER: CHANNEL EVOLUTION

Description

Channel evolution occurs when a stream system begins to change its morphology from one condition or stream type to a new condition or stream type. Channel evolution can be a negative or positive trend. As described by Leopold (1994), a stream system is a "transporting machine" for water and sediment. An open system, such as a stream, will attempt to work toward two end goals: (1) to perform a minimum amount of work and (2) to expend energy uniformly. A stream system that is in equilibrium is one where these goals are balanced (Leopold, 1994).

Channel evolution can be the result of a channel changing to a more stable or efficient form. This is commonly seen in stream restoration where new channel geometry is altered to a more stable form. Restored channels are typically constructed so that they can improve (evolve) their functional capacity over time. In a meandering stream, this generally corresponds to an evolution from a Rosgen C stream type to an E. An example of this process is shown below in Figures 8.3 and 8.4. Figure 8.3 is a 2002 photo of a riffle, taken a few months after construction and a bankfull event. Note the deposition on the right bank (left side of photo). Figure 8.4 is a photo of the riffle in 2006 after the vegetation has become more established.

The channel evolved from a C stream type with a bankfull width/depth ratio of 14 in 2003 to an E stream type in 2007, with a bankfull width/depth ratio of 9. The cross section in Figure 8.5 (below) represents the riffle. The deposition on the right bank is a natural levee that was formed between the upstream point bar and the riffle section. There was toe erosion along the left bank; however, the riffle evolved in a positive direction as shown by the decrease in bankfull width/depth ratio, while maintaining a BHR near 1.0.

Channel evolution can also be the result of a disruption to the stream or watershed. If a disruption to either the amount of stream power (such as from a change in slope or discharge) or to the work to be done (such as a change in the amount of sediment supply), the stream's equilibrium may be disturbed, and the stream channel may begin evolving to meet the new conditions. This relationship was first described by Lane (1955). Lane's diagram states that the sediment size multiplied by the sediment load is proportional to the stream discharge multiplied by the slope (Figure 8.6).

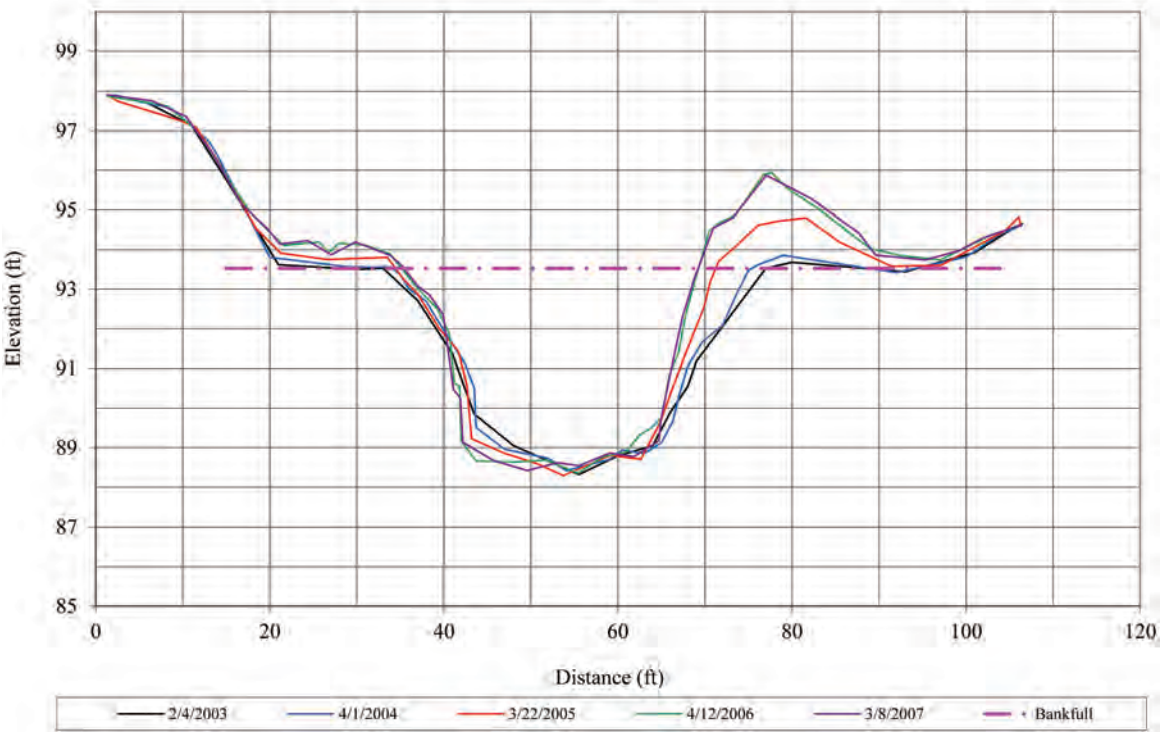
FIGURE 8.3 RESTORED RIFFLE IN 2002

Source: Reproduced with permission from Michael Baker Corporation

FIGURE 8.4 RESTORED RIFFLE IN 2006

Source: Reproduced with permission from Michael Baker Corporation

FIGURE 8.5 EVOLUTION OF THE RIFFLE CROSS SECTION FROM 2003 TO 2007



Source: Reproduced with permission from Michael Baker Corporation and Wildland Hydrology

A common sequence of physical adjustments (channel evolution) has been observed in many streams following disturbance. Disturbance can result from channelization, which is an increase in runoff due to build-out in the watershed, removal of streamside vegetation or other changes that negatively affect stream stability. These disturbances occur in both urban and rural environments. Several models have been used to describe this process of physical adjustment for a stream.

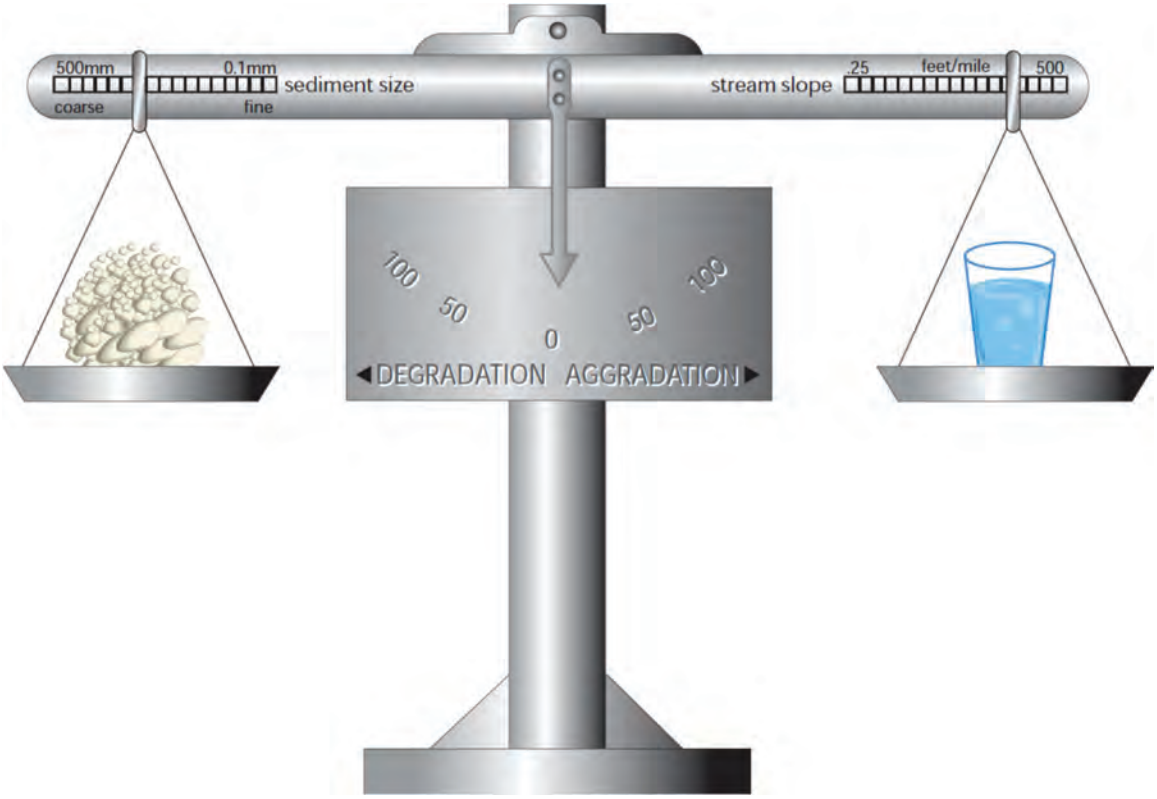
The channel evolutionary stage conveys important information about the pressures on stream systems and the stream channel's response. Stream and river restoration projects often have an end goal of stabilizing the stream system, i.e., bringing the system into equilibrium. In order to prevent or correct stream stability issues the current evolutionary stage of the channel, and the pressures acting upon it must be understood.

Measurement Method

Understanding channel evolution is helpful during geomorphic assessments, restoration goal setting and project evaluation. Channel evolution can be used during the geomorphic assessment phase to determine whether the stream reach is trending towards stability or instability. This determination helps to establish better goals. If the stream is trending towards stability (late stage of evolution), then the restoration goals can be more

FIGURE 8.6 GRAPHIC REPRESENTATION OF LANE'S DIAGRAM

The sediment size and load is shown on the left, and discharge and slope (power) is shown on the right. When one of these parameters changes, there is often a change in streambed elevation. For example, an increase in channel slope from channelization often leads to degradation.



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passive. These passive approaches often include land use management changes or simply re-establishing a wide riparian buffer. If the stream is stable but is showing signs of instability (early stage of channel evolution) like the early signs of a headcut, then the goal may be to simply stabilize the headcut to prevent further upstream damage. Full-scale restoration goals are often needed for streams that have been disturbed and are evolving towards increasingly unstable conditions or reaches that will require many years of adjustment before reaching equilibrium. Channel evolution can then be used after restoration to help show that the stream is moving from a newly constructed condition to a reference condition, e.g., a C evolving to an E.

If the stream is trending towards stability (late stage of evolution), then the restoration goals can be more passive.

Channel evolution can be assessed using Simon's Channel Evolution Model, Rosgen's Stream Type Succession Scenarios or both. Both methods involve assessing the stream in its current condition and determining its evolutionary endpoint.

1. Simon Channel Evolution Model

The Simon (1989) Channel Evolution Model (Figure 8.7) characterizes evolution in six steps, including:

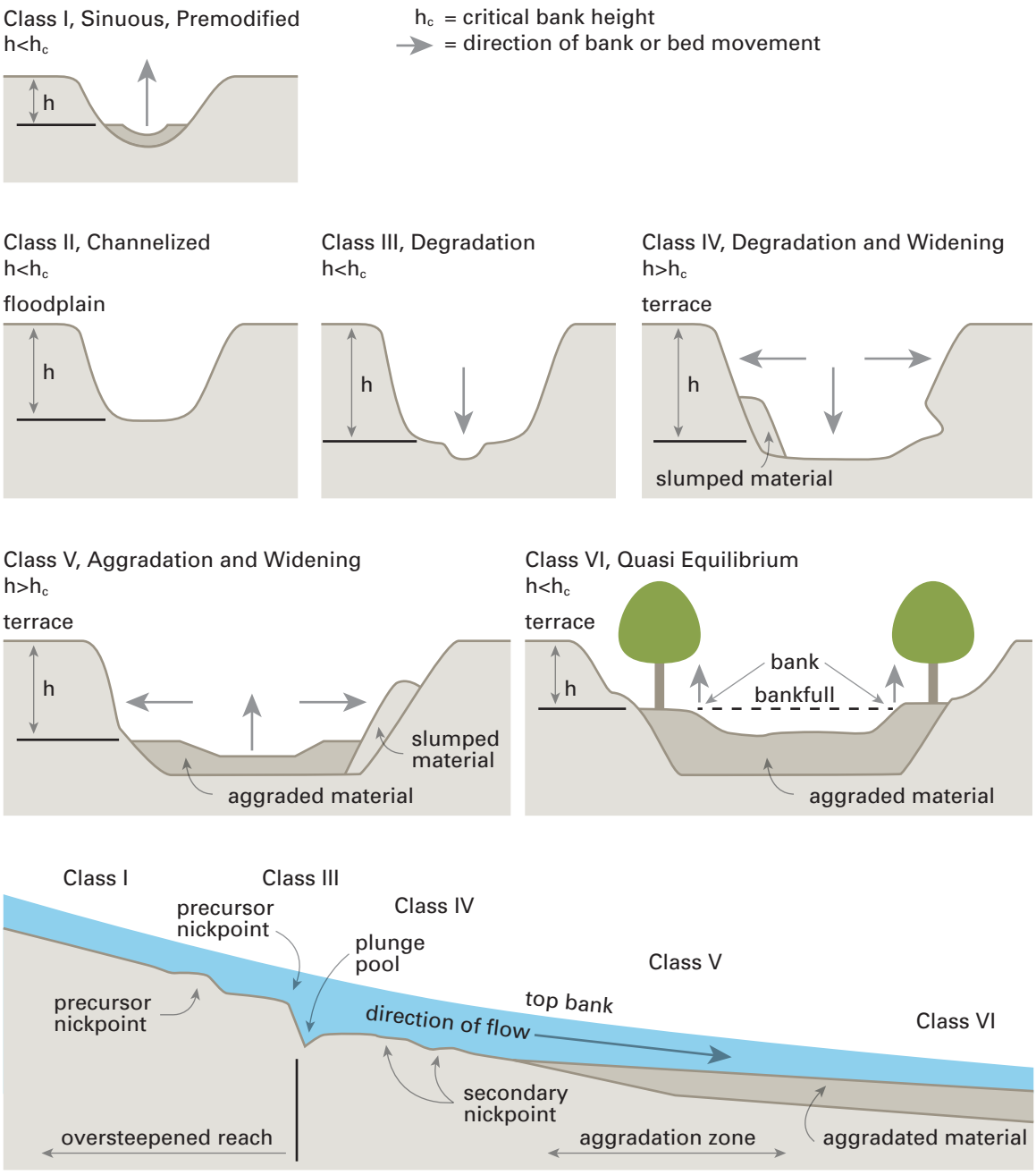
1. Sinuous, pre-modified
2. Channelized
3. Degradation
4. Degradation and widening
5. Aggradation and widening
6. Quasi-equilibrium

The channel evolution process is initiated once a stable stream that is well connected to its floodplain is disturbed. Disturbance commonly results in an increase in stream power that causes degradation, often referred to as channel incision (Lane, 1955). Incision eventually leads to over-steepening of the banks; and when critical bank heights are exceeded, the banks begin to fail. Incision and widening continue as headcutting moves upstream. Eventually the bed slope is reduced, and sedimentation from bank erosion begins to fill the channel (aggradation). A new, low-flow channel begins to form in the sediment deposits. By the end of the evolutionary process, a stable stream geometry, similar to those of undisturbed channels, forms in the deposited alluvium. The new channel is at a lower elevation than its original form, with a new floodplain constructed of alluvial material (FISRWG, 1998).

Full-scale restoration goals are often needed for streams that have been disturbed and are evolving towards increasingly unstable conditions or reaches that will require many years of adjustment before reaching equilibrium.

The first step toward determining the channel evolution using this method is to characterize the channel in its current condition. This may involve using similar morphological indicators to determine vertical and lateral stability, as well as reviewing sediment transport calculations, as described in the Rosgen (2006) method. Then an evolutionary stage from Simon's model can be selected. For example, a newly channelized stream corresponds to Stage 2 of the Simon model. If an active headcut is observed in this channelized stream, it indicates vertical instability, which corresponds to Stage 3 of the Simon model. If BHRs are high, indicating incision, the stream may begin to have rotational and slab bank failure from the changes in bank hydrostatic pore pressure caused by the drop in the water table. This will cause the channel to widen, which would indicate that the stream is in Stage 4

FIGURE 8.7 SIMON CHANNEL EVOLUTION MODEL



Source: Adapted from FISRWG(1998) and Simon (1989)

of the Simon model. Stage 4 also corresponds to an increase in width to depth ratios. As the stream continues to widen the slope decreases from down-cutting, the channel loses the capacity to transport the sediment received. Depositional features, such as mid-channel and transverse bars, begin to develop, which force velocity vectors towards streambanks and cause increased bank erosion or widening. This is Stage 5 of the Simon model.

The level of effort and complexity for using the Simon Channel Evolution Model varies depending on a qualitative versus a quantitative assessment. An experienced practitioner can predict the stage of evolution by simply observing the channel, making the level of effort "rapid" and level of complexity "simple." If field measurements are taken, the level of effort and complexity increase to moderate (Appendix Ac).

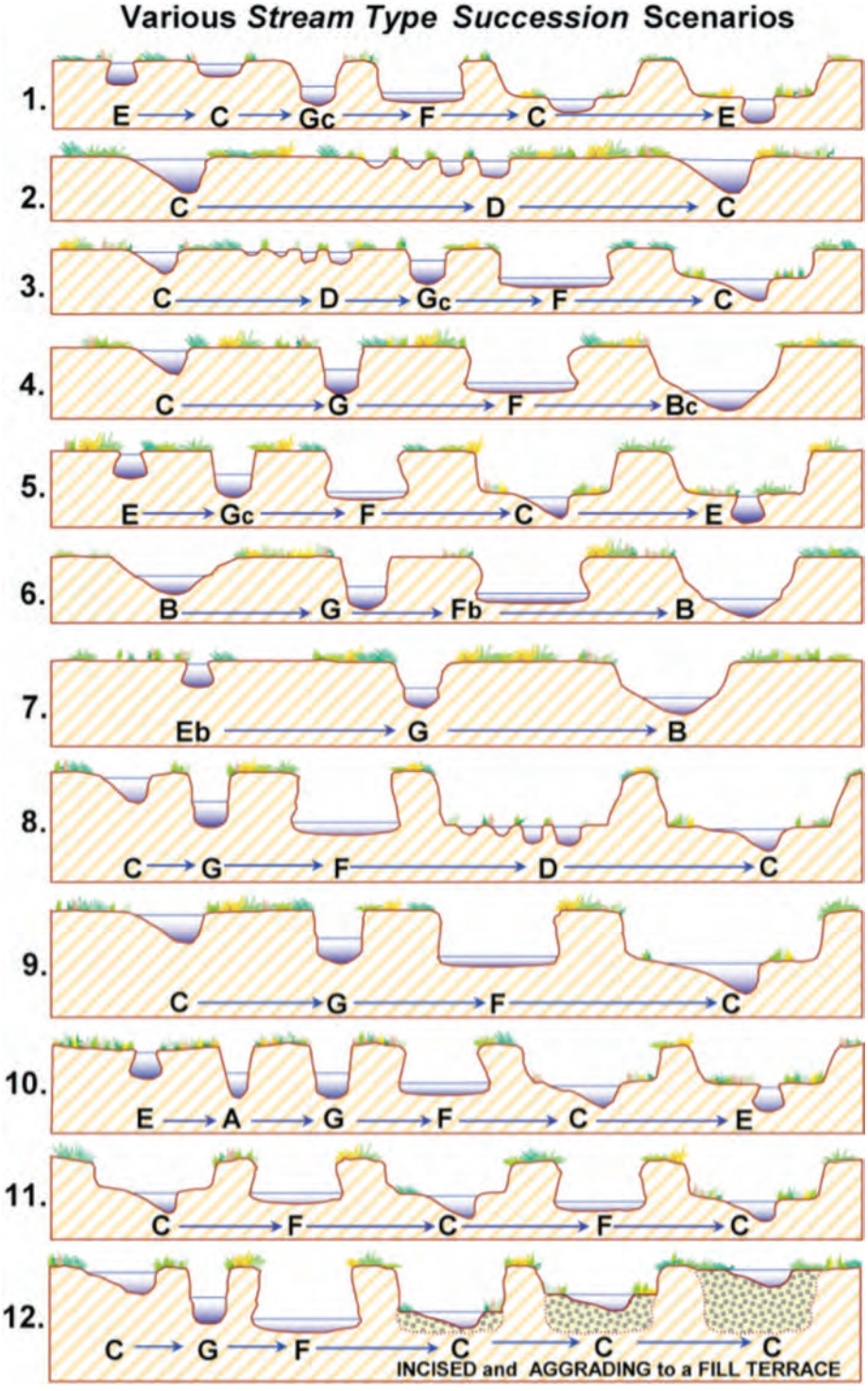
2. Rosgen Stream Type Succession Scenarios

Rosgen (2006) uses changes in stream type to illustrate channel evolution. These changes were measured in streams throughout the US. Nine different stream type succession scenarios are shown in Rosgen (2006). Since that publication, three more scenarios have been added, and all 12 are shown below in Figure 8.8 (Rosgen, 2010, personal communication). Scenario 5 most closely matches the Simon (1989) approach.

The first step toward determining the channel evolution with this method is to classify the channel using the Rosgen (1994) methodology. After determining the stream type, observations should extend to the valley to determine what the naturally forming stream type is for the given valley. Rosgen (1996) provides information regarding which stream types occur naturally in certain valleys. Knowing the naturally occurring, stable stream type provides the potential evolutionary starting and/or end point for the stream.

The next step in determining the channel evolution is to determine if the stream is already at its evolutionary end point, or if it is in one of the stages of evolution. Morphological indicators can give clues as to whether a channel is vertically unstable, laterally unstable or both. These include the presence (or absence) of features such as headcuts and depositional bars; the presence and location of bank erosion; and geomorphic channel measurements, such as bank height ratio, entrenchment ratio and width to depth ratio. These indicators provide insight into whether the channel is aggrading or degrading. These observations are then compared to sediment competency calculations to determine whether the bankfull flows have the force to entrain the sediment delivered by the watershed, or if they have excessive force and may mobilize the entire bed. Rosgen (2006) provides a detailed assessment method, which includes a series of geomorphology-based worksheets used to determine channel stability. After the geomorphic and stability data are gathered, the appropriate evolutionary sequence can be selected from one of the 12 scenarios shown in Figure 8.8. These determinations can be made visually by an experienced practitioner and can, therefore, be completed rapidly. However, they can also be measured, which increases the level of effort and complexity to moderate (Appendix Ac).

FIGURE 8.8 ROSGEN EVOLUTION MODEL BY STREAM TYPE



Source: Reproduced with permission from Wildland Hydrology

Performance Standard

Channel evolution as a performance standard is different than most of the other parameters in that it is a summary condition that integrates several parameters and processes. As such, it may be tempting to use channel evolution as the only performance standard in the Hydraulic and Geomorphology categories, stating for example that a Rosgen C stream type is Functioning and therefore meets the performance standard. This approach is strongly discouraged because stream type alone does not provide stability and functional capacity information. There are many C and E stream types that are Functioning-at-Risk or Not Functioning. Keep in mind that a channel could have a bank height ratio of 1.8, a very incised channel, and still classify as a C or E.

Channel evolution as a performance standard is different than most of the other parameters in that it is a summary condition that integrates several parameters and processes. As such, it may be tempting to use channel evolution as the only performance standard in the Hydraulic and Geomorphology categories. This approach is strongly discouraged because stream type alone does not provide stability and functional capacity information.

The reason for including channel evolution is to show the current channel condition and how it could change over time. The federal mitigation rule suggests that performance standards be based on data from reference reach streams. One reason for this is to show the natural range of variability that exists in stable, functioning streams. The rule also states that performance standards should show the expected stages of the aquatic resource development process, in order to allow early identification of potential problems and appropriate adaptive management. Channel evolution can be used along with other parameters to show the expected stages of development in a restoration project. For example, many projects are designed and built as a C stream type. Over time, the channel evolves to an E stream type. Showing this evolution indicates that the stream is trending towards a higher degree of functionality. A restored channel that is built as a C stream type but begins to evolve to a Gc stream type represents a negative trend, one that leads to instability and a loss of function. This project would require immediate attention.

Tables 8.3 and Table 8.4 summarize the various stages for each measurement method and whether they are Functioning, Functioning-at-Risk or Not Functioning. The arrow (→) means that the stream type is changing from the former to the latter. For example, a C→Gc means that the current stream type is a C, and the stream is trending towards a Gc. This table can be used as an aid in performing geomorphic assessments, goal setting and for evaluating stream restoration projects.

TABLE 8.3 PERFORMANCE MEASUREMENT FOR ROSGEN'S STREAM TYPE EVOLUTIONARY STAGES

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Rosgen's Stream Type Succession Scenarios			
1. E→C→Gc→F→C→E	E, C	C→Gc and F→C	Gc, F
2. C→D→C	C	C→D and D→C	D
3. C→D→Gc→F→C	C	C→D and F→C	D, Gc, F
4. C→G→F→Bc	C, Bc	C→G and F→Bc	G, F
5. E→Gc→F→C→E	E, C	E→Gc and F→C	Gc, F
6. B→G→Fb→B	B	B→G and Fb→B	G, Fb
7. Eb→G→B	Eb, B	Eb→G and G→B	G
8. C→G→F→D→C	C	C→G and D→C	G, F, D
9. C→G→F→C	C	C→G and F→C	G, F
10. E→A→G→F→C→E	E	E→A and F→C	A,G, F
11. C→F→C→F→C	First and last C	C→F	F
12. C→G→F→C→C→C	First and last C	C→G and C→C	G,F, Fourth C

TABLE 8.4 PERFORMANCE MEASUREMENT FOR SIMON'S CHANNEL EVOLUTION STAGES

Simon (1989) Channel Evolution Model Stages			
	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
1. Sinuous, pre-modified	✓		
2. Channelized			✓
3. Degradation			✓
4. Degradation and widening			✓
5. Aggradation and widening		✓ *	
6. Quasi-equilibrium	✓		

** Only late Stage 5 of the Simon model, where the stream has begun to construct a new floodplain at a lower elevation, is considered to be Functioning-at-Risk.*

In addition to the performance standards provided above, Table 8.5 may be helpful in illustrating the effects of stream type changes on habitat parameters. These parameters are provided by Rosgen and do not directly correspond to parameters on the Pyramid. This table is provided by Rosgen (2010, personal communication) and shows how each

variable (parameter) responds to the change in stream type. An up arrow means that there is an improvement, a down arrow means that there is a functional loss, and a sideways arrow indicates no change. The green shading indicates that these two stream type evolutionary changes are positive or, using Performance Standard terminology, Functioning-at-Risk. Once they evolve to a C or E stream type, they will be Functioning.

TABLE 8.5 THE EFFECTS OF STREAM TYPE CHANGES ON HABITAT PARAMETERS

Variable	C→G	G→F	C→D	F→C	C→E
Instream Cover	↓	↓	↓	↑	↑
Overhead Cover	↓	↓	↓	↑	↑
Substrate Composition	↑	↓	↓	↑	↑
Pool Quality	↓	↓	↓	↑	↑
Holding Cover Velocity	↓	↓	↓	↑	↑
Temperature	→	↑	↑	↓	↓
Oxygen	→	↓	↓	↑	↑
Macro Invertebrates	↓	↓	↓	↑	↑
Spawning Habitat	↓	↓	↓	↑	↑
Diversity	↓	↓	↓	↑	↑
Rearing	↓	↑	↑	↑	↑
IBI Score	↓	↓	↓	↑	↑

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8.5 » PARAMETER: BANK MIGRATION/LATERAL STABILITY

Description

Lateral stream migration commonly occurs on rivers that flow through alluvial valleys. A channel migrates within the floodplain through lateral erosion on the outside of meander bends and subsequent deposition on the interior bend, or point bar. In order to understand bank migration and lateral stability, energy expenditure in a stream system should be addressed first. Streams and rivers are open systems, which have a continual source of potential energy supplied by topographic elevation and precipitation (the hydrologic cycle). The potential energy supplied by the rain and elevation is transformed to kinetic energy as water flows downhill. The kinetic energy carries sediment downstream (sediment transport) and causes some erosion from turbulence and friction along the channel boundary. In an alluvial valley where the boundary conditions (bank materials) are erodible, meanders will form and continue to erode until the stream achieves a plan form, where energy is expended uniformly and the least amount of work possible is accomplished (Leopold, 1994). Once this equilibrium is achieved, a stream may continue to

migrate but will deposit materials in bars to maintain the bankfull cross-sectional area.

Bank migration and lateral stability are as much a function of the bank materials and bank cover as they are the in-stream hydraulic forces acting upon them. This is because bank materials and vegetative cover resist hydraulic forces, such as shear stress. A barren bank composed primarily of sand, for example, is more susceptible to erosion than a densely vegetated clay bank. In addition, some stream types are naturally more susceptible to bank erosion than other stream types. Stream types A and B are less likely to experience extreme bank migration because of their confined valleys and steep vertical profiles, often controlled by bedrock or colluvium. Stream types C and E are more likely to experience bank migration since these stream types are by nature sinuous, meandering stream channels, which actively migrate across floodplains. Stream types F and G are often associated with excessive bank erosion because they are entrenched. Bank erosion within these stream types can be extreme in disturbed systems where the former stream type was a C or E (see section on Channel Evolution). However, F and G stream types associated with bedrock-controlled gorges may be stable. Rosgen (1994) provides a table (Table 8.6) showing the sensitivity to lateral adjustment and recovery potential. In this example, recovery potential means the ability of the stream to return to a laterally stable condition without human intervention.

TABLE 8.6 Rosgen (1994)

Illustrates the sensitivity to disturbance, recovery potential, typical sediment supply conditions, streambank erosion potential and the influence of bank vegetation on stability for a wide range of stream types.

Stream Type	Sensitivity to disturbance[a]	Recovery potential[b]	Sediment supply[c]	Streambank erosion potential	Vegetation controlling influence[d]
A1	Very low	Excellent	Very low	Very low	Negligible
A2	Very low	Excellent	Very low	Very low	Negligible
A3	Very high	Very poor	Very high	Very high	Negligible
A4	Extreme	Very poor	Very high	Very high	Negligible
A5	Extreme	Very poor	Very high	Very high	Negligible
A6	High	Poor	High	High	Negligible
B1	Very low	Excellent	Very low	Very low	Negligible
B2	Very low	Excellent	Very low	Very low	Negligible
B3	Low	Excellent	Low	Low	Moderate
B4	Moderate	Excellent	Moderate	Low	Moderate
B5	Moderate	Excellent	Moderate	Moderate	Moderate
B6	Moderate	Excellent	Moderate	Low	Moderate
C1	Low	Very good	Very low	Low	Moderate
C2	Low	Very good	Low	Low	Moderate
C3	Moderate	Good	Moderate	Moderate	Very high
C4	Very high	Good	High	Very high	Very high
C5	Very high	Fair	Very high	Very high	Very high
C6	Very high	Good	High	High	Very high

TABLE 8.6 Rosgen (1994) (CONT.)

Illustrates the sensitivity to disturbance, recovery potential, typical sediment supply conditions, streambank erosion potential and the influence of bank vegetation on stability for a wide range of stream types.

Stream Type	Sensitivity to disturbance[a]	Recovery potential[b]	Sediment supply[c]	Streambank erosion potential	Vegetation controlling influence[d]
D3	Very high	Poor	Very high	Very high	Moderate
D4	Very high	Poor	Very high	Very high	Moderate
D5	Very high	Poor	Very high	Very high	Moderate
D6	High	Poor	High	High	Moderate
Da4	Moderate	Good	Very low	Low	Very high
DA5	Moderate	Good	Low	Low	Very high
DA6	Moderate	Good	Very low	Very low	Very high
E3	High	Good	Low	Moderate	Very high
E4	Very high	Good	Moderate	High	Very high
E5	Very high	Good	Moderate	High	Very high
E6	Very high	Good	Low	Moderate	Very high
F1	Low	Fair	Low	Moderate	Low
F2	Low	Fair	Moderate	Moderate	Low
F3	Moderate	Poor	Very high	Very high	Moderate
F4	Extreme	Poor	Very high	Very high	Moderate
F5	Very high	Poor	Very high	Very high	Moderate
F6	Very high	Fair	High	Very high	Moderate
G1	Low	Good	Low	Low	Low
G2	Moderate	Fair	Moderate	Moderate	Low
G3	Very high	Poor	Very high	Very high	High
G4	Extreme	Very poor	Very high	Very high	High
G5	Extreme	Very poor	Very high	Very high	High
G6	Very high	Poor	High	High	High

a Includes increases in streamflow magnitude and timing and/or sediment increases.

b Assumes natural recovery once cause of instability is corrected.

c Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.

d Vegetation that influences width/depth ratio-stability.

Measurement Method

Bank migration can be measured a variety of ways, ranging from rapid and simple methods to intensive and complex. This document provides examples from simple interpretations of aerial photographs to complex computer models. These measurement methods are listed in progressive order, from simple to complex.

1. Meander Width Ratio

Meander width ratio is the ratio of stream belt width divided by stream bankfull width. The belt width is the distance from the apex of one meander bend to the next meander bend, measured perpendicular to the fall line of the valley (Figure 8.9). To compare belt widths between different size streams, the belt width is divided by the bankfull width to create a dimensionless ratio. The minimum meander width ratio for meandering streams (C and E stream types) is between 3.0 and 3.5; this ratio is required to create a sinuosity of at least 1.2, the most common break point between meandering and non-meandering streams (Rosgen, 1996; Leopold and Wolman, 1957). If a straightened stream is eroding on both banks and readjusting its pattern, the bankfull width (measured from the aerial) can be multiplied by 3.5 (conservatively) to estimate the amount of lateral erosion that will likely occur.

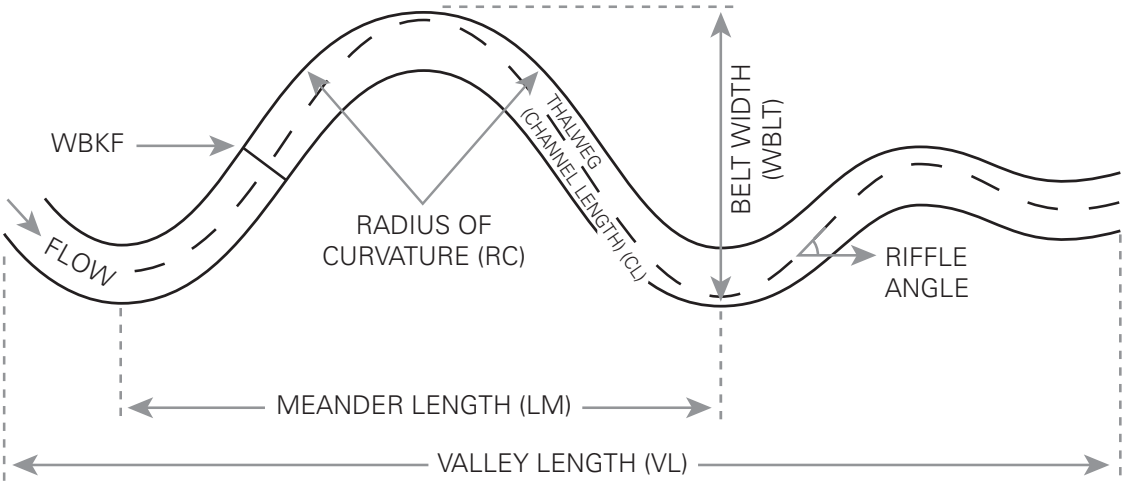
Meander width measurements can rapidly be taken from existing engineering plans, topographic maps and aerial photographs. Aerial photography, unlike other methods providing information about lateral stability and bank erosion on a local, short-term scale, can be used to determine lateral stability over a much longer time frame and over great distances. Historic aerial photography can be overlaid with current photography to determine the degree of lateral migration that has occurred between the dates of the photographs. Digital orthophotos can usually be purchased from local or state governments and are preferred over some free Web services that do not provide geo-corrected photographs.

Using aerial photography to determine lateral stability has its benefits. For relatively low cost and time expenditure, aerial photography affords long-term views of the stream channel position in the floodplain. It can also provide information about whether the channel migrated rapidly or slowly in the past, and whether a local or watershed disturbance, such as deforestation, is correlated to the channel migration changes. A limitation to aerial photography is that it only provides plan view information, i.e., it is not possible to calculate the volume of eroded sediment without a field measurement of the bank height or more advanced techniques for reading aerial photos. Aerial photograph analysis combined with reference reach surveys can be used to determine the ultimate belt width of an unstable C or E stream type.

2. BEHI/NBS

Rosgen's Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) rating methods can be used to estimate the annual amount of lateral erosion/migration. These methods involve collecting relatively simple measurements and visual observations of streambanks, including bank cover, depth of root mass, channel composition and bank slope; then a BEHI risk rating is assigned, from very low to extreme. Observations of channel flow characteristics, including water-surface slope, direction of velocity vectors and other methods, are used to assess the NBS risk rating, which can range from very low to extreme. These ratings can be used with a streambank erodibility rating curve, appropriate for the area, to derive a predicted annual linear footage of bank erosion per year. A detailed description of this method is in Rosgen (2009). The BEHI/NBS assess-

FIGURE 8.9 PATTERN MEASUREMENTS AND RATIOS, INCLUDING THE MEANDER WIDTH



CHANNEL PATTERN CALCULATIONS
RADIUS OF CURVATURE / RIFFLE WIDTH (RC / WBKF)
MEANDER LENGTH / RIFFLE WIDTH (LM / WBKF)
MEANDER WIDTH RATIO (MWR = WBLT / WBKF)
SINUOSITY (K) = CHANNEL LENGTH (CL) / VALLEY LENGTH (VL)

ment can be completed with a moderate level of effort if the practitioner is not quantitatively measuring every bank, but rather makes qualitative predictions with periodic measurements for calibration. If the practitioner is using bank pins and cross sections (see below) to develop BEHI/NBS curves, the level of effort increases to intensive (Appendix Ac).

3. Bank Pins

Another method for measuring lateral stability or bank erosion/migration is through the installation of bank pins. Bank pins are usually long steel rods (rebar) installed flush with the streambank. The pins are installed at known intervals from the toe of the bank to the top of the bank. Each time the site is visited, the length of exposed rebar is measured and can be combined with the distance between pins to provide a square-footage of bank material lost.

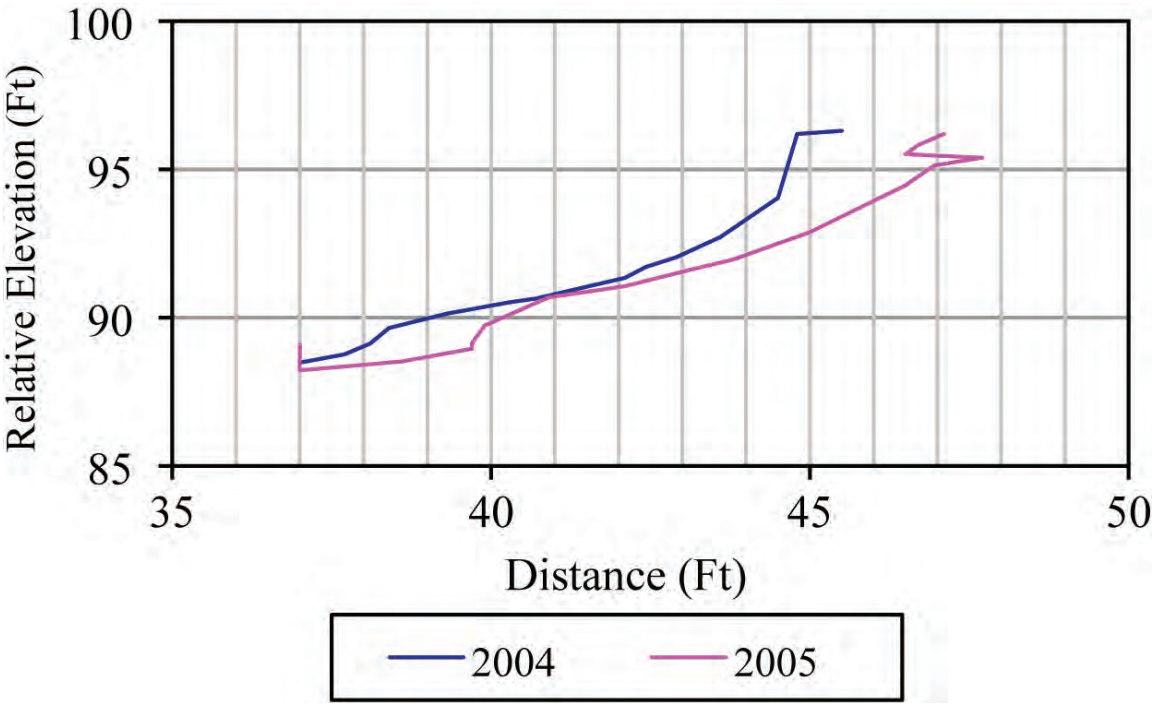
Using bank pins to perform annual monitoring of bank erosion is beneficial due to the relatively low cost and time required. Unfortunately, this method provides information about the eroding bank only and fails to capture information about developing bars (if any). Although visual observations of developing bars can be made, it is difficult to determine whether the erosion and deposition are balanced, and whether the channel is maintaining dimension, despite erosion. More information about banks pins can be found in Harrelson el al. (1994).

4. Bank Profiles

Bank profiles provide detailed information about lateral stability and bank erosion at a particular bank. These profiles involve installing permanent cross-section markers, as discussed in Cross-Sectional Surveys (below), as well as a permanent toe pin marker. The toe pin should be installed at the base of the study bank to ensure that the bank profile is taken in the same location each time. Surveys of the bank are conducted each time the site is visited. Detailed instructions about performing bank profiles are provided by Rosgen (2009).

One benefit to conducting a bank profile survey, as opposed to installing and measuring bank pins, is that a survey captures more detailed information about the bank, allowing for a more precise measurement of bank material lost due to erosion. A bank profile also causes virtually no disturbance to the bank, as opposed to bank pins that require hammering rods into the bank. Some researchers believe that bank pin installation compromises the integrity of the bank, resulting in more erosion than would typically occur if the bank were undisturbed.

FIGURE 8.10 OVERLAY OF TWO BANK PROFILES FROM WATTS BRANCH



Surveys were taken near the same date, one year apart. Note that the 2005 profile shows an overhang at the top of the bank. Overhangs and undercuts are easier to measure with a bank profile than a cross section.

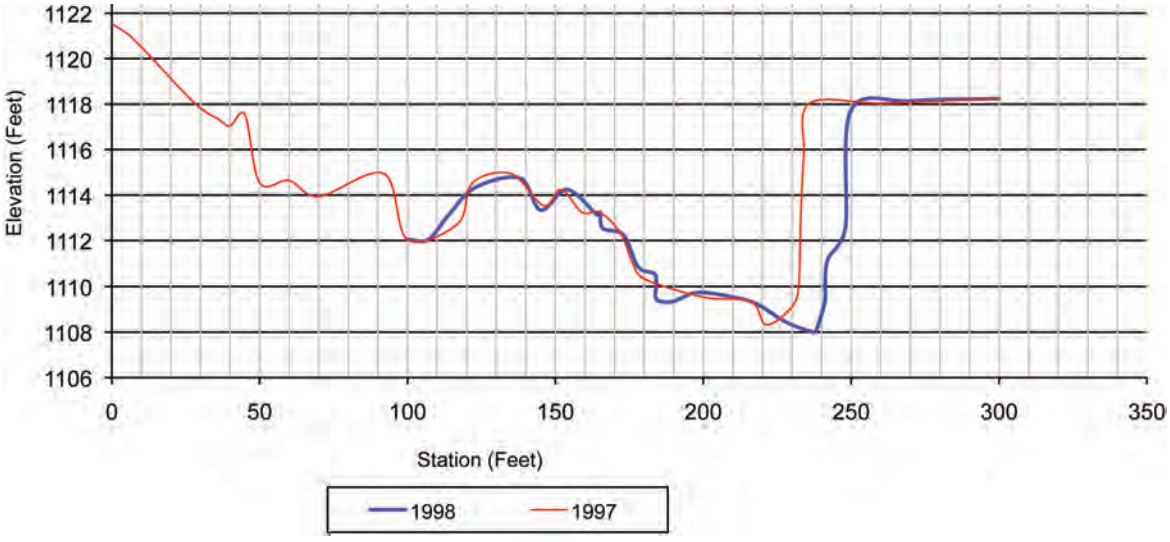
Source: Reproduced with permission from US Fish and Wildlife Service

An example of two bank profiles measured at the same location and overlaid with each other is shown in Figure 8.10. The figure shows a lateral erosion rate of 1.4 feet, which was calculated as the difference in area between the two curves, divided by the bank height. To measure the total amount of bank erosion in ft^3/year, the lateral erosion rate can be multiplied by the bank height and length that is representative of the profile.

5. Cross-Sectional Surveys

Lateral stability and bank erosion/migration can also be measured and monitored through cross-sectional surveys. Cross sections should be defined through installation of permanent markers denoting the beginning and end point of the survey to ensure the section is repeated in the same place each time. Cross sections from year to year can be overlaid and the distance of bank migration can be measured. Unlike bank pins and bank profiles, cross sections provide information about the channel bed and the opposite bank, so deposition or erosion across the entire section can be observed. This can be very useful in helping determine whether lateral erosion is a result of a stable but active and dynamic channel, or if it is the result of a stream out of equilibrium. Also useful is the ability to determine if there has been a change in cross-sectional area, width or depth, as a result of lateral erosion and/or deposition within the section. This provides insight into whether the bank migration is a result of natural migratory processes, or whether it is a result of stream disequilibrium. Detailed information on performing cross-sectional surveys can be found in Harrelson et al. (1994) and Rosgen (2009). An example of two cross sections measured at the same location one year apart is shown below in Figure 8.11. The overlay shows that the right streambank has laterally eroded 15 feet. The point bar location has remained the same, indicating that the bankfull channel width and cross-sectional area is increasing.

FIGURE 8.11 CROSS-SECTIONAL SURVEYS OF AN ERODING STREAMBANK



Source: NC State University, Stream Restoration Program

6. Bank Stability and Toe Erosion Model

Andrew Simon and Eddy Langendoen (2006) developed a computer model that can be used to estimate the potential for bank failure — or lateral instability — from horizontal layer, vertical slice with tension crack, or cantilever failures. The model requires detailed input information about the streambank, including the various soil layers and profile, the water table and stream level, the bank profile, and vegetation present on the bank. The model outputs a factor of safety that corresponds to the potential for bank failure. Due to the amount of data that needs to be collected and entered into the model, this is one of the more complex methods of predicting lateral stability.

Performance Standards

Thresholds for determining whether a stream is Functioning from a bank migration or lateral stability standpoint should be considered with stream channel type and channel evolutionary stage in mind. In general, it is good to compare what is observed in the field with what is known about stable reference reach conditions. There are several different methods for measuring lateral instability; therefore, the performance standards for each are broken down by measurement method. The performance standards provided below are most applicable to Bc, C, E, F and Gc stream types.

1. Meander Width Ratio (MWR)

The Meander Width Ratio (MWR), described above, can be used to determine whether a stream channel is Functioning from a lateral stability perspective. Each stream type has an accepted range of MWRs, as determined from reference reach surveys. MWRs determined from aerial photography can then be compared to known ranges for stable reference reach streams to establish whether the stream is Functioning. Typical ratios for C and E stream types are shown in Table 8.7.

A minimum MWR of 3.0 to 3.5 is critical for stream restoration projects that include new channel construction. If a C or E stream type is designed and constructed with a MWR below 3.0, there is a high risk of bank erosion and reach wide instability. In these cases, the restoration practitioner is trying to force a meandering channel in a confined corridor. Confinement is usually caused by land availability rather than geologic controls. These streams typically have sinuosity less than 1.2 and do not classify as meandering streams. The result is that the stream begins to straighten through bank erosion that extends from the outside of the meander bend downstream to the next point bar. A range of 3.0 to 3.5 is used in the Functioning-at-Risk category because a sinuosity of 1.2 can typically be achieved with this range. For example, W/D ratios less than 12 can often

A minimum MWR of 3.0 to 3.5 is critical for stream restoration projects that include new channel construction. If a C or E stream type is designed and constructed with a MWR below 3.0, there is a high risk of bank erosion and reach wide instability.

achieve the minimum sinuosity of 1.2 with a MWR of 3.0. Higher W/D ratio streams need a MWR of 3.5. Generally, higher MWRs lead to higher functionality (longer riffles and more stream length), as long as the sinuosity does not lower the slope to a point where the channel aggrades.

2. Lateral Erosion (BEHI/NBS)

BEHI and NBS scores can be used to determine thresholds for Functioning, Functioning-at-Risk and Not Functioning. However, a reach wide assessment of bank erosion should be conducted to determine overall functionality from a bank stability perspective. For example, a large tree could fall into a stream creating an unstable bank, perhaps with a high BEHI score and an Extreme NBS score; this would cause the bank to fall into the Not Functioning category. But if the buffer width is sufficient and the banks are well vegetated upstream and downstream of the unstable bank, it is unlikely that the bank erosion will worsen. It will likely heal over time because the overall reach is stable and Functioning. If the buffer is not well established, it is possible that the bank will erode for a long time before it becomes stable and could lead to pattern adjustment and instability for a longer portion of the reach.

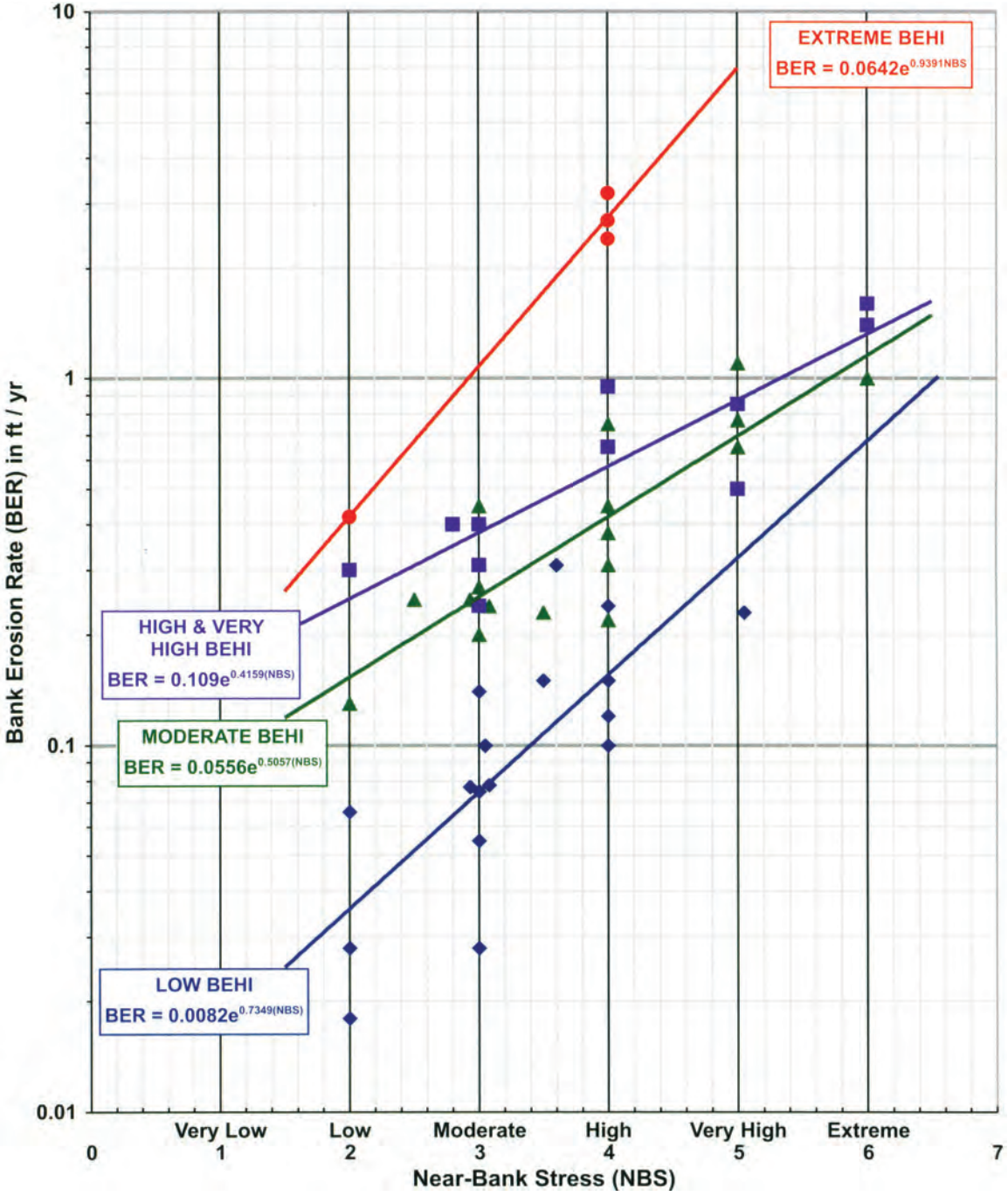
The thresholds shown in Table 8.7 came from a review of the erosion rate curve provided by Rosgen (2001). This curve was developed in Colorado (Figure 8.12), so these ranges could be modified based on locally developed curves. The Rivermorph software package provides erosion rate curves for other parts of the US.

Table 8.7 shows the BEHI categories/curves as rows and the NBS rating in the individual columns for Functioning, Functioning-at-Risk and Not Functioning. The Colorado erosion rate curve shown in Figure 8.12 was used as a guide to determine the level of functionality. In general, if the curve predicted below 0.1 ft/year, a Functioning category is shown. If the erosion rate fell between 0.1 and 0.5 ft/yr, a Functioning-at-Risk category was shown. Not Functioning categories were assigned to curves that predicted above 0.5 ft/yr. This curve was only used as a guide, however, as some curves deviate from this range based on the slope of the curve and its relationship to other curves. Again, these classifications can be modified based on locally generated curves and their comparison to reference reach data.

3. Lateral Erosion (Bank Profile)

Bank profiles provide an actual measurement of erosion in feet/year. Therefore, performance standards can be created based on those measurements as long as several years of data are available that represent varying weather conditions, including bankfull events. The performance standards should be developed from reference streams for the Functioning category, moderately eroding streambanks for Functioning-at-Risk, and highly eroding for Not Functioning. These values are then compared to the erosion rates from project streams, providing an estimate of functional capacity. Typical values for Functioning, Functioning-at-Risk and Not Functioning are provided in Table 8.7. These values are based on the Colorado erosion rate curve shown in Figure 8.12 and data collected by the

FIGURE 8.12 EROSION RATE CURVES BASED ON BEHI AND NBS SCORES IN COLORADO



Source: Reproduced with permission from Wildland Hydrology

authors in North Carolina streams. They are typical values and can be adjusted based on local site conditions.

It should also be noted that these values came from an assessment of a short length of streambank and are not representative of the overall reach length. Many reference reach streams that would be considered laterally stable will have varying levels of bank erosion. Most of the streambanks will be stable with erosion rates similar to what is shown in Table 8.7; however, there may be short sections that have higher erosion rates. If the erosion is localized and will not lead to further instability or reach wide instability, the overall reach should still be considered Functioning.

4. Lateral Erosion (Cross Sections)

Cross-sectional data can give a broader perspective of functionality than the bank profiles, and they are often used together to assess lateral erosion and instability. Cross-sectional data can be used to calculate bankfull cross sectional, area, width and mean depth. From these data, the bankfull width/depth ratio can be calculated as the bankfull width divided by mean depth (W/D). Increases in the W/D ratio are often associated with accelerated bank erosion rates and bed aggradation (Rosgen, 2006). This information is not provided by the bank profile. Rosgen (2009) developed a comparison of project W/D ratios to reference reach W/Dref by simply dividing the W/D by the W/Dref. As the ratio increases, the risk of bank erosion and bed aggradation increases. These values are shown below in Table 8.7 and are used to determine functionality. The values are most applicable to C stream types in Western states. In the Southeastern US, the values can likely be increased slightly because most streams in alluvial valleys are E stream types. It will take bigger changes in the W/D before bank erosion leads to aggradation.

5. Bank Stability and Toe Erosion Model

Simon and Langendoen's (2006) model calculates a Factor of Safety (Fs) value to determine the lateral stability of a bank. The Factor of Safety can be used to establish the functionality for the bank; however, the previous comments still apply. The overall reach should be assessed to determine if the bank erosion is simply a localized problem or symptomatic of a larger, system-wide problem.

TABLE 8.7 LATERAL STABILITY PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Meander Width Ratio for C and E stream types	≥ 3.5 (based on reference reach surveys)	3.0 to 3.5 as long as sinuosity is ≥ 1.2	< than 3.0
Lateral Erosion rate – Low BEHI Curve	Very low to Moderate NBS	Moderate to Very High NBS	Extreme NBS
Lateral Erosion rate – Moderate BEHI Curve	Very low to Low NBS	Low to High NBS	High to Extreme NBS
Lateral Erosion rate – High and Very High BEHI Curve	N/A	Low to Moderate NBS	Moderate to Extreme NBS
Lateral Erosion rate – Extreme BEHI Curve	N/A	Low NBS	Low to Extreme NBS
Lateral Erosion Rate (Bank Pins and Bank Profiles)	Erosion rate is similar to reference reach values, generally < 0.1 ft/yr	0.1 to 0.5 ft/yr	> 0.5 ft/yr
Lateral Erosion Rate Potential for C4 streams (W/Dproj / W/Dref*	1.0 to 1.2	1.2 to 1.4	= > 1.4
Bank Stability and Toe Erosion Model	Fs > 1.3	1.0 < Fs > 1.3	Fs < 1.0

* *W/Dproj = Bankfull width divided by bankfull mean depth from the project reach*
W/Dref = Bankfull width divided by bankfull mean depth from the reference reach

8.6 » PARAMETER: RIPARIAN VEGETATION

Description

The lateral migration parameters discussed above primarily focus on maintaining streambank stability and do not evaluate the overall condition of the riparian buffer. The BEHI/NBS method for predicting streambank erosion, for example, does include assessments of streambank vegetation, but is only for the purpose of providing bank stability. Riparian buffers or zones are the vegetated region adjacent to streams and wetlands that are critical to providing channel stability, cover/shade, wood recruitment to the channel, and a source of carbon (Sweeney, 1993; Hession et al., 2000; Sweeney et al., 2004; Hoffman, 2006; Sweeney and Blaine, 2007). Therefore, the restoration of riparian vegetation as part of a Level–3 assessment and design approach provides the vegetative structure to support many of the Level 3, 4 and 5 functions.

Research has shown that a well-managed restored buffer can trap and/or convert up to 75% of nitrogen and 70% of phosphorus from nonpoint source runoff, if the source is from land uses that are adjacent to the stream corridor (Orzetti et al., 2010; Claussen et al., 2000; Lee et al., 2003; Schoonover and Williard, 2005). Additional research has shown 50% to 80% reductions in sediment loads from adjacent nonpoint source pollution (Orzetti et al., 2010; Cooper et al., 1987; Daniels and Gilliam, 1996; Lowrance and Sheridan, 2005; Schoonover and Williard, 2005; Tomer et al., 2007). Orzetti et al. (2010) went on to show that habitat, water quality and benthic macroinvertebrate parameters improved with the age of the restored buffer. In their study of 30 streams in the Piedmont of Maryland and Virginia, habitat scores (measured using EPA Rapid Bioassessment Protocols) stabilized between 10 and 15 years after restoration. In addition to habitat improvements, the study showed improvements to water quality and macroinvertebrate communities within 5-10 years post-restoration, leading to conditions similar to mature buffers within 10-15 years post-restoration. Mayer et al. (2005) provides a broader review of the science and regulation of riparian buffers. This literature review focused primarily on research related to nitrogen removal by riparian buffers. The study found that buffers greater than 150 feet wide more consistently removed significant portions of nitrogen entering the riparian zone. The study also found that in order to maintain buffer effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation and stream incision. Stream incision is a key point because a lot of the dentrification occurs through subsurface flow interacting with the root zone of the buffer. If the stream becomes incised and the water table drops, the subsurface flow essentially bypasses the buffer, not allowing dentrification to occur. The assessment of stream incision is part of the Level 2 assessment of Hydraulic functions and the floodplain connectivity parameter.

It is important to note that buffer composition, density and function vary across the country based on climatic and geologic differences. Many of the studies listed above focus on hardwood forests in the Eastern US; however, bottomland hardwoods would not be expected in prairie lands of the Great Plains and Midwest, or arid areas of the Southwest. Reference reach analyses should be completed to determine the functional capacity for a given region. Nevertheless, riparian buffers are important for providing channel stability and supporting Level 4 and 5 functions, regardless of their setting.

For stream assessments and restoration projects, it is also important to identify the potential impacts from land use and other stressors that may exist within and surrounding the riparian buffer area. Watershed disturbances, including livestock grazing, agriculture and urbanization may have affected the soils and hydrology of the buffer and may continue to be a challenge after restoration. Soil compaction and loss of soil fertility can hinder riparian vegetation establishment and growth along with lowered water table elevations. Land disturbance activities also increase the potential for invasive species populations to affect the native vegetation and limit the riparian buffer function. Herbivory and beaver activities can also add pressure on riparian vegetation during establishment and growth in certain watersheds. Although impacts and stressors may be difficult to control outside the buffer area, stream restoration design should always consider these

factors when selecting vegetative species, specifying methods to improve soil conditions and by attempting to reconnect the groundwater table to the riparian buffer root zone. Vegetation maintenance plans are desirable that address these impacts and stressors for the estimated duration of buffer function development.

Overall benefits provided by riparian buffers include:

1. Shade cover, which reduces both air and water temperature fluctuations due to sun exposure within the riparian zone (Barton et al., 1985);
2. Organic matter contributions, including leaf litter that supports macrobenthos food webs and woody debris that creates more diverse bed form and additional organic matter (Dolloff and Warren 2003, Quinn et al., 2007, Opperman et al., 2004);
3. Dissipation of energy and capturing of sediment from upslope overland flow and floodwater (Magette et al., 1989);
4. Nutrient uptake by roots of the riparian vegetation from groundwater moving downslope, acting as a sink to limit what reaches the stream (Lowrance et al., 1984);
5. Stabilization of the streambank by roots that extend throughout the bank (Wynn et al., 2004); and
6. Landscape connectivity for animals traveling along the stream corridor, connecting patches of riparian habitats across the landscape (Fisher et al., 1998).

These are just some of the key benefits that a functioning riparian zone provides; more details can be found in Knight and Bottorff (1984), and Naiman and Decamps (1997).

Measurement Method

Riparian buffers are often assessed by measuring the width, vegetation density, vegetation composition, age-class distribution, and growth and canopy density. Air and water temperature may also be included as a method for assessing buffer functionality, but these measurements are made as part of the Physicochemical assessment (Level 4). Methods for measuring each of these parameters are described below. In addition, rapid methods called the Proper Functioning Condition (PFC), EPA Rapid Bioassessment Protocol (RBP), NRCS Rapid Visual Assessment Protocol (RVAP), and USFWS Stream Assessment Ranking (SAR) are described that can be used to determine the overall functionality of the riparian corridor.

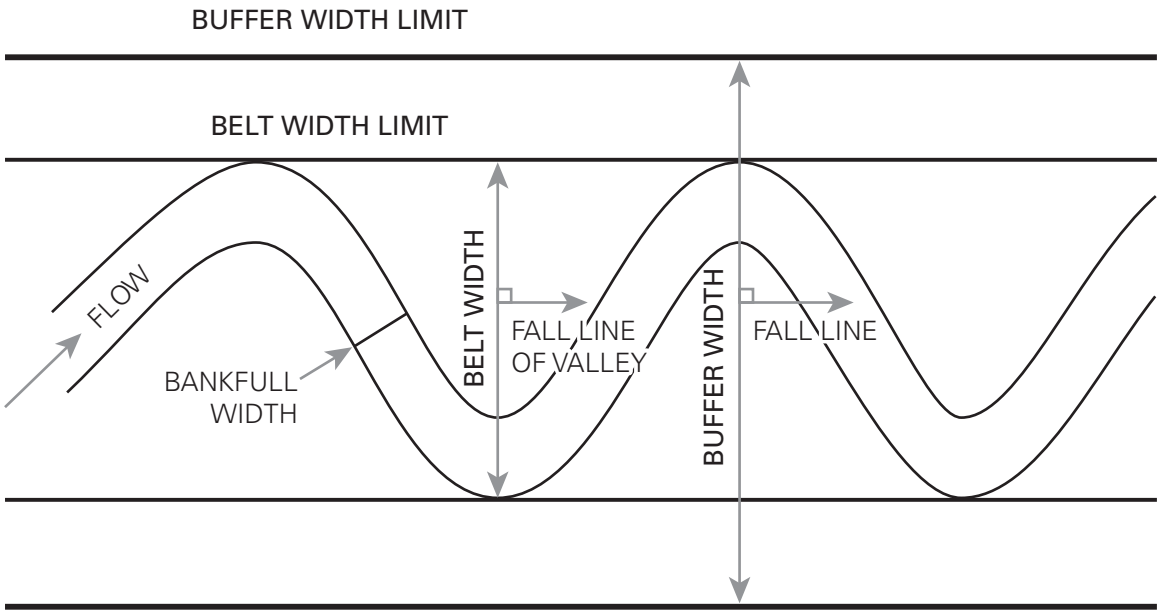
1. Buffer Width

Buffer width is measured from the top of the streambank (bankfull for restored reaches), perpendicular to the fall line of the valley and moving away from the channel. Buffer width is sometimes expressed as an average width or a minimum width. An average width is often used in meandering streams to keep the riparian corridor relatively straight. The average width includes shorter distances at the meander bends and longer distances from the point bar. Each measurement is added together and divided by the total to get the average. The minimum width approach creates a buffer that meanders

with the channel and can be a challenge for establishing conservation easements or fencing requirements.

An alternative approach for meandering streams is to measure the buffer width from the belt width, rather than the top of the bank. The belt width is the distance from one meander bend to the next, measured perpendicular to the fall line of the valley. In this case, a best-fit belt width would be used to establish a straight corridor. The riparian buffer width would be added to the belt width (Figure 8.13).

FIGURE 8.13 BUFFER WIDTH MEASURED FROM BELT WIDTH



NOTE
The buffer width limit is established as a parallel line to the belt width.
The minimum belt width is 3.5 times the bankfull width.
The minimum width from the belt width limit to the buffer width limit is 15 feet.

2. Buffer Density

Buffer density is defined as the number of stems per unit area, e.g., stems/acre. Density is typically measured by establishing rectangular monitoring plots within the riparian corridor. The total area of the plots should be statistically representative of the entire buffer and should be well distributed throughout the buffer. Plots are surveyed annually and include the total number of trees (stems) within the plot. The level of effort varies from moderate to intensive depending on how the results are used. If the results are

compared to a reference condition so that additional measurements are not required, the level of effort is moderate. If measurements are made annually and compared against each other, then the level of effort is intensive (Appendix Ac).

3. Buffer Composition

In conjunction with determining the planted stems surviving year to year, the same plot should be used to determine how species change within the plot. All trees that begin growing in the plot should be identified and counted each year. A size should be determined above which the volunteer stems will be counted, in order to avoid the many individuals that can start each year but will die before the next sample period. This data should be expressed as total stems per area, percent planted and percent volunteer. This data should also indicate if undesirable species are developing, such as exotic species. Exotic species should be removed and not allowed to continue growing until the next growing season. Like buffer density, the level of effort varies from moderate to intensive depending on how the results are used. If the results are compared to a reference condition so that additional measurements are not required, the level of effort is moderate. If measurements are made annually and compared against each other, then the level of effort is intensive (Appendix Ac).

4. Buffer Age

The age-class distribution of vegetative cover should be evaluated to determine the opportunity for recruitment, maintenance and recovery following flooding or other disturbance. A diverse age-class distribution may also limit invasive species establishment and their ability to out-compete native species. This distribution is particularly important for shrub and tree species. Although recently established riparian buffers associated with restoration projects will have minimal age-class distributions initially, the riparian buffer should develop this characteristic over time to more resemble a reference condition for the particular vegetative species established. The age of vegetative cover can be recorded within similar monitoring plots used to determine buffer density and species composition. Buffer age and growth (below) are almost always measured periodically (typically annually) and compared to previous measurements. Therefore, the level of effort is intensive (Appendix Ac).

5. Buffer Growth

Buffer growth can be sampled by measuring stem diameter and height using the methods of Lee et al. (2008). For stems less than 1.37 m in height, measure height (in cm) and ddh (diameter at one decimeter height above the ground) to the nearest mm of the thickest stem. For stems between 1.37 and 2.5 m in height, ddh and height are measured as above, and stem DBH (Diameter at Breast Height or 1.37 m above the ground) is also measured. For stems in excess of 2.5 m in height, DBH and height are measured, but not ddh. These measurements can be used to express the basal area of woody stems that are maturing within the riparian zone.

6. Canopy Density

The angular canopy density, which is an index of cover or shading by the foliage of riparian trees, can be measured using a densiometer. The densiometer consists of a convex mirror divided into grids that allows a visual estimate of the percent of the stream or soil shaded by surrounding vegetation. The canopy density should be taken at the same location and same height above ground each year, and multiple sample locations should be used to provide an estimate of the entire restored riparian zone. The density of the canopy should become greater each year, after about year five when trees begin to get large enough to shade the stream and riparian zone. The level of effort varies from moderate to intensive depending on how the results are used. If the results are compared to a reference condition so that additional measurements are not required, the level of effort is moderate. If measurements are made annually and compared against each other, then the level of effort is intensive (Appendix Ac).

7. Proper Functioning Condition (PFC)

The Bureau of Land Management, with the assistance of other federal agencies, developed a quantitative rapid assessment method for evaluating proper functioning condition for lotic areas. The document was prepared by Prichard et al. (1998) and is available online at *ftp.blm.gov/pub/nstc/techrefs/Final1737-15.pdf*. Proper Functioning Condition (PFC) is both an assessment methodology and a condition that describes riparian-wetland areas. As an assessment methodology, PFC evaluates hydrology, vegetation and erosion/deposition processes. A checklist is used to assess these functions and to determine the overall health of the streambanks and riparian-wetland area. Therefore, PFC can be used to assess lateral stability (Geomorphology functions), as well as the overall health of the riparian corridor (Biology functions). As a condition, PFC describes how well the physical processes are functioning in order to provide stability and habitat. A stream corridor that is in a Proper Functioning Condition will remain stable during high flow events. This resiliency allows an area to produce desired conditions over time, such as fish habitat, neo-tropical bird habitat or forage. Riparian-wetland areas that are not functioning properly cannot sustain these conditions.

PFC is less quantitative than bank profiles, cross sections or the bank stability toe erosion model. However, it is the only method described here that assesses the stream channel and the riparian buffer to determine bank stability. As such, it is more than a bank stability assessment. According to the manual, a riparian-wetland area is functioning properly when there is adequate vegetation, landforms or woody debris to:

- Dissipate stream energy associated with high flows;
- Filter sediment, capture bedload and aid in floodplain development;
- Improve floodwater retention and groundwater recharge;
- Develop root masses that stabilize streambanks;
- Develop diverse channel characteristics to provide habitat; and
- Support greater biodiversity.

8. NRCS Rapid Visual Assessment Protocol

The NRCS Stream Visual Assessment Protocol (SVAP) is another rapid assessment method that includes the riparian zone as a variable in an overall stream health evaluation. This protocol can be found at *www.nrcs.usda.gov/technical/ecs/aquatic/svapfnl.pdf*. The SVAP riparian zone assessment is based on the natural vegetation width, its function as a surface flow filter and its potential for vegetative regeneration.

9. The EPA Rapid Bioassessment Protocol (RBP)

The EPA Rapid Bioassessment Protocol (RBP, Barbour et al., 1999) includes riparian areas as part of Habitat Assessment and Physicochemical Parameters (Chapter 5 of the RBP manual). This method includes an index for rating natural vegetation buffer function based on buffer width on each side of the stream, and based on human impacts to the buffer function (Barton et al., 1985).

10. USFWS Stream Assessment Ranking (SAR)

The USFWS Stream Assessment Ranking (SAR) is a component of the US 301 Environmental Stewardship Study, which is a green infrastructure study. The stream assessment component consists of a GIS-based stream stability assessment method and a rapid stream habitat and stability assessment method. It also includes restoration feasibility protocols. The rapid assessment protocols have both office and field components. The office component requires the use of a regional curve to determine bankfull channel width, depth, and cross-sectional area based on the drainage area of the proposed project site. This information is required for the field assessment portion of the protocol since several of the assessment parameters evaluate bankfull channel conditions. The field component of the protocol contains four sections: stream stability assessment; restoration potential, cost and feasibility; existing riparian/instream habitat assessment; and proposed riparian/instream habitat assessment. The stream stability assessment section consists of four parts: lateral stability, vertical stability, stability trend and stream classification. The parameters of the restoration potential, cost and feasibility include construction access, constraints, potential success/risk, and restoration potential description. The existing and proposed riparian/instream habitat assessments consist of the same assessment parameters to allow for comparison between the existing site condition and the proposed site condition, based on the potential restoration solution. The parameters of the riparian/instream habitat assessment include instream cover, epifaunal substrate, velocity/depth regimes, shading, water appearance, nutrient enrichment, riparian vegetation, riparian zone, and sediment supply potential.

11. Watershed Assessment of River Stability and Sediment Supply (WARSSS)

The Rosgen (2009) Watershed Assessment of River Stability and Sediment Supply (WARSSS) includes assessment of riparian vegetation in the Prediction Level Assessment (PLA) Index as part of its overall channel stability analysis procedure. The existing riparian vegetation composition and density along the impacted reach is compared to the

potential vegetation that would be present along a reference reach. The riparian buffer species composition and density are used to interpret the potential for streambank erosion and channel instability. The assessment is a qualitative description recorded using worksheets (See Worksheet 14 and 15, *water.epa.gov/scitech/datait/tools/warsss/pla_box07.cfm*) and should be performed by a trained biologist. There are no performance standards developed for this assessment at this time.

Performance Standard

1. Buffer Width

There are several performance standards established for buffer width measurements. Two standards are listed in Table 8.8. The average width performance standard for C and E stream types is based on the literature review by Mayer et al. (2005). This research primarily focuses on the effects of buffer width and other parameters on reducing nitrogen. The results showed that while some buffers with widths less than 45 feet did remove nitrogen, buffers that were wider than 150 feet more consistently removed nitrogen. The results also showed that, in general, buffers were effective as nitrogen filters with widths between 30 and 150 feet. Buffer widths for A and B stream types can probably be narrower given that their valleys are narrower; however, the literature does not provide recommendations on buffer widths for these stream types. The second standard is the buffer width to meander belt width as shown in Figure 8.13. This is a new approach that is being introduced in this document for those who want to create a straight riparian corridor with easy to manage conservation easements (if required). A minimum meander width ratio of 3.5 is used because this is typically the minimum average value required to yield a sinuosity of 1.2, the break between meandering and non-meandering streams. The additional 15 feet has more to do with constructability issues for restoration projects that include excavated floodplains. This width and the meander width ratio can be increased if necessary to meet other project goals; however, they should not be decreased to meet a Functioning performance standard.

2. Buffer Density, Composition, Age, Growth and Canopy Density

Other measurement parameters, including buffer density, species composition, age-class distribution, growth, and canopy density do not have published performance standards established at this time. A suitable reference reach from the same region and at the same successional stage, however, can be used to compare riparian buffer function. Performance decisions should be made by a trained biologist or botanist with experience in the region. For this framework, a Functioning riparian buffer would have a measurement method result similar to the reference reach. A Functioning-at-Risk would have a measurement method result that is not functioning at the level of the reference buffer, but has existing potential for this to occur over time or with minimal additional maintenance. Maintenance may include additional plantings, soil amendment or invasive species control. Not Functioning would designate a riparian buffer that does not resemble the reference buffer and that does not have reasonable potential to develop riparian function

over time without significant restoration efforts. These buffers may have limited establishment of intended vegetative species due to environmental conditions (drought, poor soils, disease or flooding) occurring after planting, or they may be inundated with invasive species encroaching from the surrounding landscape. A Not Functioning buffer determined by reference reach parameters may need to be completely re-established with more frequent maintenance to function properly.

3. Rapid Assessment Methods

The rapid assessment methods described above all have associated performance standards with the exception of the WARSSS method. The performance standards have been recategorized as Functioning, Functioning-at-Risk or Not Functioning. The Proper Functioning Condition (PFC) method components for Functioning are listed above in an order relative to how processes work to achieve a proper Functioning condition. If the riparian-wetland is not in PFC, it is placed into one of three categories (two for this document: Functioning-at-Risk and Not Functioning). The PFC manual uses the term Functional-at-Risk, which is defined as being functional but with an existing soil, water or vegetation attribute that makes them susceptible to impairment. Nonfunctional or Not Functioning means that the riparian-wetland area clearly does not provide adequate vegetation, landform or woody debris to dissipate stream energy associated with high flows, and thus is not reducing erosion or improving water quality. The PFC manual adds a third category, called Unknown, which means that the riparian-wetland manager lacks sufficient information to make a functional determination.

The NRCS Stream Visual Assessment Protocol (SVAP)score ranges from 1 (Not Functioning) to 10 (Functioning) based on natural vegetation riparian buffer width and coverage. The EPA Rapid Bioassessment Protocol (RBP) index values range from optimal (10) to poor (0) based on riparian buffer widths on each side of the stream. The USFWS Stream Assessment Ranking (SAR) scores each assessment parameter with a numerical range of 1 to 10, with 10 being the best score. Since the assessment protocol has four separate sections, a variety of scoring combinations can be created for ranking purposes. Each of the assessment section scores can be used individually or tallied together for ranking and prioritization purposes.

8.7 » PARAMETER: BED FORM DIVERSITY

Description

Natural streams rarely have flat uniform beds (Knighton, 1998). Instead, the hydraulic and sediment transport processes described above shape the stream bed into myriad forms, depending on channel slope, type of bed material (sand, gravel, cobble, boulder, bedrock) and other factors. These bed forms are symptomatic of local variations in the sediment transport rate and represent vertical fluctuations in the stream bed (Knighton, 1998), dissipating energy and creating habitat diversity. These vertical fluctuations are essentially a form of meandering, but in the vertical direction rather than horizontal (like sinuosity).

TABLE 8.8 RIPARIAN BUFFER PERFORMANCE PARAMETERS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Average Buffer Width (Ft) from Top of Bank C and E Stream Types	> 150 ft	30 to 150 ft	< 30 ft
Buffer Width (Ft) from Meander Belt Width	Meander belt width at least 3.5 times the bankfull width plus ≥ 15 feet from outside meander bend	Meander belt width at least 3.5 times the bankfull width plus 10 to 15 feet from outside meander bend	Meander belt width ≤ 3.5 times the bankfull width and/or ≤ 10 feet from outside meander bend
Buffer Density (Stems/ac) Buffer Composition Buffer Age Buffer Growth Canopy Density	Parameter is similar to reference reach condition, with no additional maintenance required.	Parameter deviates from reference reach condition, limiting function; but the potential exists for full functionality over time or with moderate additional maintenance.	Significantly less functional than reference reach condition; little or no potential to improve without significant restoration efforts
Proper Functioning Condition (PFC)	Proper Functioning Condition	Functional-at-Risk	Nonfunctional
NRCS Stream Visual Assessment Protocol (SVAP)	Natural vegetation extends at least one to two active channel widths on each side; or if less than one width, covers entire floodplain (8-10)	Natural vegetation extends at least one-half to one-third active channel widths on each side, or filtering function moderately compromised (3-5)	Natural vegetation less than a third of the active channel width on each side, or lack of regeneration, or filtering function severely compromised (1)
EPA Rapid Bioassessment Protocol (RBP) Habitat Assessment	Width of riparian zone > 18 meters on each side; human activities have not impacted zone (Optimal, 9-10)	Width of riparian zone 12-18 meters on each side; human activities have impacted zone only minimally (Sub-Optimal, 6-8); width of riparian zone 6-12 meters on each side; human activities have impacted zone a great deal (Marginal, 3-5)	Width of riparian zone <6 meters on each side; little or no riparian vegetation due to human activity (Poor, 0-2)

TABLE 8.8 RIPARIAN BUFFER PERFORMANCE PARAMETERS (CONT.)

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
USFWS Stream Assessment Ranking (SAR)	All three zones of vegetation exist; runoff is primarly sheet flow; hillslopes < 10%; hillslopes >200 ft from stream; ponding or wetland areas and litter or debris jams are well represented.	Only Zone 2 of vegetation is well represented; runoff is equally sheet and concentrated flow (moderate gully and rill erosion); hillslopes 20-40%; hillslopes 50-100 ft from stream; ponding or wetland areas and litter or debris jams are minimally represented.	No zones of vegetation well represented; runoff is primarily concentrated flow (extensive gully and rill erosion); hillslopes >40%; hillslopes <50 ft from stream; ponding or wetland areas and litter or debris jams are not well represented or completely absent.

Numerous classifications of bed form exist, many of which are described in Knighton (1998). At a broad level, bed form diversity can be grouped into three categories: sand bed forms (ripple, dunes and antidunes), gravel/cobble bed forms (riffle, run, pool and glide) and step-pool channels. These different bed forms are important because they provide the environmental conditions that a variety of aquatic organisms need for survival. For example, macroinvertebrates often colonize in riffle habitats and fish tend to stay in pools. Without the diversity of riffles and pools, there is also a loss of diversity in macroinvertebrates and fish. A brief description of each bed form category is described below.

Sand Bed Forms

While gravel bed streams have riffle-pool sequences, with riffles composed of gravel-size particles, sand bed channels are characterized by median bed material sizes less than 2 mm in diameter (Bunte and Abt, 2001). Bed material features called ripples, dunes, planebeds and antidunes characterize the sand bed form. Although sand bed streams technically do not have riffles, the term is often used to describe the crossover reach between pools. ("Riffle" is used in this document as an equivalent to crossover.) The size, stage and variation of sand bed forms are created by changes in unit stream power, as described below. These bed forms are symptomatic of local variations in the sediment transport rate and cause minor to major variations in aggradation and degradation (Gomez, 1991). Sand bed forms can be divided between low-flow regimes and high-flow regimes, with a transitional zone between the two (Figure 8.14).

Ripples occur at low flows where the unit stream power is just high enough to entrain sand size particles. This entrainment creates small wavelets from random sediment accumulations that are triangular in profile, with gentle upstream and steep downstream

slopes. The ripple dimensions are independent of flow depth, and their heights are less than 0.02 meters.

As unit stream power increases, dunes eventually replace ripples. Dunes are the most common type of sand bed form and have a larger height and wavelength than ripples. Unlike ripples, dune height and wavelength are proportional to flow depth. The movement of dunes is the major cause of variability in bedload transport rates in sand bed streams. Dunes are eventually washed out to leave an upper-flow plane bed characterized by intense bedload transport. This plane bed prevents the patterns of erosion and deposition required for dune development. This stage of bed form development is the transitional flow regime between the low-flow features and the high-flow regime features (Knighton, 1998).

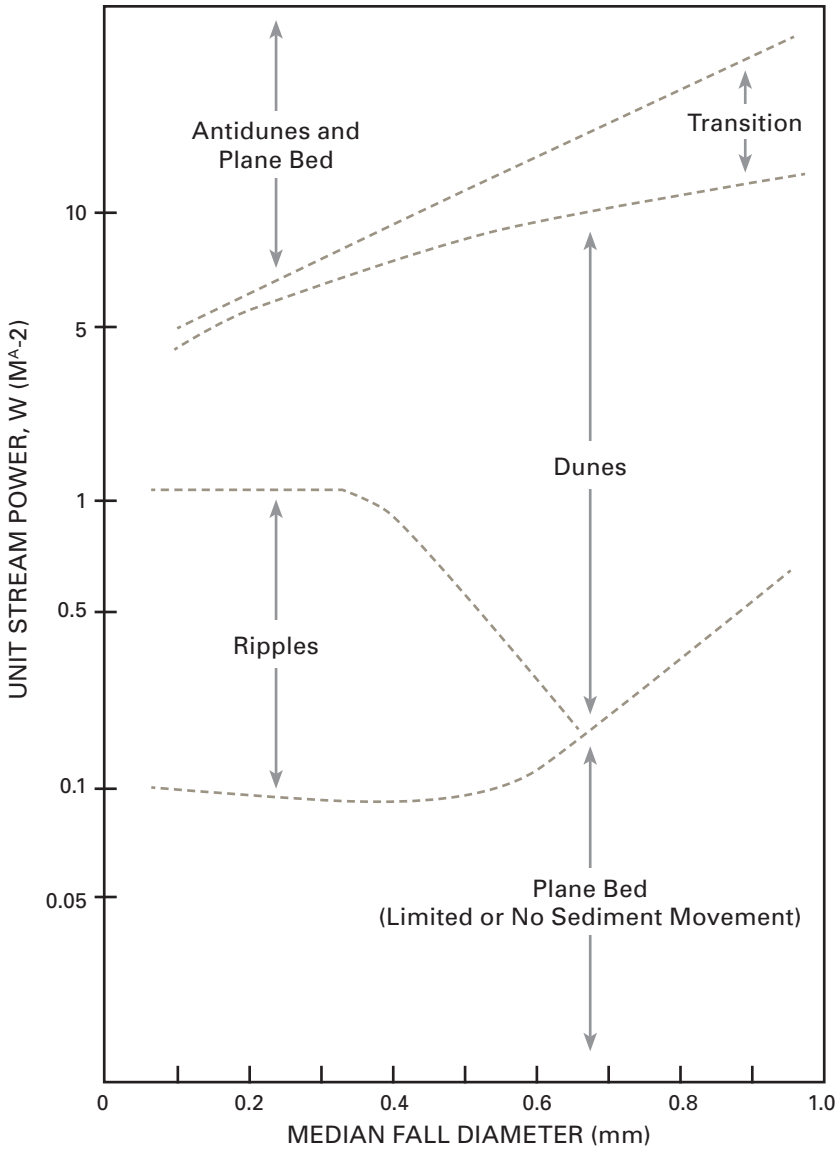
As flow continues to increase, standing waves develop at the water surface, and the bed develops a train of sediment waves (antidunes) that mirror the surface forms. Antidunes migrate upstream by way of scour on the downstream face and deposition on the upstream face, a process that is opposite of ripples and dunes. Antidunes can also move downstream or remain stationary for short periods (Knighton, 1998).

Gravel/Cobble Bed Forms

Meandering gravel bed streams in alluvial valleys have sequences of riffles, runs, pools and glides that help maintain channel slope, bed stability and habitat diversity (Figure 8.15). The riffle is a bed feature composed of gravel or larger-size particles. During low-flow periods, the water depth at a riffle is relatively shallow, and the slope is steeper than the average slope of the channel, so water moves faster over riffles. Riffles control the stream bed elevation and are usually found between meander bends. Runs are a transitional bed form between the riffle and the pool. The pool is located along the outside of a meander bend and is much deeper than the riffle. The slope of the pool is also much flatter than the riffle. Pools can also be found in riffle settings if scour is created by a flow obstruction, like a boulder or large woody debris, further improving the overall diversity. The inside of the meander bend is a depositional feature called a point bar. A glide is the transitional bed form between the pool and the next riffle and is the only bed form that slopes uphill (i.e., if a person was walking through the pool in a downstream direction, he/she would have to walk uphill to reach the next riffle). The glide serves as a spawning area for many species of fish because oxygen is forced up through the sediments, as the water from the deep pool is forced up through the gravel to reach the riffle.

As stage increases, water and sediment transport character changes as they travel over riffles and through pools. At low flows, pools are depositional features, and riffles are scour features. At high flows, the water surface becomes more uniform, i.e., the water surface slope increases at a faster rate over the pools than the riffles. The pools, therefore, have a slope that is similar to the riffle but a much greater depth. This means that the shear stress is greater in the pool than the riffle. With a relative increase in shear stress, pools scour; a decrease in shear stress occurs over the riffle during the falling limb of the hydrograph, causing bed material deposits (Knighton, 1998).

FIGURE 8.14 SAND BED FORMS (after Knighton, 1998)



Source: Adapted from Knighton (1998)

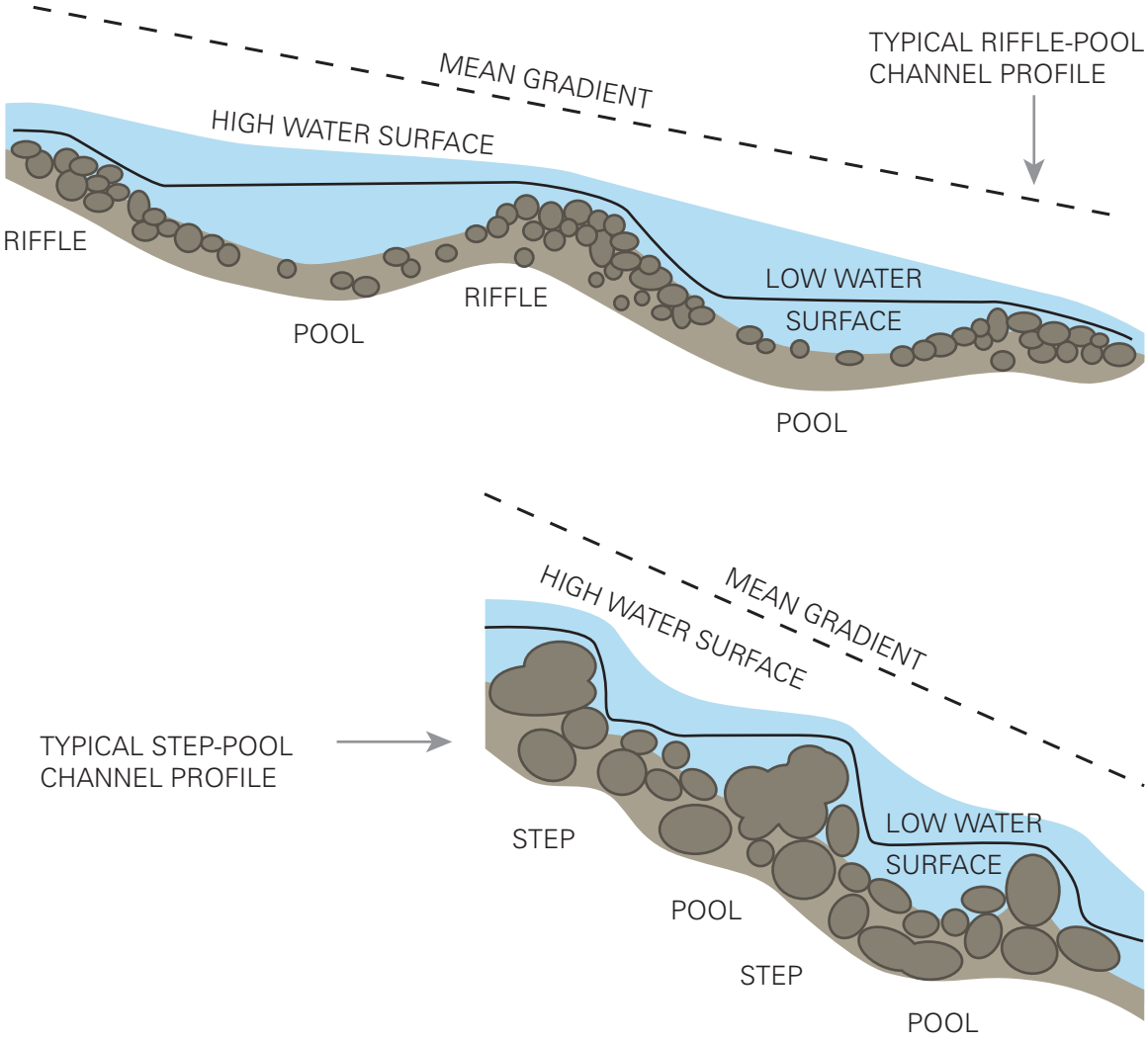
Step-Pool Channels

A step-pool bed profile is characteristic of steep streams formed within colluvial valleys, with valley slopes typically greater than 2% or 3% (Wohl, 2000). Steep mountain streams demonstrate step-pool morphology as a result of episodic sediment transport mechanisms. Because of the high energy associated with the steep channel slope, the substrate in step-pool streams contains significantly larger particles than streams in

flatter alluvial valleys. Steps form from accumulations of boulders and cobbles that span the channel, resulting in a backwater pool upstream and a plunge pool downstream. Smaller particles collect in the interstices of steps, creating stable, interlocking structures (Knighton, 1998). An example is shown in Figure 8.15.

In contrast to meandering streams that dissipate energy through meander bends, step-pool streams dissipate energy through drops and turbulence. Step-pool streams have relatively low sinuosity, and pattern variations commonly result from debris jams, topographic features and bedrock outcrops.

FIGURE 8.15 TYPICAL RIFFLE-POOL AND STEP-POOL PROFILES



Source: Adapted from Knighton (1998)

Measurement Method

Bed form diversity is relatively simple to assess. A longitudinal profile of a stream channel provides detailed information about the bed form and can be used to quantify diversity (Harrelson et al., 1994). Parameters that quantify bed form diversity include: percent riffle and pool, facet slope, pool-to-pool spacing and depth variability. A description of each parameter is provided below.

1. Percent Riffle and Pool

This parameter measures the percentage of riffles and pools for a stream reach. Runs and glides, although important habitat features, are included under the riffle and pool percentage, respectively. The percentages can be determined by comparing the thalweg profile to the water-surface profile, and measuring the length of the feature from the stationing. This approach requires a moderate level of effort and complexity because a profile must be surveyed to collect the data. A rapid approach can be used where the feature lengths are simply measured using a tape, rather than taken from the profile (Appendix Ac). The facet length (riffle or pool) is then divided by the total reach length to calculate the percentage.

Riffles are identified on the profile as the sections of channel that are steeper than the average channel slope. The water surface over the riffle should also be steeper than the average slope. Beware of channel blockages, such as beaver dams, that create flat water-surface slopes (backwater) over previously established riffles. An example is shown at station 760 on the profile in Figure 8.16. The upstream riffles have been "drowned out" to station 550 and are now classified as a pool.

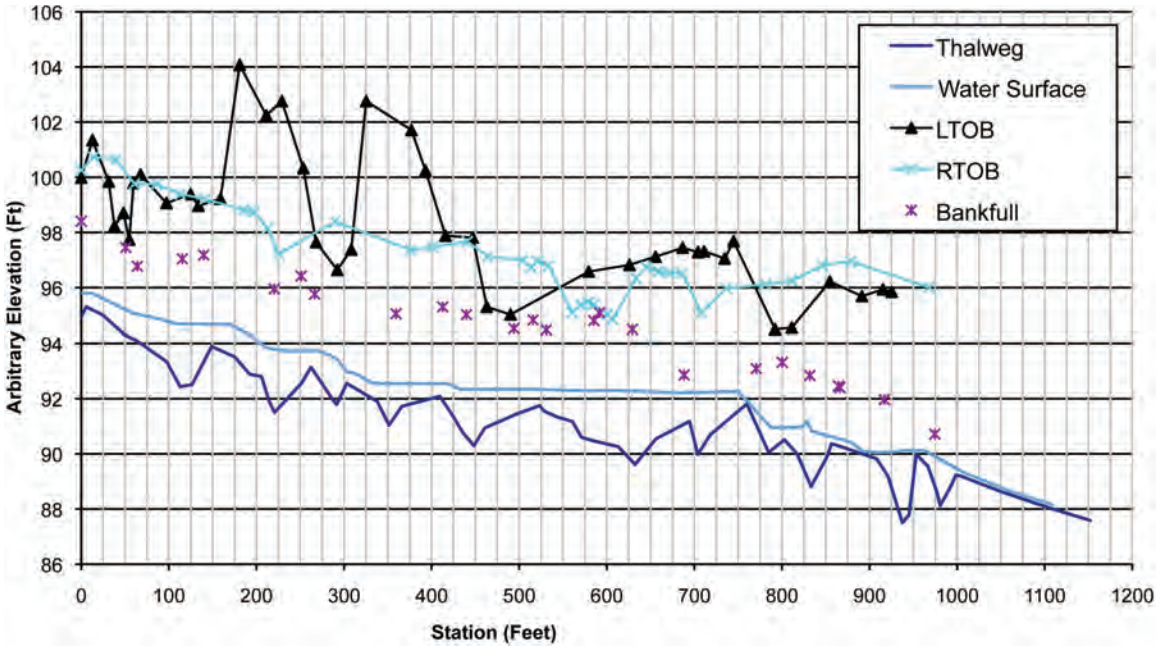
After the riffles and pools have been identified on the longitudinal profile, they can be plotted on the plan view as shown of Figure 8.17. The location of the riffles and pools can now be compared with the meander geometry. Ideally for C and E stream types, the pools will be located at meander bends, and the riffles will be between meander bends. Figure 8.17 shows a riffle at station 2+00, which is the outside of an eroding meander bend. The erosion is partly caused by the steep slope and, therefore, high shear stress associated with the riffle. Pools that are located in meander bends help dissipate energy by having a lower slope, among other things, such as a greater cross-sectional area and depth.

Figures 8.16 and 8.17 show that overall the stream reach has 43% riffle and 57% pool bed forms. Rosgen C and E reference reach streams in the Southeastern US generally have riffle-pool percentages from 60:40 to 80:20, so more riffle bed form than pool. In this example, the bed form is predominately pool because of the beaver dam. The riffles that are present are in unstable locations (meander bend) or very short; the longest riffle is near the end of the reach. The determination of whether a bed form was a riffle or pool was made from an analysis of the bed and water-surface profile (Figure 8.17).

2. Facet Slope

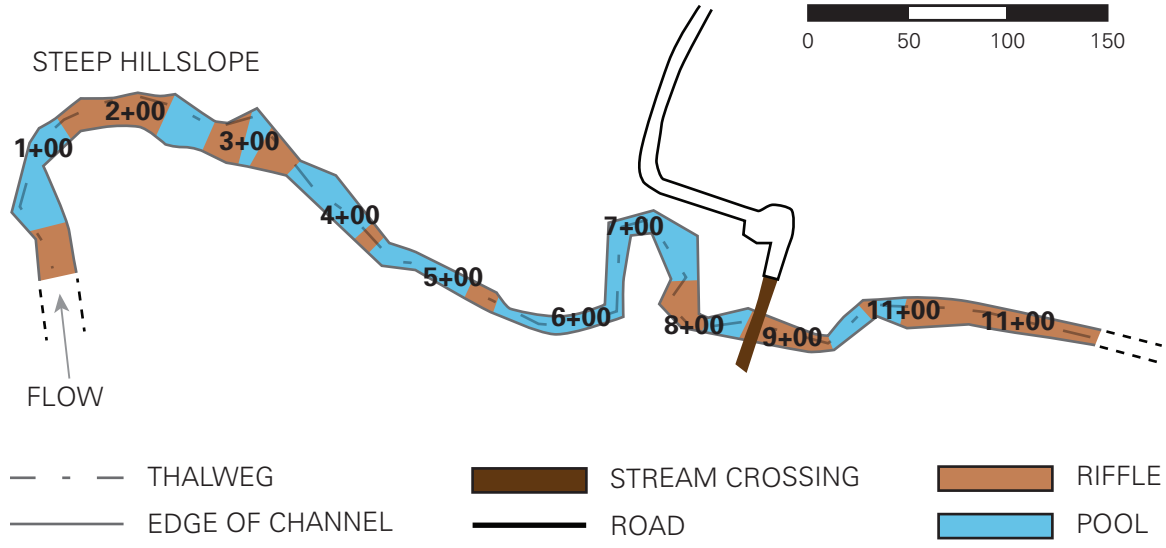
Facet or feature slopes help to identify riffles and pools as described above. In addition, facet slopes can be used to measure the quality and stability of the bed form, e.g., steep

FIGURE 8.16 EXISTING (PRE-RESTORATION) LONGITUDINAL PROFILE SHOWING THALWEG, WATER SURFACE, BANKFULL STAGE, LEFT TOP OF BANK (LTOB) AND RIGHT TOP OF BANK (RTOB)



Source: Adapted from original graph by Michael Baker Corporation

FIGURE 8.17 PLAN VIEW MAP SHOWING RIFFLES IN BROWN AND POOLS IN BLUE



Source: Adapted from original graph by Michael Baker Corporation

riffles are often comprised of coarser bed material because the finer sediments are transported downstream. However, if the riffle gets too steep, larger particles will be transported and the riffle could degrade. Riffle slope stability can be assessed with competency equations by comparing the riffle slope ratio to reference reach ratios. The riffle slope ratio is the riffle slope divided by the average channel slope (Rosgen, 2009). Pool slopes are also important descriptors of quality and stability and should be much flatter than the overall water surface slope to minimize erosional forces acting on the outside bank. However, if the pool slope is zero, the pool does tend to fill and stagnate at low-flow stages.

3. Pool-to-Pool Spacing

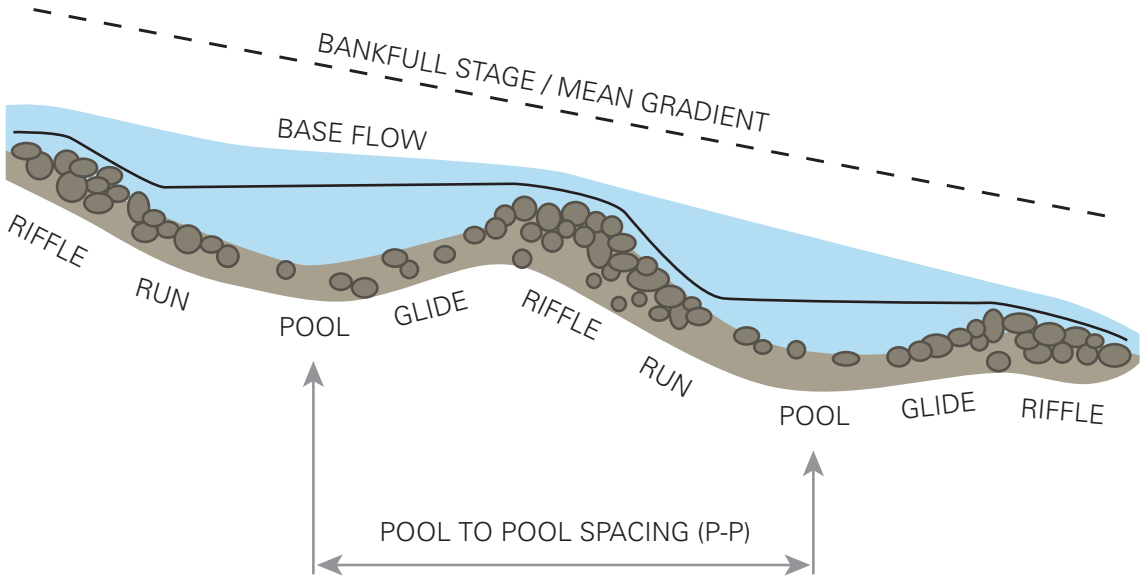
Pool-to-pool spacing measures the frequency of pools in the stream reach and is the distance measured along the stream centerline or thalweg, between the deepest point of two pools. It is most often measured from the longitudinal profile; however, it can be estimated rapidly by simply using a tape. A rapid approach may be used by regulatory agencies to estimate the pool-to-pool spacing of a restored reach. The value is often converted into a dimensionless ratio by dividing the result by the bankfull riffle width. Dimensionless ratios can then be compared to known reference reach ratios of the same channel type to determine if the spacing is within the normal range.

For C and E stream types, stability problems often occur when the pool-to-pool spacing becomes too low. Monitoring studies in North Carolina showed that severe bank erosion occurred when the pool-to-pool spacing ratio was less than 3.0 to 3.5. In these cases, erosion was observed from the outside meander bend to the downstream point bar. For streams in colluvial valleys (B stream type), it is the opposite. Generally, closer pool-to-pool spacing leads to more stable and diverse bed forms. Pool-to-pool spacing ratios greater than 5 often have minor to major headcut problems, especially in areas where the channel was reconstructed (Harman and Starr, 2008). (See Figure 8.18.)

4. Depth Variability

Depth variability can be assessed by measuring the bankfull pool depth at each pool along the stream reach, and then dividing these depths by a representative mean riffle bankfull depth. For this assessment, the pool depths can be measured from the longitudinal profile. The bankfull riffle mean depth can be measured at a representative riffle cross section. The mean depth is then calculated as the cross-sectional area divided by the bankfull width. This dimensionless ratio is referred to as the Pool Max Depth Ratio (Rosgen, 2009). When looking at a stream reach, the variability between Pool Max Depth Ratios provides information on how the stream is processing sediment. If all the ratios are near the same value, it indicates that the pools are all the same depth and are likely filling with sediment. However, this does vary by geologic setting and stream type. It is most desirable to have a range of Pool Max Depth ratios, as it indicates a wide variety of pool depths and high pool habitat diversity.

FIGURE 8.18 TYPICAL POOL-TO-POOL SPACING MEASUREMENTS



POOL TO POOL SPACING RATIO = pool to pool spacing (P-P)/bankfull riffle width

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Performance Standard

Performance standards for determining whether a stream is Functioning from a bed form diversity standpoint should be considered with stream channel type and expected habitat diversity in mind. In general, it is good to compare what is observed in the field with what is known about stable, reference reach channel conditions.

1. Percent Riffle and Pool

Reference reach streams in alluvial valleys, like C and E stream types, typically have more riffles than pools. It is generally agreed that having more riffles than pools is one important factor to support healthy fish populations; however, it is difficult to find literature that provides guidance on ideal percentages for riffles and pools. In NC, projects that had 60-70% riffle and 30-40% pool seemed to be preferred over streams that were riffle or pool dominated. As the percentage increased to 70-80% riffle, the quality of fish habitat was diminished due to a lack of pool habitat. Streams with greater than 80% riffle often resemble the bed form of a channelized stream.

A stream reach dominated by pool bed forms in C and E stream types also lacks the necessary diversity for varied aquatic species, especially macroinvertebrates. If 60-70% of the reach is riffle (Functioning), then 30-40% of the reach should be pool. As the percentage of pools increase, bed form diversity goes down (Table 8.9). Once the reach exceeds 50% it is unlikely that the bed form diversity is comparable to high-quality C and E

reference reach streams. This can be a problem in older stream restoration projects where cross vanes were installed at the head of the riffle. The intent was to keep the upstream pool slope fairly flat, which it does. However, the cross vane also creates a pool downstream of the structure, which in this case is the riffle. The result is that a scour pool replaces part of the riffle length, and depending on the meander geometry, this can create too much pool length and not enough riffle length. There is very little data in the literature to provide riffle and pool length percentages for B type channels. However, there is information on pool-to-pool spacing and substrate quality, so performance standards are discussed in the following sections.

The percent riffle and pool is the most subjective measurement method provided in this document. If this method is used as a performance method, it should be used in conjunction with another method that better defines bed form complexity, like LWD measurement methods, pool-to-pool spacing ratios or slope ratios.

2. Pool-to-Pool Spacing Ratios

The performance measures for pool-to-pool spacing are shown below in Table 8.9. Separate ratios are shown for watershed drainage areas below and above 10 square miles. Results from past projects show that severe bank erosion occurs when the pool-to-pool spacing ratio is less than 3.0. This problem is related to the MWR problem (discussed under lateral stability) and often occurs when practitioners force a meandering stream into a confined setting. This problem may also show up in the percent riffle-pool measure, e.g., there may be more pool length than riffle length. Projects in drainage areas below 10 square miles tend to be more stable and have better bed form diversity if the pool-to-pool spacing ratio is between 3.5 and 5.0. However, for larger streams, the ratio increases to between 5.0 and 7.0 (Langbein and Leopold, 1966; Gregory et al., 1994). But as the ratio decreases, the same problem can exist in these larger streams.

The spacing of pools is inversely related to slope, i.e., as slope increases, pool-to-pool spacing decreases. Whittaker (1987) and Chin (1989) report an average pool-to-pool spacing of 2 to 3 times the channel width for stream slopes between 3% and 5 %. Grant et al. (1990) reported pool-to-pool spacing of 2 to 4 times the channel width for two Oregon streams. These ranges can be more variable based on the presence of bedrock outcrops and large boulders. The Functioning category shown in Table 8.9 uses a value of less than 4, which is the higher end of the range between these two studies. A minimum number was not provided because a lower spacing typically does not lead to stability problems or a decrease in functionality. As the spacing increases in these moderately steep channels, the risk of bed instability increases and functionality decreases.

3. Depth Variability

Depth variability is assessed by measuring the Pool Max Depth Ratio. Performance measures are shown below for gravel bed C and E streams (C4 and E4) and gravel bed B streams (B4). When the ratio is above 1.5 for B4, C4 and E4 stream types, the pools are typically well formed and Functioning. This ratio is less variable in gravel and cobble bed

These ratios are based on reference reach streams in NC and may need to be adjusted based on local reference reach conditions.

streams than streams with sand beds. Pool depth in sand bed channels (C5 and E5) fluctuate more because the sand is mobilized from the riffle (crossover) sections during lower flows. As a result, the pools may fill in more during low-flow periods and scour during bankfull events. A ratio of 1.2 is used to indicate a Functioning C5 or E5 stream type. Like the C4 and E4 stream types, as the ratio decreases, bed form diversity decreases. These ratios are based on reference reach streams in NC and may need to be adjusted based on local reference reach conditions.

TABLE 8.9 BED FORM DIVERSITY PERFORMANCE PARAMETERS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Perennial Streams in Alluvial Valleys (C, E)			
Percent Riffle	60 to 70	70 to 80 40 to 60	> 80 < 40
Pool-to-Pool Spacing Ratio (Watersheds < 10 mi^2)	4 to 5	3 to 4 and 5 to 7	< 3 and > 7
Pool-to-Pool Spacing Ratio (Watersheds > 10 mi^2)	5-7	3.5-5.0 and 7 to 8	< 3.5 and > 8
Depth Variability – Gravel Bed Streams (Pool Max Depth Ratio)	> 1.5	1.2 to 1.5	< 1.2
Depth Variability – Sand Bed Streams (Pool Max Depth Ratio)	> 1.2	1.1 to 1.2	< 1.1
Moderate Gradient Perennial Streams in Colluvial Valleys			
Pool-to-Pool Spacing Ratio (Slope between 3 and 5%)	0.5 to 4	4 to 6	>6
Depth Variability (Pool Max Depth Ratio)	> 1.5	1.2 to 1.5	< 1.2

8.8 » PARAMETER: BED MATERIAL CHARACTERIZATION

Description

Bed material (substrate) characterization is an important parameter in function-based assessments and stream restoration designs in gravel bed streams. The composition of the stream bed influences the character of the bed forms, sediment transport, macroinvertebrate habitat and fish habitat (Harrelson et al., 1994). The influence of substrate on chan-

nel form and process varies by stream type. For example, large boulders and cobbles create step-pool bed morphology in steep gradient A and B stream types. Gravel bed material creates riffle-pool sequences in lower gradient C and E stream types, and sand bed material creates ripples and dunes in low gradient C, E and DA stream types.

Characterizing the bed material for the purpose of showing functional lift associated with a stream restoration project is most appropriate in gravel bed streams. The goal for these projects is to show that the bed coarsens after restoration; this implies that the stream bed has excessive fine-grained sediments (sand) prior to restoration, which is typically caused by streambank erosion. Restoration techniques are used to minimize streambank erosion and thereby decrease the supply of the fine-grained sediments. Other restoration techniques, like reconnecting the stream to the floodplain and creating the appropriate geometry, can improve sediment transport processes, which may transport the finer-grained material out of the project reach.

An example of this type of project is shown below in Figure 8.19. Prior to restoration, the project reach was channelized and had eroding streambanks that were comprised mostly of sand. Streambanks were also eroding upstream of the project reach. The restoration project created a meandering C/E stream type with a bank height ratio of 1.0 (well connected to the floodplain). The photo was taken during the first year after construction and soon after a winter flood event. Sandy material from upstream bank erosion deposited on the point bar and floodplain; however, the riffle remained coarse and the pool maintained a depth that was much deeper than the riffle.

FIGURE 8.19 SOUTH FORK MITCHELL RIVER, KRAFT STREAM RESTORATION PROJECT

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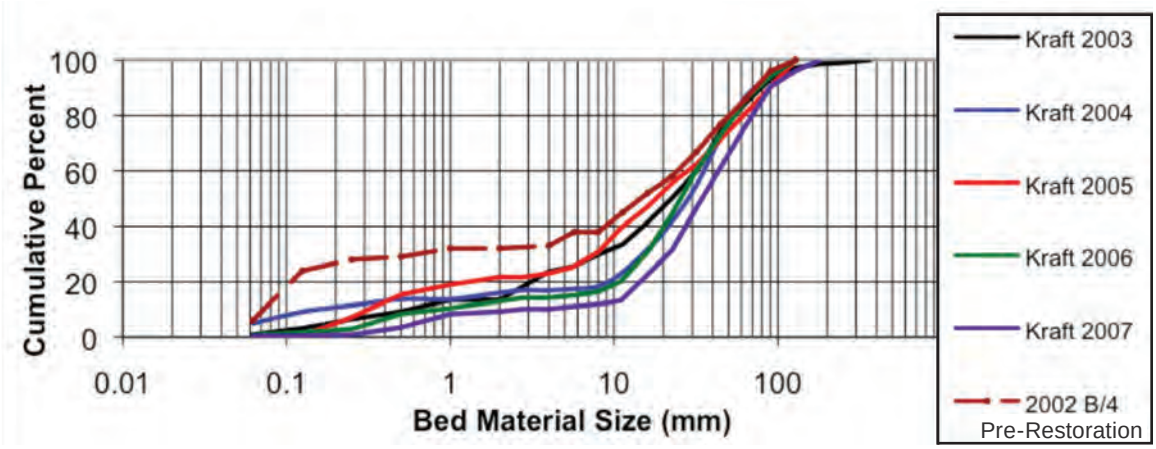
The bed material was characterized before restoration and for five years after restoration. Figure 8.20 shows the grain size distributions prior to restoration and for five years post-restoration. The x-axis is the size class of the bed material samples in millimeters, and the y-axis is the cumulative percent. The median particle size is where 50 on the y-axis intercepts the line. This value is called the D50, meaning that half of the values are larger and half are smaller than this value. The D84 means that 84% of the values are smaller than this value. Figure 8.20 shows that in general, the bed material coarsened after restoration when compared to the 2002 pre-restoration curve. The suite of curves also shows that there was more variability in the finer-grained sediments (less than the D50) than there was in the coarser grained sediments (greater than the D50). This is common because smaller particles are much more mobile than large particles. The curves also show periodic coarsening and fining during the monitoring years. This is shown more clearly in Figure 8.21.

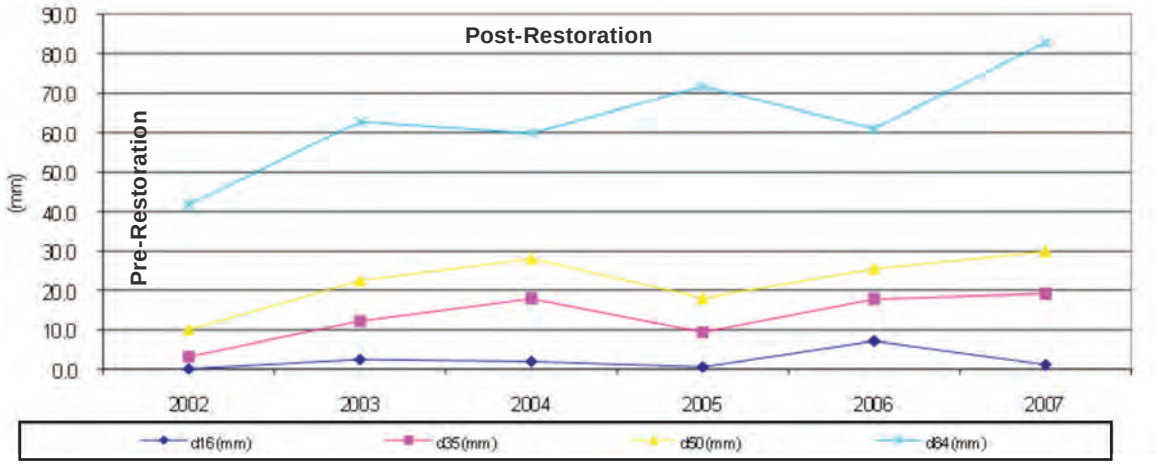
FIGURE 8.20 BED MATERIAL CHARACTERIZATION OF THE KRAFT STREAM RESTORATION PROJECT 2002-2007



Source: Adapted from original graph by Michael Baker Corporation

Figure 8.21 shows how the D16, D35, D50 and D84 change from the pre-restoration condition in 2002 through the last year of monitoring in 2007. The D16, which is a fine sand, changes very little between the monitoring years. This is due to the large amount of sand that is in the channel from upstream bank erosion. This material is easily transported and is mobilized in most storm events. The D35, D50 and D84 all coarsen after restoration with the D35 and D50 changing from sand-size to gravel-size particles. Interestingly, the dip in 2005 occurred during the same year as the remnants from hurricane Francis moved through the area, causing the largest flood of the monitoring period. The bed did shift towards finer-grained sediments that year, but still remained coarser than the pre-restoration condition. The bed material then rebounded in 2006 and was the coarsest of the monitoring period in 2007.

FIGURE 8.21 BED MATERIAL CHARACTERIZATION OF D16, D35, D50 AND D84 PRIOR TO RESTORATION AND FOR FIVE YEARS POST-RESTORATION



Source: Adapted from original graph by Michael Baker Corporation

The point of showing these graphs is to illustrate that under the correct conditions, stream restoration projects can show an improvement (coarsening) due to restoration activities, even if the upstream watershed is not pristine. The best cases for showing improvement are stream reaches that have gravel and cobble in the bed material, but with sandy material being supplied by bank erosion. Projects that are the least likely to show improvement are sand bed streams that do not have gravel and/or cobble sources of bed material.

Measurement Method

The most common method for measuring bed material or substrate is the Wolman (1954) pebble count procedure. The two measurement methods described below use the pebble count method for sampling the bed material. Based on project goals, however, there are many ways that the pebble count procedure can be implemented. Bunte and Abt (2001) provide a comprehensive manual on sampling and analyzing surface and subsurface particles. This manual is available online at *www.stream.fs.fed.us/publications/documentsStream.html*. The level of effort for these two methods is moderate if the values are compared to existing reference reach data sets and can become intensive if the reference data sets need to be developed (Appendix Ac).

1. Size Class Pebble Count Analyzer

Potyondy and Bunte (2007) and Bevenger and King (1995) provide spreadsheet tools and instructions for managing pebble count data. These spreadsheets are useful for stream restoration monitoring projects because they can be used to compare a project reach to a reference reach/watershed. The spreadsheet includes statistical applications

that can be used to determine if select sediment size classes from the project reach are statistically different than the reference reach. (Spreadsheets are available at *www.stream.fs.fed.us/publications/software.html.*)

2. Riffle Stability Index (RSI)

Kappesser (2002) developed a Riffle Stability Index (RSI) to estimate the degree of increased sediment supply to riffles in streams with gradients between 2% and 4%. Kappesser states that the RSI can be used where sediment supply from headwater activities is depositing materials on riffles and filling pools, and reflects qualitative differences between reference watersheds and managed watersheds.

Performance Standard

Performance parameters for substrate distributions are shown below in Table 8.10. The Size Class Pebble Count Analyzer developed by Potyondy and Bunte (2007) and Bevenger and King (2005) can be used in low- and high-gradient channels. Using this method, a Functioning stream is defined as one where select bed material classes are not statistically different than the reference reach or watershed. A Not Functioning stream is where the project stream is statistically finer than the reference reach/watershed. One issue with this method is that there is no guidance or data to suggest an appropriate range for Functioning-at-Risk, so this would need to be determined by the user.

The RSI is recommended for B3 and F3b channels because the method provides scores for Functioning, Functioning-at-Risk and Not Functioning (although the terminology differs). Kappesser (2002) stated that riffles from Idaho and Virginia scoring less than 70 were indicative of watersheds in good condition (Functioning). Values between 70 and 85 indicated watersheds in fair condition (Functioning-at-Risk), and values greater than 85 indicated poor conditions (Not Functioning).

TABLE 8.10 BED MATERIAL CHARACTERIZATION PERFORMANCE PARAMETERS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Size Class Pebble Count Analyzer	Project Reach is not statistically different than reference reach	N/A	Project Reach is statistically different (finer) than reference reach
Riffle Stability Index (RSI) for Rosgen B3 and F3b	< 70	70 to 85	> 85

Chapter 9
Physicochemical

The Physicochemical functions of a stream are determining factors of aquatic ecosystem health. Many lotic organisms are affected by even small changes in water chemistry and habitat. Physicochemical functions include the interaction of physical and chemical processes to create the basic water quality of the stream (including temperature, dissolved oxygen, conductivity, pH and turbidity), as well as to facilitate nutrient and organic carbon processes. The parameters used to describe Physicochemical functions are included in Level 4 of the Pyramid. These parameters provide both direct and indirect indications of stream condition and its ability to support biological communities (Level 5). Understanding what is expected for these parameters in a project stream, based on the reference condition and what the stream actually demonstrates, will provide a comprehensive Physicochemical stream assessment. Determination of the reference condition using data from reference streams that support desired biological communities is important. Before beginning an assessment, a review of Total Maximum Daily Load (TMDL) values determined based on water quality standards, as well as review of specific watershed plans, can determine what Physicochemical constituents are of concern for the stream. These resources can identify what is being measured and what approaches are currently being applied to monitor Physicochemical parameters and to improve water quality.

Measurement of Physicochemical functions also requires an understanding of what influential variables are present that cannot be affected by restoration at the reach scale. These variables include external discharges from upstream, point source and non-point source contributions, and the effects of land-use changes in the watershed. These variables highlight the need for preliminary considerations of site selection and reach length if the goal is to improve stream Physicochemical function. Climate factors will also have a significant effect on Physicochemical functions, but these environmental variables cannot be controlled at any scale. Some of these variables that are beyond the scope of the restoration plan can be differentiated from variables that are controllable through comparisons with upstream, downstream and reference stream conditions. The ability to evaluate the actual effects of stream restoration within a reach with statistical confidence should be considered by performance standards.

Table 9.1 provides a list of the Physicochemical parameters included in this chapter, along with their associated measurement methods and availability of performance standards. Although there are many additional parameters that can determine Physicochemical function, e.g., alkalinity, pollutants and metals; however, those included in this chapter are considered the most common and the most important parameters for assessment and restoration. Appendix Ac includes a list of all the example Physicochemical

measurement methods along with information about the method's type, level of effort, level of complexity, and whether it is a direct or indirect measure of the function-based parameter. The criteria used to make these determinations are provided in Chapter 4.

TABLE 9.1 PHYSICOCHEMICAL PARAMETERS, MEASUREMENT METHODS AND AVAILABILITY OF PERFORMANCE STANDARDS

PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD
Water Quality	1. Temperature 2. Dissolved Oxygen 3. Conductivity 4. pH 5. Turbidity	Yes Yes Yes Yes Yes
Nutrients	1. Field test kits using reagents reactions 2. Laboratory analysis	Yes Yes
Organic Carbon	1. Laboratory analysis	Yes

9.1 » PARAMETER: WATER QUALITY

Description

Temperature

Temperature is a physical property that indicates the relative hotness or coldness of water. Stream temperature can influence several other Physicochemical parameters directly, including dissolved oxygen (DO) concentrations, conductivity and pH (USGS, 2010). As temperature increases, DO held in the water column is reduced based on changes in solubility of gases with temperature. Warm water holds less DO than cold water (Mortimer, 1981). As temperature increases, conductivity increases as more molecules become dissolved and release ions into solution. These ions can also have an effect on pH, which is a measure of hydrogen and hydroxide ions in the water column (Stumm and Morgan, 1996). Biological functions within streams are also affected by temperature, which regulates lifecycles, spatial distribution and metabolism of all trophic levels. Temperature cues control the lifecycles of most stream organisms, signaling activities such as reproduction by microbial communities, emergence by macroinvertebrates, and spawning by fish (Hynes 1970). Stream temperature can be highly variable within a short distance between microhabitats, such as temperature differences between warmer backwater depositional areas and the main channel (Hauer and Hill, 2006). Warmer stream temperatures increase the rate of metabolic processes, such as photosynthesis and respiration, while most aquatic organisms reduce their metabolic processes during colder months (Hynes, 1970). Fishery managers have long recognized the importance of temperature to fish distribution and have separated lotic systems into warm-water streams

and cold-water streams to describe habitat (Moyle and Cech, 1982).

Stream temperatures are influenced by climate, streamflow and depth, sunlight exposure and the riparian canopy. Air temperature above the water surface affects stream temperature through heat transfer. Daily and seasonal stream temperatures fluctuate with air temperatures over the same time period, although the stream has less fluctuation due to the higher latent heat of water (Hauer and Hill, 2006). Precipitation and watershed runoff influence stream temperatures when there is a great enough temperature difference between watershed runoff and streamflow, and when there is a large enough volume of runoff entering streamflow. The same effect occurs with point-source discharges from power plants and industrial processes, and with hyporheic groundwater inputs through the streambed and banks (USEPA, 1997b).

Groundwater tends to be cooler than ambient water temperatures in summer months and warmer in winter months, due to the influences of soil temperature (Smith, 2005). Streamflow can affect temperature through turbulence, mixing surface and subsurface waters for a more even temperature distribution in running water compared to stagnant water. Shallow flow depth in small streams has less variation compared to deeper, larger streams where a temperature gradient can occur between surface and subsurface water (Hynes, 1970). Temperature generally decreases as depth increases due to less sunlight and atmospheric influence (Wetzel, 2001). Exceptions do occur, however, such as when surface water temperatures drop below freezing and act as an insulating layer that keeps deeper waters warm (Hynes, 1970). Sunlight can be the most influential factor for stream temperature, particularly in open waters (Hauer and Hill, 2006). Effects of sunlight are primarily dependent on the presence and relative density of a riparian canopy. A dense, tall canopy will filter more sunlight, diminishing the rise in temperature caused by solar radiation and reducing variability in stream temperatures over time (Allan and Castillo, 2007). Exposure to sunlight is also dependent on geographic latitude and variations throughout the day and the seasons.

Stream temperatures that are significantly different from ambient temperatures measured within reference streams should be regulated to maintain healthy biological communities. Even though temperatures of external flow contributions from watershed runoff and point-source discharges generally cannot be controlled, they should be considered to determine their impact and potential incorporation into a restoration plan. Stream restoration techniques can help regulate temperatures by providing adequate baseflow and flow duration (Level 1), since flowing water is well mixed with less temperature fluctuation. There are several methods that can be used to improve groundwater exchange through the hyporheic zone and streambanks to help regulate temperatures. Floodplain connectivity described in Level 2 will slowly recharge groundwater for a more consistent discharge through the hyporheic zone (Winter et al., 1998). Lateral stream stability, the riparian buffer and the degree of bed form diversity are all Level 3 parameters that can be used to regulate temperature. Creating a stable channel that carries its sediment and water effectively will help maintain consistent baseflow. Riparian buffers and large woody debris (LWD) within the channel can maintain consistent and generally

cooler temperatures over time by providing shade (Figure 9.1). Changes to the stream channel that improve bed form diversity, including deep pools, will help regulate temperatures in various biological habitats.

Ambient water temperatures with less fluctuation occur in lotic systems when the following conditions are present:

- Minimal variability between watershed runoff temperatures and stream temperatures;
- Adequate baseflow to provide mixing to prevent stagnant water;
- Floodplain connectivity to support hyporheic groundwater recharge for more consistent temperatures;
- Established riparian buffer to provide shade to help keep the water cool on hot sunny days and provide thermal regulation with less fluctuation over time; and
- Bed form diversity, as deep pools offer cooler waters for fish habitat, cover features (such as logs, rocks and undercut streambanks) and provide shade for cooler temperatures.

FIGURE 9.1 OVERHANGING VEGETATION PROVIDES SHADE IN NEWLY RESTORED STREAMS

Figure 9.1a Restoration site immediately after construction.

Figure 9.1b Same restoration site seven years after construction with overhanging vegetation that provides shade and reduces temperature variation.

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Dissolved Oxygen

Oxygen dissolved in the water column is required by stream biota to sustain life. The amount of dissolved oxygen (DO) significantly affects biological respiration rates, as well as the solubility of other chemical constituents like inorganic nutrients. In lotic systems, these effects become important in the substrate hyporheic zone where exchange of DO from surface waters to subsurface waters maintains microbial communities and provides habitat for stream biota (Wetzel, 2001).

Oxygen enters the water column primarily through diffusion from the atmosphere. Streamflow creates turbulence, which leads to additional entrainment of oxygen from the atmosphere (USEPA, 1997b). Turbulence is increased by rough channel beds (Hynes,

1970) and structures, such as rocks and large woody debris that rise above the water surface, creating eddies and mixing (Gordon et al., 2004). The water column is considered saturated when DO concentrations are in equilibrium with oxygen in the atmosphere. The amount of DO is also influenced by temperature, altitude and salinity. DO is more soluble in colder water than warmer water. In larger rivers, temperature may play a greater role than diffusion in influencing DO levels, due to smaller surface area relative to volume and less turbulence. Small streams with turbulent flow, however, can maintain DO concentrations near saturation, regardless of daily and seasonal temperature changes (Allan and Castillo, 2007). Streams at higher altitudes generally have higher DO concentrations than those at lower elevations due to differences in atmospheric pressure (USEPA, 1997b); and DO concentrations decline as salinity increases (Wetzel, 2001).

Oxygen is both produced and consumed within the lotic system through biological and chemical processes. Primary producers such as phytoplankton, algae and aquatic plants (macrophytes) release oxygen during photosynthesis, a process that produces organic material using inorganic carbon (CO_2) and energy from sunlight. Aquatic organisms, from microbes to fish, consume oxygen during the process of respiration when they metabolize the organic materials. In larger, slow-moving rivers with ample sunlight exposure, photosynthetic activity can be high enough to elevate DO levels during day while subsiding overnight. Without these biological processes, the effects of daily temperature changes and reduced diffusion rates would cause the opposite trend in rivers (Allan and Castillo, 2007). Dissolved oxygen concentrations can also be affected by availability of dissolved organic matter, whether through direct chemical reactions or through indirect stimulation of microbial respiration (Wetzel, 2001).

In natural streams, there is a balance between the rate of oxygen supply from diffusion, entrainment and photosynthesis, and the rate of oxygen consumption through biological metabolism and abiotic chemical reactions (Wetzel, 2001). This balance ensures that oxygen production is greater than consumption, and sufficient oxygen is available to support life at all trophic levels. Pollutants, such as excess nutrients and organic waste contributed from surface runoff and point-source discharges, can alter this balance and create conditions where more oxygen is consumed. One popular example is the *algal bloom* (when algal production increases as a result of excess nutrient loading), also referred to as eutrophication. Even though algal photosynthesis produces oxygen, microbial respiration rates increase DO consumption to a greater extent during decomposition of the algal biomass and its waste products (Carpenter et al., 1998). Drastic oxygen depletion may occur, causing anaerobic conditions within the water column that harm other organisms, e.g., fish kills (Hynes, 1960).

DO concentrations in impaired streams can be improved through removing sources of excess nutrients and organic pollutants in watershed discharges that influence streamflow. On a reach scale, stream restoration techniques can improve DO concentrations using channel modifications that enhance flow dynamics described in Level 2. Narrowing a channel that has been over-widened and increasing channel slope can maintain baseflows for better oxygen diffusion rates. Removal of stream impoundments, such as dams,

will restore flowing water and prevent the increase in temperature that occurs behind the obstruction. In-stream structures used to improve Geomorphology function can increase streamflow turbulence, including boulder clusters and cross vanes (Fischenich and Seal, 1999). (See Figure 9.2.) Riparian buffer establishment will indirectly improve DO concentrations by reducing stream temperature through shading.

Higher concentrations of DO occur in stream systems when the following conditions are present:

- Excess nutrient and organic pollutant loads are controlled, maintaining a balanced biological system in which respiration does not consume more dissolved oxygen than is produced;
- Flowing water, which contains more oxygen than stagnant water through entrainment and mixing;
- In-stream structures, breaking the water surface to create turbulence and mixing; and
- Established riparian buffer, which provides shade for cooler water temperatures to increase the solubility of oxygen in the water column.

FIGURE 9.2 FLOW TURBULENCE CREATED FROM ROCK CROSS VANE STRUCTURE

Source: Reproduced with permission from Michael Baker Corporation

Conductivity

Conductivity is the measure of water's ability to conduct electrical current through dissolved ions. Inorganic compounds are good conductors, while organic compounds are poor conductors. This makes conductivity a good estimate of the total inorganic dissolved solids present in the water column (Eaton et al., 2005). Some of the more common inorganic dissolved ions include anions such as chloride, nitrate, sulfate and phosphate, and cations such as sodium, magnesium, calcium, potassium and aluminum. Conductivity is

primarily used as a baseline chemical indicator of stream health and is a good screening tool for stream restoration projects. Conductivity can be used to measure changes in discharge characteristics, external flow contributions, pollutant load and other factors affecting the chemical composition of streamflow (USEPA, 1997b).

The amount of conductivity depends to a greater extent on the concentration of charged ions rather than the types of ions present. This characteristic makes it a good measure of total dissolved solids across aquatic resources (Allan and Castillo, 2007). Conductivity is significantly influenced by temperature. Higher temperatures cause more ions to be released into solution, increasing conductivity. The effects of temperature can be accounted for by comparing the conductivity at the standard temperature of 25°C, which is referred to as specific conductance (USGS, 2010). Conductivity is also influenced by external factors, including geology, soils and climate. Dissolved ion concentrations are much higher in streams flowing through sedimentary rock that is more easily weathered compared to igneous and metamorphic rock (Allan and Castillo, 2007). Streams flowing through clay and silt soils tend to have higher conductivity than inert sandy soils due to the presence of charged molecules in clays and silts (Essington, 2005). Precipitation and runoff characteristics can influence stream conductivity. In temperate climates, precipitation events can dilute the dissolved ion concentrations in surface waters. In some cases, however, more precipitation can increase conductivity if rainwater has a higher concentration of dissolved solids compared to the receiving stream water. Arid climates have surface waters with high conductivity due to less rainfall. Salts accumulate in soils with little precipitation and high evaporation, readily dissolving in surface water runoff and groundwater (Walling, 1984; Allan and Castillo, 2007).

Conductivity measurements comparable to reference stream conditions are maintained in stream systems when the following conditions are present:

- Low pollutant loads in watershed runoff and point-source discharges, which eliminates direct impact of flows with higher conductivities than those inherent in the receiving stream; and
- Established riparian buffer, which provides shade to stabilize temperatures, allows filtration of surface-runoff contaminants, and decreases evaporation that can concentrate dissolved ions.

pH

Measurements of pH indicate the relative acidity or alkalinity of water. The pH scale (0–14) measures the logarithmic concentration of hydrogen (H+) and hydroxide (OH-) ions that compose the water (H_2O) molecule. The pH is 7.0, or neutral, when both ions are in equilibrium, such as in pure water. Streamwater contains dissolved ions that interact with these water ions to alter the equilibrium. When the pH drops below 7.0, the water is considered acidic; when the pH is above 7.0, water is considered alkaline (USEPA, 1997b). Stream pH can have a significant effect on biological communities, which prefer pH values in the 6.5 to 8.0 range. Diversity can be reduced in streams with pH outside

this range, favoring only certain species that can tolerate more extreme pH conditions (Hynes, 1970). Like condutivity, pH is a good screening tool for stream restoration projects. At low pH values, ions from metals and toxic compounds can be released into the water column and negatively impact biological communities (Allan and Castillo, 2007).

Stream pH can be influenced by chemical reactions and dissolved constituents present in the water. In natural streams, H+ and OH- ions are typically produced during the dissociation or hydrolysis of carbon compounds (Wetzel, 2001). Conductivity can be altered by changes in pH, and vice versa, due to the interaction between water ions and dissolved ions present in the water column. The effects of temperature on stream pH are similar to those experienced by conductivity (Stumm and Morgan, 1996).

The pH of streams can be controlled by precipitation and runoff, as well as by soils and geology. Precipitation typically has an average pH of 5.6 due to the dissolved ions captured in the atmosphere. An increase in atmospheric pollution from anthropogenic sources can create acid rain, with even lower pH values (USEPA, 2008). Watershed runoff can increase the acidity of streamflow, depending on the amount of precipitation, runoff volume and contaminants carried from the surface. Streams that flow through soils with high organic acid content, such as wetlands and swamps, generally have inherently lower pH values. Streams that flow through soils with high carbonate and hydroxide content, such as those derived from limestone, have higher pH values due to the buffering capacity provided when binding with hydrogen ions of acids occurs. Weathering of sedimentary rock produces alkaline soils, while soils derived from igneous rock are low in alkalinity (Wetzel, 2001). The effects of groundwater inputs on stream pH are similar to conductivity, due to the relationship between groundwater and surrounding soil chemistry.

Stream pH values comparable to reference conditions are maintained in stream systems when the following conditions are present:

- Low pollutant loads in watershed runoff and point-source discharges, which eliminates direct impact of flows with higher conductivities than those inherent in the receiving stream; and
- Established riparian buffer, which provides shade to stabilize temperatures, allows filtration of acid rain and surface runoff contaminants, and decreases evaporation that can concentrate dissolved ions.

Turbidity

Turbidity is a measure of water clarity based on how much light passes through the water column (USEPA, 1997b). Turbid water appears colored or cloudy due to suspended and dissolved materials, including soil particles, organic matter, plankton and dyes (USGS, 2010). Turbidity influences other Physicochemical parameters and significantly impacts biological communities. When the water is turbid, temperatures increase due to higher absorption of heat by the suspended particles. Dissolved oxygen can be reduced as a result of increased temperatures and reduced photosynthetic activity when light penetration is impeded. Biological lifecycles and habitats are negatively affected by high

turbidity. In the water column, suspended materials can reduce visibility needed for feeding activities and disrupt respiration, such as clogging of fish gills. As the fine particles settle, they blanket the stream bottom covering substrates used for habitat, and they fill interstitial spaces of the hyporheic zone where oxygen exchange occurs. High turbidity for extended lengths of time will reduce reproduction and development of aquatic organisms (Hynes, 1960; USEPA, 1997b).

Natural causes of turbidity are observed in streams with high plankton productivity, as well as in streams that flow through organic soils with dissolved humic acids (Hynes, 1970). Turbidity can also be caused by watershed runoff, flow dynamics and channel instability. Fine sediment particles, such as clays, silts and fine sands derived from anthropogenic activities, are common causes of turbidity, particularly in disturbed watersheds and unstable stream channels (Whipple et al., 1981). These particles are entrained in stormwater runoff over bare soils during development of the watershed or with agricultural activities (Wolman and Schick, 1967; USEPA, 2003a). Developed watersheds with impervious surfaces deliver larger volumes of runoff at a faster rate, accelerating streambank erosion as the channel becomes increasingly unstable. Studies have shown that turbidity can remain elevated long after a storm event has ended in disturbed watersheds due to channel instability (Hammer, 1972; Whipple et al., 1981). Fine sediment particles can also have adsorbed nutrients that enrich the streamwater. The excess nutrients increase microbial productivity and biomass to perpetuate the turbidity problem. Fine sediment particles may also carry pollutants that are detrimental to aquatic life, such as pesticides and metals (Hynes, 1960).

Stream restoration projects can include several methods to control turbidity. Stabilizing the watershed and treating turbid stormwater runoff are desired practices in coordination with a reach-scale restoration project. Designing a channel with floodplain connectivity will provide for sediment deposition outside of the main channel and reduce shear stress during large storm events. Creating a stable channel that can convey the water and sediment delivered from the watershed effectively and protecting streambanks from shear stress will prevent channel erosion as a source of fine sediments in the water column. Establishing a riparian buffer will significantly reduce fine sediment in runoff, while increasing infiltration for reduced runoff volume.

Low turbidity concentrations occur in stream systems when the following conditions are present:

- Watershed stability, which prevents entrainment of fine sediments and associated nutrients from exposed watershed soils;
- Floodplain connectivity, which promotes sediment deposition on the floodplain and not within the channel, provides energy dissipation, and reduces channel erosion during large storm events.
- Channel stability, reducing stream bed and streambank erosion; and
- Established riparian buffer, which slows runoff rates for deposition of fine sediments and associated pollutants, and provides streambank stability for less erosion.

Measurement Method

In order to measure basic water quality parameters effectively, a stream monitoring plan must be developed that considers the significant spatial and temporal variability of the parameters, as well as fluctuations caused by flow conditions. Collecting individual (discrete) samples provides information about the parameter at one point in time, which may yield limited information in lotic systems with such dynamic variability. Continuous monitoring is recommended in order to better capture variability and allow for comparison over time and between the target reach and reference reach. In order to demonstrate whether significant changes have occurred over time, the number of samples and frequency of collection are important for statistical analyses of results. The level of effort for water quality parameters is rapid for discrete samples, but is considered intensive for continuous monitoring used to capture high variability. The level of complexity for all the water quality measurement methods is considered simple to moderate, depending on the instruments used and the statistical detail or level or expertise required for analyses to determine deviation from the reference condition and species requirements (Appendix Ac).

When measuring basic water quality parameters to determine Physicochemical function of a restored stream, it is imperative to identify influential variables that cannot be affected by restoration at the reach scale. External discharges from upstream, point-source and non-point-source contributions, and the effects of land-use changes in the watershed are all variables that may not be included in a reach-scale project. In order to fully restore these water quality parameters, a watershed scale effort may be required along with the presence of a healthy upstream watershed. These variables demonstrate that site selection and reach length must be considered during the planning stage of a stream restoration project. Climate, geology and soils can also have a significant effect on basic water quality but cannot be controlled at any scale. Environmental variables that are beyond the scope of the restoration plan can be differentiated from variables that are controllable through comparisons with upstream, downstream and reference stream conditions.

The measurement methods listed below are brief summaries for each basic water quality parameter. All measurement methods are considered direct assessments of water quality parameters for Physicochemical function (Appendix Ac). Details for each method can be found in the associated references, as well as outlined in the Standard Methods for the Examination of Water and Wastewater (Eaton et al., 2005). There are many resources to assist with deriving a monitoring plan, including those published by state environmental agencies and federal agencies, such as the USEPA (1997b) guide, *Volunteer Stream Monitoring: A Methods Manual*. Recommended references for methods and sampling plans include *Methods in Stream Ecology* (Hauer and Lamberti, 2006) and *Limnological Analyses* (Wetzel and Likens, 2000).

1. Temperature

Temperature is typically recorded in degrees Celsius for metric units and degrees Fahrenheit for English units. Temperature can be measured using a standard liquid-in-glass thermometer, electronic thermistor or thermocoupler in-situ (Hauer and Hill 2006).

Temperature sensors are commonly included with meters and probes that measure other parameters, including dissolved oxygen, conductivity and pH; therefore, a separate device may not be needed (USGS, 2010). Calibration of all devices with a NIST-certified thermometer is recommended (Eaton et al., 2005).

Temperature can be one of the most variable stream parameters to measure. This variability should be captured to the fullest extent possible, considering how many Physicochemical parameters and Biological (Level 5) functions are affected by changes in temperature.

External factors that affect temperature should also be taken into account during monitoring. Air temperature and precipitation should be measured, and sampling locations should be selected with the understanding that riparian canopy and external discharges, especially from groundwater seepage, can significantly influence water temperature. Therefore, the purpose of the sampling should be determined before the temperature sensors are deployed. Localized influences on temperature, like groundwater seepage, should be avoided if the goal is to determine a well-mixed, average temperature. Alternatively, sensors may be deployed in areas with groundwater seepage if the influence of groundwater and surface water exchange need to be determined.

2. Dissolved oxygen

Dissolved oxygen (DO) is measured as a concentration (mg/L) or as a percentage of the amount required for complete saturation of the water column. Saturation is based on the total amount of oxygen that can be dissolved in pure water at a specific atmospheric pressure and water temperature. Reference tables are available to determine what these DO concentrations should be (Mortimer, 1981; Eaton et al., 2005). DO should be measured in-situ or immediately after sample collection to avoid changes in concentrations associated with microbial processes and temperature. For in-stream measurements, a probe and meter combination can be used. The most common DO probes have selectively permeable membranes or optical sensors to detect DO within the water column. When using a probe and meter, temperature and barometric pressure should also be measured to adjust DO measurements to environmental conditions (USGS, 2010). In order to measure DO concentrations using water samples, the method must immediately stabilize DO in the water column. A common method is the Winkler titration that uses reagents added in the field prior to titration (Hauer and Hill, 2006). Although the Winkler method is typically not as accurate as a meter and probe combination, it is generally more economical.

Due to the variability of DO along the stream length and its requirement by many organisms, the sampling protocol should include measurements from different stream features,e.g., pool, riffle, upstream and downstream of an impoundment, stream areas with different riparian cover densities, and near areas where significant external flow contributions are suspected, e.g., groundwater seeps and springs, stormwater, point sources).

3. Conductivity

Conductivity is commonly measured with a probe and meter combination that measures resistance by dissolved ions to an electric charge in units of milliSiemens (mS)/cm

or milli-ohms (mhos)/cm (USEPA, 1997b; Eaton et al., 2005). A temperature sensor is most always included with the conductivity probe and meter due to the relationship between the two parameters. Specific conductance is a measure of conductivity that has been normalized to unit length at the standard temperature of 25 °C (USGS, 2010). Conductivity measurements indicate the amount of total dissolved solids (TDS) within the water column. Actual TDS can be calculated by multiplying the conductivity reading by an empirically determined factor between 0.55 and 0.9 (Eaton et al., 2005). Conductivity measurements also provide useful baseline data that can indicate changes in water quality over time, particularly due to additions of external discharges and pollutants.

4. pH

The pH value can be collected in the field or laboratory using a color treatment test or using a pH probe and meter combination. Samples collected should be evaluated within two hours due to the effects of CO_2 exchange with air on pH; therefore, field measurements are generally easier and more accurate. For the color treatment test, reagents are added to the sample causing coloration of the water. The color and its intensity are compared to a standard color chart to determine the estimated pH unit. For a more accurate measurement, a pH meter and probe can be used (USEPA, 1997b). The pH meter measures hydrogen ion activity as a function of electric potential generated between a glass pH electrode and a reference electrode. Results are reported by the meter in pH units or millivolts. Temperature should also be measured by the probe to compensate pH measurements for water temperature (USGS, 2010).

5. Turbidity

Turbidity can be measured directly using a turbidity meter and probe in the field or by laboratory analysis. The meter uses a light source and a photoelectric cell to measure light intensity that is scattered and absorbed by suspended and dissolved particles in water. Without turbidity, light would be transmitted in straight lines through a sample. The most common unit is the Nephelometric turbidity unit (NTU), and most meters measure a range from 0 to 1000 NTU (USEPA, 1997b and USGS, 2010). Turbidity can be measured indirectly using a Secchi disk in deep, slow-moving rivers (Wetzel and Likens, 2000) or using a transparency tube (USEPA, 1997b).

Turbidity is highly dependent on streamflow with typical increases as stage rises during storm events that entrain excess sediments during surface runoff and within the channel. Measurements taken during or immediately after rain events or snowmelt will result in higher turbidity readings. It is recommended that streamflow measurements be recorded over time, along with continuous monitoring of turbidity, to capture changes during storm events. Baseflow samples alone will not yield information about turbidity levels and their potential impacts on the biological community.

Performance Standard

Since external factors such as upstream discharges, point-source discharges and watershed land use changes cannot always be controlled, it is important to measure basic water quality parameters within the proposed restoration reach prior to construction, as well as within the reference stream(s). Measurements should also be taken upstream and downstream of the restored reach to determine what is coming into and exiting the restored reach. These locations will provide baseline measurements of existing and reference conditions for each parameter for comparison of post-restoration performance.

Existing condition and reference stream measurements along with water quality standards should be used when assessing the functionality of stream chemistry. To determine whether or not an aquatic system is meeting its pre-determined designated use, regulators use water quality standards. The designated uses are determined by taking into consideration the desired use and value of a stream for public water supply, protection of fish, shellfish and wildlife, and for recreational, agricultural, industrial and navigational purposes (USEPA, 2011). Streams meeting these standards are only meeting the minimal requirements determined for the use by the state in which the system is located. Water quality standards vary depending upon specific state regulations; therefore, it is recommended that monitoring programs use their state's standards as the minimum requirements for stream assessment. The EPA has compiled a database of each state's water quality standards on their website (*www.epa.gov/waterscience/standards/wqslibrary*; USEPA, 2007). EPA has also compiled water quality monitoring information from across the country. This data set is available at *www.epa.gov/storet*.

Reference conditions and certain species requirements may exceed the water quality standards, depending on the designated use. An example in the East would be restoring a stream for native brook trout, which would have higher water quality standards than restoring a stream for recreational fishing of rainbow trout, due to species requirements. Both measurements from reference streams and appropriate water quality standards for the desired use are, therefore, the best assessments to determine if the project reach is Functioning. Measurements that only meet the minimum water quality standards, but are not representative of the reference stream conditions and are limiting to certain species, are considered Functioning-at-Risk; those not meeting minimum water quality standards, not representative of the reference conditions, and not supporting species requirements should be considered Not Functioning. For parameters that do not have water quality standards, reference conditions and species requirements are used to determine performance level (Table 9.2). Turbidity may or may not have regulated water quality standards, depending on the location; therefore, turbidity is listed in both categories in the table.

TABLE 9.2 BASIC WATER QUALITY PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Temperature DO Turbidity	Meets water quality standards for designated use Representative of reference stream conditions and meets species requirements	Meets water quality standards for designated use Is not representative of reference stream conditions and does not support species requirements	Does not meet water quality standards for designated use Is not representative of reference stream conditions and does not support species requirements
Conductivity pH Turbidity	Representative of reference stream conditions and meets species requirements	Is not representative of reference stream conditions *or* Does not support species requirements	Statistically different than reference stream conditions and Does not support species requirements

9.2 » PARAMETER: NUTRIENTS

Description

Nutrients are chemical elements required by all organisms to live and grow. The most important nutrients found in both aquatic and terrestrial ecosystems are nitrogen and phosphorus due to their influence on growth (Allan and Castillo, 2007). Nitrogen is found in dissolved inorganic form primarily as nitrate (NO_{3^-}) and ammonium (NH_{4^+}) ions, and as organic nitrogen. Nitrogen enters the stream through precipitation, atmospheric deposition and diffusion, in situ nitrogen fixation, groundwater, and surface runoff. Phosphorus is present as inorganic phosphate (PO_{4^+}) and as organic phosphorus (USEPA, 1997b). Both inorganic and organic phosphorus can be dissolved in water or suspended in the water column as living biomass or attached to solid particles within the sediments (USEPA, 1997b; Allan and Castillo, 2007). Phosphorus enters the stream mainly through weathering of soils and rock and adsorbed to soil in surface runoff (Hynes, 1970).

In natural streams, most nutrients are stored within the biomass of the biological community. Nutrient uptake by living organisms is in equilibrium with nutrient release during excretion and decomposition of dead organic matter. Dissolved inorganic forms of nitrogen (NO_{3^-} and NH_{4^+}) and phosphorus (PO_{4^+}) are present in very low concentrations (Hynes, 1970; Maybeck 1982). Dissolved nutrients move downstream, continuously cycling between abiotic and biotic forms, and between inorganic and organic forms, in a process known as nutrient spiraling. Dissolved inorganic nutrients are assimilated by

living organisms, bound to sediments or chemically transformed, moving from the water column to sediments and then released again for downstream transport (Stream Solute Workshop, 1990; Newbold, 1992). Nutrient cycling can help maintain water quality by sequestering nutrients within the biological community and substrates, reducing downstream nutrient loads. The nutrient spiraling equilibrium can be significantly disrupted, however, by excess nutrient inputs. Details of nutrient spiraling can be found in Stream Solute Workshop (1990) and Webster and Valett (2006).

Excess nutrients are contributed from anthropogenic sources such as fertilizers, animal waste and sewage from agricultural runoff, urban runoff and direct point-source discharges (Figure 9.3; USEPA, 2000). Nitrogen is also added from atmospheric pollutants through precipitation, commonly referred to as acid rain (USEPA, 2008). Excess nutrients in the stream can over-stimulate microbial productivity causing eutrophication (Figure 9.4; USEPA, 2000). Excess nutrients from nonpoint sources are one of the leading causes of stream impairment in the nation (Carpenter et al., 1998; Allan, 2004; USEPA, 2009). There are several processes that can naturally remove excess nutrients from the water column. Nitrogen can be assimilated into biomass, removed through denitrification, adsorbed to sediments and volatilized (Bernot and Dodds, 2005). Phosphorus is removed from the water column by assimilation and adsorption to sediments (USEPA, 1997b). Nutrient storage processes can be temporary, however, so the most effective way to reduce excess nutrients in streams is to control the sources from the watershed.

Stream restoration projects can include several techniques to reduce excess nutrients. Establishing floodplain connectivity is important for deposition of nutrient-laden sediments outside the channel, and for providing a healthy riparian buffer that can store nutrients. A riparian buffer can remove nutrients if the root zone is in contact with the groundwater table to facilitate denitrification. In-stream modifications that restore incised channels to proper geomorphic dimensions will connect the riparian buffer to the groundwater table. Channel modifications that increase stream length and residence time will promote nutrient uptake by the biological community and denitrification (Gucker and Pusch, 2006). (See Figure 9.5.) Channel stability will also reduce nutrients in the water column by conveying water and sediments effectively, by preventing sediment inputs from streambank erosion, and by maintaining a healthy hyporheic zone where microbial processes can sequester nutrients (Hendricks, 1993).

Removal of excess nutrients occurs in stream systems when the following conditions are present:

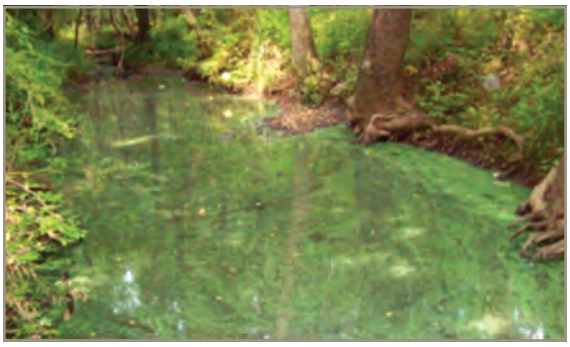
- Nonpoint sources of excess nutrients are controlled;
- Floodplain connectivity facilitates sediment deposition, provides sediment storage, and establishes the water table to be in contact with the root zone of the riparian buffer, which is required for dentrification to occur;
- Established riparian buffer, which slows runoff rates and facilitates sediment deposition with associated nutrients, stabilizes streambanks and provides nutrient uptake by riparian vegetation;

- Meandering channel increasing stream length, which decreases stream velocity and increases hydrologic residence times (required processes for nutrient processing);
- Channel stability, which reduces streambank erosion and fine sediment inputs; and
- Healthy hyporheic zones, promoting habitat for the microbial community that processes nutrients.

FIGURE 9.3 SOURCE OF LATERAL RUN-OFF FROM GOLF COURSE

Source: Reproduced with permission from Michael Baker Corporation

FIGURE 9.4 AREA OF NUTRIENT ENRICHMENT DOWNSTREAM OF GOLF COURSE



Source: Reproduced with permission from Michael Baker Corporation

FIGURE 9.5 RESTORED MEANDERING CHANNEL

Source: Reproduced with permission from Michael Baker Corporation

Restored meandering channel that is well connected to the floodplain. The water table is in contact with the newly established stream buffer. The meandering channel with diverse bed forms and complexity increase the hydrologic residence times. Together, these elements support nutrient processing.

Measurement Method

Chemical measurements for nutrients can be conducted in the field or in a laboratory, dependent upon the measurement method used and the desired accuracy of results. Field test kits are available for the rapid and simple assessment of many nutrient forms, usually containing reagents and a color wheel/colorimeter to determine concentrations. Many of the nutrient tests performed in the laboratory use specialized analytical equipment and complex chemical reactions for better accuracy. For details on these analytical methods, refer to Eaton et al., (2005). The level of effort for nutrient measurements ranges from rapid to intensive, depending on the instrument used and the number of samples required to capture variability and to determine deviation from reference conditions. The level of complexity is considered simple when using field test kits, but complex when laboratory analysis is required (Appendix Ac).

Nitrogen concentrations (mg/L) can be measured by analyzing water samples for inorganic forms, including nitrate (NO_3) and ammonia (NH_3). Nitrite (NO_2) is an intermediate inorganic form produced during denitrification (NO_3 to nitrogen gas) and nitrification (NH_3 to NO_3). However, it is generally not measured due to its very minute concentrations at any given time. Nitrate is important to quantify because it is readily produced by oxidation of ammonia (nitrification), readily dissolved in water and leached from soils, and an essential nutrient for primary producers (Wetzel, 2001; Eaton et al., 2005). Nitrate can be analyzed in the field with an electrode and meter combination; however, this method is currently unable to detect quantities of less than 1 mg/L. Nitrate can also be quantified using the cadmium reduction method in which NO_{3-} reacts with cadmium ions to produce a color reaction that can then be interpreted for concentration. Ammonia concentrations are generally low in natural streams, since ammonia does not readily leach from soils and is rapidly converted to NO_3 for biological assimilation. Ammonia can be analyzed in the field with an electrode and meter combination or using a salicylate reagent method (USEPA, 1997b; Eaton et al., 2005). Other common nitrogen quantities that can be measured are briefly described to assist with parameter selection. These quantities can be combined with nitrate and ammonia tests in various ways to estimate individual nitrogen components, including organic N concentrations. Total nitrogen (TN) is the sum of all nitrogen forms, inorganic and organic. It can be quantified in the laboratory using a persulfate digestion method. Total Kjeldahl nitrogen (TKN) is named for the method used and is the sum of organic N and ammonia concentrations (Wetzel and Likens, 2000; Eaton et al., 2005).

Phosphorus concentrations (mg/L) can be measured by analyzing water samples for (ortho)phosphate (PO_4) using the ascorbic acid method. To determine total phosphorus (TP) concentrations (organic and inorganic), the sample is first digested with an acidic solution containing a strong oxidizer that first converts all forms to phosphate (PO_4) in preparation for the ascorbic acid test. These two values allow for determination of organic P. The dissolved phosphorus portion can be determined in water samples by filtering out the phosphorus associated with suspended particles first, then using the above phosphate and TP methods. An important form to measure is the soluble reactive phosphorus

(SRP), which is the soluble inorganic PO_4 fraction available for biological assimilation. It is determined by subtracting the filtered PO_4 concentration from the original PO_4 concentration (Wetzel and Likens, 2000; Eaton et al., 2005).

When measuring nutrients within a stream reach, the process of nutrient spiraling should be accounted for since nutrients are being continuously cycled between inorganic and organic states, and between the biological community, substrate and the water column (Newbold, 1992). Adequate upstream and downstream sampling before restoration activities occur is recommended in order to get a good baseline survey of nutrient concentrations entering and exiting the reach. Nutrient cycling can also result in significant nutrient storage within microbial biomass and bottom sediment over long periods of time. Stored nutrients can be reintroduced into the water column under certain stream conditions, causing persistent nutrient release long after the pollutant source has been removed. It is recommended that post-restoration monitoring occurs over a sufficient time period to evaluate whether nutrient reductions have been achieved (USEPA, 2000). Nutrient processing methods are not discussed due to their relative complexity compared to water sample analyses. But these methods are recommended if a more detailed assessment is allowed by time and funding. Resources for these processing methods include Newbold et al. (1981), Payn et al. (2005), and Hauer and Lamberti (2006).

External discharges entering the stream reach of interest along with watershed activities affect nutrient concentrations and must be accounted for in nutrient monitoring plans. Nutrients should be measured within the proposed project reach before and after restoration. Baseline sampling should also occur upstream and downstream of the project reach and within the reference reach for comparisons over space and time. It is recommended that nutrient monitoring extend far enough downstream to observe nutrient cycling effects. This distance would be dependent on the nutrient load, the availability of nutrient sinks and flow rate. A nutrient with/without tracer release study can be used to determine specific distances. It is recommended that nutrient monitoring also occur for an extended period of time after restoration to observe the effects of nutrient storage. Comparisons between existing condition and reference reach measurements along with state water quality standards should be used when assessing nutrient loads.

Performance Standard

Performance standards for nutrients are similar to basic water quality parameters. Due to the predominance of excess nutrients in aquatic systems, the nutrient parameters are evaluated based on amount of eutrophication versus biological limitations. Both measurements from reference streams to establish reference condition and appropriate water quality standards for the desired use can be used to determine whether a project stream is Functioning. It is assumed in this performance standard that the reference stream condition will meet species requirements to qualify as a suitable comparison reach. Measurements that only meet the minimum water quality standards, but are not representative of the reference stream condition and are limiting to certain species, are considered Functioning-at-Risk; those not meeting minimum water quality standards, not

representative of the reference stream condition and not supporting species requirements should be considered Not Functioning. For nutrients that do not have water quality standards, reference conditions and species requirements are used to determine performance level (Table 9.3).

TABLE 9.3 NUTRIENT PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Field Test Kits and Laboratory Analysis	Meets water quality standards for designated use Representative of reference stream conditions Does not cause eutrophication	Meets water quality standards for designated use Is not representative of reference stream conditions Does not cause eutrophication	Does not meet water quality standards for designated use Is not representative of reference stream conditions Causes eutrophication

9.3 » PARAMETER: ORGANIC CARBON

Description

Energy is made available in lotic ecosystems through metabolism of organic carbon. The majority of organic carbon is added from outside the stream channel, referred to as allochthonous. This material is contributed from riparian vegetation and soil organic matter. The remainder of organic carbon is generated within the stream channel, referred to as autochthonous. This material is contributed from organic processing, particularly through photosynthesis by macrophytes and algae (Allan and Castillo, 2007). The largest proportion of OC is non-living (detritus) and not associated with living biomass (Wetzel, 2001). Organic carbon availability significantly influences the biological community in streams. Small streams with dense canopies and limited photosynthesis rely mostly on microbial uptake and decomposition of OC for energy transfer to higher trophic levels. In larger rivers microbial metabolism is still important, even with additional photosynthesis opportunity due to turbidity, depth, downstream transport of OC and floodplain inputs (Vannote et al., 1980).

Organic carbon can either be in dissolved (DOC) or particulate form (POC), and generally composes half of organic matter (OM) on a weight basis (Allan and Castillo, 2007). Due to this consistent relationship between the two organic forms, these terms are commonly used interchangeably in the literature. Dissolved organic carbon (DOC) is commonly the largest pool available to the biological community on an annual basis, and the ratio of DOC:POC is greater than 1 in most streams (Maybeck, 1982; Webster and Meyer, 1997). DOC is composed primarily of humic materials derived from organic

matter in soils and contributed through groundwater to the stream. Within the stream, DOC is assimilated by the microbial community or produced by microbial processing of larger particulate organic materials within the substrate hyporheic zone. DOC can also be transformed by abiotic processes such as precipitation, flocculation, and adsorption to soil particles, and direct mineralization by sunlight. DOC is processed rapidly, generally within days (Wetzel, 2001). Particulate organic carbon (POC) is commonly referred to in the context of organic matter, and is divided into fine particulate organic matter (FPOM) and coarse particulate organic matter (CPOM). FPOM is generally between 0.5µm and 1mm and is derived from the decomposition of CPOM in the form of plant litter and woody debris (Wetzel, 2001). It can be found floating in the water column (seston) or within the bottom sediments (Wallace et al., 2006). CPOM is anything greater than 1mm, providing an important fixed carbon source to streams (Lamberti and Gregory, 2006; See Level 3, Organic Matter Transport). Particulate forms of organic matter are generally processed over weeks (FPOM) to years (CPOM) by microbial decomposition or direct consumption by higher trophic levels, including macroinvertebrates and fish. The amount of POC available in the stream is dependent on the amount of riparian vegetation present, watershed runoff characteristics and streamflows (Wetzel, 2001).

Organic carbon processing occurs in a similar pattern as that of nutrients, through carbon spiraling moving downstream (Newbold et al., 1982). Organic carbon is assimilated by living organisms, adsorbed to bottom sediments, or abiotically transformed in a cyclical pattern. Biological metabolism either transfers organic carbon up the food chain during consumption, or remineralizes it to inorganic carbon dioxide gas (CO_2) that is released into the water column. These processes can be complex, and details can be found in Newbold et al. (1982), Thurman (1985) and Webster and Benfield (1986). Organic matter budgets can be created for streams to quantify organic carbon pools and their availability (Cummins et al., 1983; Webster and Meyer, 1997). Due to the importance of organic carbon in lotic systems, stream restoration practitioners should always consider how to enhance organic carbon availability within their projects. The establishment of lateral connectivity between the stream and riparian zone can provide significant OC sources (Gregory et al., 1991; Lake et al., 2007). A riparian buffer contributes both DOM and POM directly from vegetation and watershed surface runoff, and indirectly by enhanced infiltration through the soil to groundwater (Figure 9.6). Floodplain connectivity exposes streamflow to OM sources in the riparian areas and prevents excessive removal of POM by hydraulic scouring during large flow events. Designing a stable channel that can maintain a healthy hyporheic zone with adequate groundwater interaction and oxygen availability is essential for organic processing and has been well documented (Stanford and Ward, 1988; Kasahara and Hill, 2006; Kasahara, 2007; Boulton et al., 2010). Restoring a meandering pattern with deep pools and installing structures, such as root wads, large woody debris (LWD) and cross vanes, will enhance retention of organic materials (James and Henderson, 2005). (See Figure 9.7.)

Organic carbon availability and processing occurs when the following conditions are present:

- Established riparian buffer, which contributes OC directly through vegetation and indirectly through infiltration to groundwater;
- Floodplain connectivity, providing access to riparian vegetation and organic matter and reducing stream velocities during high flows;
- Healthy hyporheic zones, which promote habitat for the microbial community that processes OC and provides a groundwater interface for DOC contributions; and
- Channel meandering and in-stream structures, which create opportunities for OM storage in deep pools and increase POM retention.

FIGURE 9.6 RIPARIAN BUFFERS PROVIDE ALLOCHTHONOUS MATERIAL

Source: Reproduced with permission from Michael Baker Corporation

Figure 9.6 is an urban stream restoration project six years after construction. The photo was taken in the Fall and shows leaves falling from the riparian buffer into the stream channel.

FIGURE 9.7 ROOT WADS AND MEANDER BENDS HELP RETAIN ORGANIC MATERIAL

Source: Reproduced with permission from Michael Baker Corporation

Measurement Method

The relative amount of organic carbon in a water sample (mg/L) is determined using laboratory analyses. These methods are considered intensive for the level of effort and complex for the level of complexity, due to the different samples that must be collected to evaluate the different forms of organic carbon, due to the equipment required, and due to the level of expertise needed to interpret the measurement results in comparison to the reference condition (Appendix Ac).

Filtration is generally used to separate out the CPOM portion (1mm), the FPOM (0.45µm) and the dissolved fraction (DOC). The dissolved portion is then quantified using a of total organic carbon (TOC) analyzer after removing the inorganic carbon fraction (CO_2, bicarbonate and carbonates). The analysis method uses high temperature combustion or UV/persulfate oxidation. POC concentrations (mg/L) in each size class are determined by placing the filtered portion from the water sample into a high temperature oven (550 °C) and quantifying mass lost upon combustion (Wetzel and Likens, 2000; Eaton et al., 2005).

Measurement methods of organic carbon associated with substrates and bottom sediments, primarily DOC and FPOC, are not described in this section. These measurements, along with inorganic carbon (CO_2) methods, are described in Level 5: Microbial Communities. Specific methods of measuring organic carbon can also be found in Wetzel and Likens (2001), Eaton et al., (2005), and Hauer and Lamberti (2006). Retention of CPOM, particularly leaves and small woody debris, can be estimated using methods described in Ehrman and Lamberti (1992) and James and Henderson (2005). In general,

the retention and release of CPOM is modeled by using a log proportional linear regression equation that compares the amount of CPOM remaining in the system to the distance it has traveled within the system.

Similar to nutrient measurement methods, external discharges entering the stream reach of interest along with watershed activities should be considered due to their effects on OC quantities. OC concentrations should be measured within the proposed project reach before and after restoration. Baseline sampling is recommended both upstream and downstream of the project reach and within the reference stream(s), in order to adequately compare measurements spatially and temporally. It is recommended that OC monitoring extend far enough downstream and over an extended period of time after restoration to observe OC spiraling effects, particularly the storage component. Specific measurements of OC spiraling are complex and not covered in this section (see references above). All measurements should be compared to reference conditions for effective evaluation.

Performance Standard

There are no published performance standards for organic carbon concentrations and for organic processing in streams. The best evaluation of organic carbon concentrations is by comparison of quantities with reference reach conditions (Table 9.4). Measurements that meet reference stream conditions are indicative of a Functioning stream reach. Measurements where results do not meet reference stream conditions could be considered Functioning-at-Risk. Measurements of OC concentrations that do not meet reference stream conditions could be considered Not Functioning. A threshold can be determined based on biological species biomass and OC processing found in the reference stream. Suggested performance standards for OC processing are not covered in this section, but they can be found in Level 5 (Biology) due to the dependence of biological metabolism on OC concentrations. Species biomass and assemblage measurements, particularly those of the microbial and benthic macroinvertebrate communities, can be incorporated into evaluations of effective OC concentrations, if desired.

TABLE 9.4 ORGANIC CARBON PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Laboratory Analysis	Meet reference stream conditions	Do not meet reference stream conditions	Do not meet reference stream conditions and is below a threshold determined for adequate organic processing.

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Chapter 10
Biology

Biology functions are at the top of the Stream Functions Pyramid. These functions include processes that support the life histories of aquatic and riparian plants and animals. The ability of the lotic system to support biological processes is dependent upon the Hydrology, Hydraulic, Geomorphology and Physicochemical functions as described previously. Stream biological communities have a highly interconnected trophic structure starting from primary producers and moving up the food chain to fish. When habitat degradation occurs due to functional loss in the lower levels, and when valuable energy resources are removed, the trophic structure is disrupted and biological assemblages lose diversity and abundance.

The Biology function-based parameters include microbial communities, macrophyte communities, benthic macroinvertebrate communities, fish communities and landscape connectivity. A variety of measurement methods are provided for each parameter. The parameters, measurement method and indication of whether or not a performance standard is provided are shown below in Table 10.1. Scientists have researched the detailed and complex effects of stream condition on biological function and have developed biological indices that integrate ecosystem dynamics into simple, rapid assessments of stream condition. Biological indices are commonly used to assess water quality, but some have been developed to evaluate overall stream condition. Some of these indices are provided below and are included in the Biology category even though they also include parameters from the lower levels, as their purpose is to provide an overall assessment of biological condition. Appendix Ac includes a list of all the Biological measurement methods along with information about the method's type, level of effort, level of complexity, and whether it is a direct or indirect measure of the function-based parameter. The criteria used to make these determinations are provided in Chapter 4.

Landscape connectivity is included in the Biology category because it represents the ability of a target aquatic or riparian species to migrate upstream and downstream along a continuous corridor that meets their habitat requirements. Physical breaks in the corridor, like roads, create a disconnection to their habitat requirements. Landscape connectivity only becomes important after the species of interest are identified. For example, landscape connectivity requirements will be different for turtles than for large mammals like deer and bear. Once the species of interest are identified, landscape connectivity requirements can be determined.

TABLE 10.1 BIOLOGY PARAMETERS, MEASUREMENT METHODS AND AVAILABILITY OF PERFORMANCE STANDARDS

PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD
Microbial Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	No No Yes
Macrophyte Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	No No Yes
Benthic Macroinvertebrate Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	No No Yes
Fish Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	No No Yes
Landscape Connectivity	1. Spatial Analysis 2. Species Tracking 3. Habitat Models	No No No

10.1 » PARAMETER: MICROBIAL COMMUNITIES

Description

The microbial community in lotic systems is the foundation of the food chain, providing the organic energy to all of the higher trophic levels, including invertebrates and fish. This community is composed of autotrophs and heterotrophs. Autotrophs are the primary producers, making organic compounds through the process of photosynthesis with the uptake of inorganic carbon (CO_2) and release of oxygen. Phytoplankton and algae are the major primary producers within the microbial community. Heterotrophs are the primary consumers of the food chain, including bacteria and fungi. They break down particulate organic carbon (POC) and consume dissolved organic carbon (DOC) for energy, which is transferred to higher trophic levels as they in turn are consumed. This organic processing occurs through microbial respiration and release of CO_2 (Allan and Castillo, 2007). In most lotic systems, heterotrophic production is the predominant source of energy input. Primary production becomes significant, however, in higher order streams and rivers where light is more available (Vannote et al., 1980; Minshall et al., 1985).

The microbial community can be found suspended in the water column, referred to as plankton or seston, and found inhabiting substrates along the bottom of the stream, referred to as periphyton. Plankton is defined as any drifting organism, including autotrophic phytoplankton and algae, and heterotrophic zooplankton and bacteria. Periphyton is a complex community of both autotrophic and heterotrophic microbes, including algae,

fungi, bacteria, protist and other species that provide a link between the substratum and the overlying water column (Wetzel, 1983 and Wetzel, 2001). In lotic systems, periphyton is generally the most important biological community for providing energy to higher trophic levels. Energy contributions from plankton communities become important in larger rivers where light is plentiful and deep water prevents significant periphyton development. Within the periphyton layers, primary production and heterotrophic consumption create a microbial loop that effectively cycles carbon and nutrients (Lowe and LaLiberte, 2006 and Allan and Castillo, 2007). The balance between primary production and decomposition within the microbial community can determine the availability of organic matter and nutrients to higher trophic levels, as well as the amount of oxygen available for aquatic organisms. For a more detailed discussion of primary producer and consumer interactions, refer to Lamberti et al. (2006).

Microbial communities are influenced by hydrology, availability of substratum, light, carbon and nutrients, water quality, and consumer populations (Biggs, 1996; Janauer and Dokilul, 2006). The availability of stable substrates (including rocks, wood, sediments and macrophytes) that are exposed to limited scouring during storm events allows for development of diverse and productive microbial assemblages. Light is required for primary productivity and determines the extent of periphyton development (Figure 10.1). Temperature is one of the most important basic water quality parameters that affect microbial productivity due to thermal regulation of metabolism. Both light and temperature change daily and seasonally to define microbial population dynamics. The availability of carbon as inorganic CO_2 for primary producers, and dissolved and particulate organic carbon (POC) for heterotrophic bacteria and fungi is essential. The hyporheic zone and flow of interstitial water has a significant influence on periphyton productivity because it contributes a source of DOC from the groundwater (Boulton et al., 1998; Wetzel, 2001). Excess nutrients and organic pollution can over-stimulate microbial production, however, which is detrimental to streams as oxygen consumption during decomposition becomes greater than oxygen production (See Physicochemical Chapter: Nutrients and Organic Carbon). Consumer populations of invertebrates and fish can also have a considerable effect on microbial communities, especially periphyton, through their feeding habits (Lamberti, 1996). Although most microbial biomass is consumed as detritus, feeding on living tissues is significant because living tissues are more nutritious (Cummins and Klug, 1979).

Many of the stream restoration techniques used for Levels 1-4 will help develop a stable and productive microbial community. Non-point sources of excess nutrients and organic pollution should be controlled as much as possible within stormwater runoff to ensure there is a balance within the microbial population that contributes more dissolved oxygen than consumed. Large fluctuations in stream velocities during stormflow can be controlled by providing floodplain connectivity and designing a channel to attenuate erosive flows. Floodplain connectivity can also provide organic carbon resources while promoting sediment deposition outside of the channel. Periphyton on most substrates is negatively affected by scour, and may take a long time after large flow events to recolo-

nize and provide food and habitat. Maintaining a stable and healthy hyporheic zone especially benefits periphyton by providing DOC and nutrient resources. Bed form diversity is important to create shallow habitats and substrate protected from increases in stream velocity. Designing a channel for adequate transport of the sediment load and channel stability will prevent sediment inundation of periphyton substrate and reduce turbidity that limits light availability for both plankton and periphyton communities. The presence of large woody debris and in-stream structures can create habitat for microbial communities and help dissipate the energy of higher flows. Overall, stream restoration practices that ensure channel stability and improve water quality will encourage establishment and balanced growth of microbial communities that will provide dissolved oxygen, food and habitat for all trophic levels.

A healthy functioning microbial community occurs when the following conditions are present:

- Removal of excess nutrients and organic pollution, which prevents overstimulation of microbial productivity that will remove dissolved oxygen;
- Floodplain connectivity and bankfull channel, which dissipate energy of large storm events to prevent excessive scouring of substrate, provide access to organic carbon sources available on the floodplain, and prevent sediment inundation of substrate;
- Healthy hyporheic zones, which provide periphyton habitat, and provide an interface with groundwater and DOC inputs;
- Bed form diversity and in-stream structures, which create shallow habitats for light availability, dissipate flow energy, provide opportunities for organic carbon storage and retention, and provide substrates such as large woody debris and rocks; and
- Channel stability that prevents sediment inundation of periphyton habitat and the detrimental effects of turbidity on plankton and periphyton communities.

FIGURE 10.1 GOOD PERIPHYTON HABITAT IN AN INTERMEDIATE SIZE RIVER WITH SHALLOW DEPTH, LIMITED SCOUR, AND PLENTY OF AVAILABLE COBBLE SUBSTRATE

Source: Photo by Will Harman

Measurement Method

Microbial community samples are collected from the field and generally brought back to the laboratory for analysis. Plankton can be collected for measurement from the water column by filtering techniques using a known water sample volume. Periphyton can be collected by scraping known areas of natural substrates and various artificial substrates that have been allowed to colonize over time. The samples can then be analyzed for both taxonomic and non-taxonomic parameters. Algae are the most common microorganism evaluated within samples due to their predominance within the microbial community, as well as because of their well-developed taxonomy and extensive research of their tolerance to environmental stressors (Hines, 1970; Stevenson and Pan, 1999; Stevenson and Smol, 2003). Detailed methods for sampling microbial communities and measurement methods can be found in Weitzel (1979), Wetzel (1983), Hill (1998) and Steinman et al. (2006). A summary of common measurements is presented below, including the direct methods of taxonomic and non-taxonomic measurements and the indirect method of the biological index method.

1. Taxonomic Measurements

Species are indentified using visual observations and microscopes. This information is used to determine species composition, their relative abundance (numbers present), species diversity and taxa richness. This information is collected in a project reach, preferably upstream or downstream of the project, and within reference stream(s). Statistical techniques are used to determine if the populations in the project reach are different than the reference conditions established using reference stream data.

2. Non-Taxonomic Measurements

Biomass and productivity are two non-taxonomic measures of microbial communities. For biomass, samples are filtered and the dry weight of the filtered biological material is determined (105°C oven). Ash-free dry mass is then measured (AFDM; 500°C oven) to determine biomass on a carbon basis per volume for plankton and per area for periphyton. Chlorophyll a content can also be assessed to estimate algal biomass proportion, since most all plants contain chlorophyll a in known quantities per species. Microbial productivity can be measured using several methods. A change in biomass over time is a measure of microbial productivity. Artificial substrates, such as dowel rods, clay tiles and Plexiglas plates have been used to evaluate colonization rates over time as a measure of productivity. These methods must take into consideration the effects of disturbance, seasonal changes in microbial communities and consumer interactions, and changes in water quality that may have occurred between sampling dates. For algal species, primary productivity (mass/volume/time or mass/area/time) can also be assessed using gas exchange measurements, generally of oxygen in light and dark containers or over a 24-hour period (Hynes, 1970). These measurements assume that primary production (PP) and community respiration (CR) occur in the light and only CR occurs in the dark. For benthic studies, specialized chambers have been used with stream substrates enclosed to

measure primary production and respiration (Bott et al., 1978; Dodds and Brock, 1998). Net primary productivity (NPP) is the fixed carbon that is stored in biomass and equals gross primary productivity (GPP) measured in the light minus CR measured in the dark. Another method involves measuring the rate of the radiotracer (^{14}C isotope) uptake over time, which is a suitable method for low densities of algae (Peterson and Fry, 1987 and Finlay, 2001).

3. Biological Index

Microbial communities have become good biological indicators of water quality and overall stream condition. Their responses to environmental stressors occur over a shorter time span than other aquatic organisms, and they have higher population turnover rates to measure response. Algae within the periphyton assemblage are the predominant members used as biological indicators for reasons stated above (Hill and Herlihy, 2000; Hill et al., 2000). Algal species have specific response characteristics to habitat loss, and contamination by nutrients, metals, herbicides, hydrocarbons and acidification. Many biological indices have been developed for periphyton algae, based on large surveys of reference data that integrate both taxonomic and non-taxonomic metrics with measurements of stream condition (Karr, 1993). The EPA Rapid Bioassessment Protocol (RBP) for periphyton can be used to guide the development of these biological indices specific to different regions and stream types (Hill and Herlihy, 2000). These indices allow for rapid stream assessments using only a handful of metrics. Measures of microbial communities should not be used alone, however, due to interactions between these populations and their consumers, and due to frequent disturbance of assemblages during storm events (Stevenson, 1996).

The level of effort for all of the measurement methods described above is considered intensive, except for maybe certain biological indices that require only moderate efforts. These methods are also complex because they require trained biologists to adequately collect the organisms, determine characteristics of the community, and effectively compare the community to the reference conditions. Again, certain biological index methods may be moderate in their level of complexity, depending on the variables and methods included (Appendix Ac).

Performance Standards

It is a general assumption that that stream degradation reduces species diversity while creating environments that select for a few tolerant species. In healthy streams, there are generally moderate numbers of many species, including tolerant species that maintain an ecological balance within the biological community. This difference in species assemblages is the underlying premise for development of a biological index that can be used as a tool for rapid stream assessments. Microbial monitoring tools using the periphyton community have been developed for the states of Kentucky, Montana and Oklahoma (Stevenson and Bahls, 1999), Idaho (Fore and Grafe, 2002) and the mid-Atlantic region (Fore, 2003); many more are under development. What some of these biological indices

have found, however, is that the general assumption does not always occur in certain regions and environmental conditions. This research highlights the need for species-specific, regional information from appropriate and adequate reference reaches to develop a reliable biotic index for microbial communities.

An example of a biological index is the Periphyton Index of Biological Integrity (PIBI), based on data collected in the Appalachian region (Hill et al., 2000). The PIBI included algal taxa richness, relative abundances, chlorophyll and biomass (ash-free dry mass) standing crops, and alkaline phosphatase activity. Functioning refers to streams with good stream condition that have PIBI scores in the upper 25th percentile. Not Functioning refers to streams with degraded condition that have PIBI scores in the lower 25th percentile. Functioning-at-Risk streams have PIBI scores between these two percentiles.

TABLE 10.2 MICROBIAL COMMUNITY PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Periphyton Index of Biological Integrity (PIBI; Hill et al., 2000)	≥ 72	61-71	≤ 60

10.2 » PARAMETER: MACROPHYTES

Description

Macrophytes are the vascular plants, bryophytes and macroscopic algae that grow in and near lotic environments (Hynes, 1970; Westlake, 1974). They are commonly divided into subgroups based on their spatial growth form, including emergents (terrestrial to 1-m depth), floating-leaved (1- to 3-m depth), submerged macrophytes (up to 10-m depth), and free-floating (Sculthorpe, 1967; Eaton et al., 2005). When abundant, macrophytes can be an important autochthonous energy source through primary production. During photosynthesis they transform CO_2 absorbed from the air and water into organic carbon using energy from sunlight. Oxygen is released into the air and water during the process (Wetzel, 2001).

The influence of macrophyte communities on lotic ecosystems is dependent on their abundance and the species present. Vegetative and root structures provide habitat for the microbial community. Benthic macroinvertebrates and fish use macrophyte beds for feeding, reproduction and shelter (Bowden et al., 2006; Janauer and Dokulil, 2006). Macrophyte communities are also highly effective at nutrient cycling and organic matter processing (Clarke, 2002). Most macrophytes are consumed during senesce and as detritus during decomposition with secretion of dissolved organic carbon. Consumption of living tissue is a minor carbon source (Wetzel, 2001). Macrophytes that are rooted to the substrate provide channel stability and have been shown to improve surface-subsurface exchange

of gases, particularly O_2 and CO_2, and nutrients (White and Hendricks, 2000; Clarke, 2002).

Macrophytes are affected by many environmental factors that influence their abundance and diversity. Hydrologic stability is one of the most important variables that control establishment and growth (Westlake, 1974; Haslam, 1987). Rivers with low gradients can have good community development in the littoral areas and backwaters near the bank (Janauer and Dokulil, 2006). As macrophyte density increases, the community can actually modify local flow conditions by decreasing streamflow velocity, protecting habitat and limiting scouring during storm events (Wetzel, 2001; Clarke, 2002). Channel modifications that alter the natural flow regime and sediment dynamics, such as vertical incision, channelization and impoundments, negatively impact macrophytes. Studies have shown that macrophyte communities can experience loss of species, declines in relative abundance and a shift to species that are more tolerant (Baattrup-Pedersen and Riis, 1999; O'Hare et al., 2006). Another important physical requirement of macrophytes is adequate light. In small forest streams, light is generally limited by the riparian canopy, and macrophytes are not abundant. In larger rivers, light is attenuated with increase in depth and turbidity; therefore, macrophytes are found only in shallow waters near the streambanks. Macrophytes are most common in intermediate size rivers where current is low, depths are shallow and there is plenty of sunlight exposure (Westlake, 1974; Baattrup-Pedersen, 2006).

Macrophytes, like all lotic organisms, can be significantly affected by the stream physicochemical conditions. They have preferences for specific temperature and pH ranges, and available carbon and nutrient sources are required for growth and productivity. Carbon and nutrients are typically not limiting, however, due to the ability of most macrophytes to absorb them through both vegetative structures and roots, and due to constant source replenishment by the current (Bowden et al., 2006). When excess nutrients and organic pollution are present, macrophyte communities react based on their species-specific tolerances. Many studies have measured the effects of nutrient and organic pollution on macrophyte assemblages, demonstrating species tolerances, shifts in species composition and changes in abundance (Holmes et al., 1999; Schneider et al., 2000; Haury et al., 2006; Janauer and Dokulil, 2006). Based on the sensitivity of macrophytes to changes in water quality, macrophytes can be good biological indicators of stream condition and are closely linked to Level 4 functions.

Establishment of healthy macrophyte communities in restored channels should only be considered in streams that are appropriate for population establishment, including those with low gradients, shallow depths and adequate sunlight exposure. If the reference stream(s) have significant macrophyte development, then stream restoration techniques should help create that habitat. Hydraulic methods that dampen large fluctuations in discharge, including effective floodplain connectivity and attenuation of stream velocities during large storm events, will allow for establishment and reduce scouring of macrophyte beds. Maintaining a stable and healthy hyporheic zone especially benefits macrophytes with roots that depend on the substrate for nutrients, carbon and gas exchange. Bed form diversity is important to create shallow habitats, and adequate sediment trans-

port prevents inundation of macrophyte beds. The presence of large woody debris and in-stream structures can create habitat for macrophytes, diverting higher flows and creating backwaters (Figure 10.2). Stream restoration practices that ensure channel stability and improve water quality will also encourage establishment and growth of macrophytes that in turn will provide dissolved oxygen, organic carbon and habitat for stream organisms.

Healthy macrophyte communities will be present in lotic environments when the following conditions are met:

- Communities are present in the reference reach, as macrophytes requires certain flow regimes controlled by stream gradient, adequate light and relatively shallow depths that are not present in all stream types;
- Floodplain connectivity, which attenuates stormflows and creates a healthy hyporheic zone benefiting plant roots;
- Relatively constant stream velocities, as less fluctuation in stream velocities allows for macrophyte establishment;
- Bed form diversity, which provides available shallow habitat and helps to transport sediment effectively to avoid inundation of macrophyte beds;
- Large woody debris, which creates backwater areas and provides shelter from high flows for macrophyte establishment and growth; and
- Good water quality, which encourages species diversity and balanced population dynamics that will perpetuate good water quality and provide essential stream habitat.

FIGURE 10.2 PHOTO OF MACROPHYTE DEVELOPMENT IN A RESTORED CHANNEL

Source: Reproduced with permission from Michael Baker Corporation

Measurement Method

Macrophytes should be evaluated within the growing season in order to better identify species and measure growth. Biomass measures should include the entire plant with leaves, shoots and roots differentiated for several reasons. Some species have portions of their communities that senesce quickly before reaching maturity. Other species may have biomass concentrated within the root structure during certain times of their lifecycle (Wetzel, 2001). Since productivity varies seasonally and with light, samples should be taken at the same time of year and same location. Macrophytes respond to physicochemical conditions such as temperature and nutrient concentrations and flow conditions; therefore, it is recommended that these parameters and perhaps others be measured during appropriate macrophyte sampling intervals. Consult state sampling methodologies for detailed instructions.

Macrophytes are commonly evaluated by field observations and by measurements of standing crop collected from the stream and analyzed in the laboratory. Field observations can be made by visual assessment, with glass bottom buckets and other apparatuses in deeper waters. Macrophyte samples are generally collected in a defined area, such as a quadrant or transect, to determine quantitative measurements. Samples can be collected by hand or using specialized equipment, such as a grapnel, in deeper waters. Detailed methods for measuring macrophyte communities can be found in Westlake (1974), Dawson, 2002, Eaton et al. (2005), and Bowden et al. (2006).

Three categories of measurement methods are presented below for macrophyte communities. These categories are the same for the other biological communities discussed in this chapter, including the direct methods for taxonomic and non-taxonomic measurements, and the indirect method of the biological index measurement. The level of effort for all of the measurement methods described below is considered intensive, except for certain biological indices that may require only moderate efforts. These methods are also complex because they require trained biologists to adequately collect the algae and plants, determine characteristics of the community, and effectively compare the community to the reference conditions. Again, certain biological index methods may be moderate in their level of complexity, depending on the variables and methods included (Appendix Ac).

1. Taxonomic Measurements

Examples of taxonomic measurements include species composition, relative abundance and taxa richness. Macrophyte species can typically be identified by visual observation with taxonomic keys. Physical condition and density are additional measurements that can be used to evaluate macrophyte populations.

2. Non-Taxonomic Measurements

Macrophyte biomass and primary productivity are the common methods used to assess communities. Biomass can be determined using measurements of wet weight, dry weight or ash-free dry mass. Chlorophyll a content can be quantified as a measure of biomass, with knowledge of species composition and their typical concentrations. Popu-

lation productivity can be determined by collecting biomass data over time. This method yields net productivity without corresponding measurements of loss to grazing, injury, mortality and respiration. Primary productivity can be measured using similar methods described for algae in the microbial communities section above.

3. Biological Indices

Macrophytes can be used as reliable biological indicators of water quality and stream habitat because they are sessile, have established taxonomy, exhibit species diversity in their ecological tolerances, and there are well-developed sampling techniques available. Certain community characteristics should be kept in mind, however, when sampling to evaluate stream condition. Macrophyte identification may be limited to the growing season, there may be significant natural variation along a reach, and macrophytes may experience a lag-time in recolonization after stream condition has improved, if resources are limited upstream (Tremp and Kohler, 1995; Cronk and Fennessey, 2001).

Biological indices for macrophytes in lotic ecosystems have not yet been developed in the United States. However, the use of macrophytes as biological indicators is historically well established in Europe and is included in regulatory assessments of aquatic systems for impacts and mitigation (Water Framework Directive; European Commission, 2000). Three examples of commonly used biological indices are the Mean Trophic Rank index (MTR; Holmes et al., 1999), the Macrophytical Biological Index for Rivers (IBMR; Haury et al., 2006), and the Trophic Index of Macrophytes (TIM; Schneider et al., 2000). These index methods focus on evaluating the effects of eutrophication in streams due to the common occurrence of this impact. More integrative methods to assess river degradation as a whole are described in Ferreira et al. (2002), Passauer et al. (2004), Schaumburg et al. (2004), and Meilenger (2005). These methods use various ecological metrics for macrophytes that are similar for all organism biological indices, including methods that measure relative abundance, taxa richness, species diversity and distribution, and species tolerances to environmental conditions. The recommended reach length of assessment is typically 100m, and adequate reference reach (unimpacted stream) data should be collected for comparative use with each biological index.

Performance Standards

Performance standards for macrophytes in rivers have not been derived in the United States. The current European standards can be used as guidance for deriving these standards in the United States. These biological indices are based on plant species and their determined tolerance values for ecological condition. These determinations must be made for species present in the United States. The Mean Trophic Rank method (Holmes et al., 1999) is provided in this publication as an example biological index that evaluates the effects of excess nutrients in rivers, a common problem in most streams in our country (Table 10.3). This index uses calculated variables, including Species Trophic Rank (STR) with values representing species tolerance between 1 (eutrophic conditions) and 10 (unenriched waters), and Species Cover Value (SCV) as a percentage ranked between 1 (<

1%) and 9 (> 75%) to determine an overall MTR Score. Streams in the Functioning category would not require nutrient reductions. Functioning-at-Risk would require monitoring of nutrient inputs and nutrient reduction plans. Not Functioning would require reductions in nutrient inputs within a reach. Another biological index presented as an example is one that assesses overall stream condition compared to reference conditions, called the Reference Index (RI; Meilenger, 2005). Streams are divided into categories based on a classification system. The example given in Table 10.3 is for river type TN, which are medium-sized lowland rivers. The results provide an ecological status classification based on the deviation in macrophyte composition and abundance from reference conditions. Streams in the Functioning category would be classified as high or good; Functioning-at-Risk would be classified as moderate, and Not Functioning would be classified as poor or bad.

TABLE 10.3 MACROPHYTE BIOLOGIC INDICES PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Mean Trophic Rank (MTR); Holmes et al. 1999	> 5	25-65	< 25
Reference Index (RI)	-50 to 100	-70 to -50	< -70

10.3 » PARAMETER: MACROINVERTEBRATE COMMUNITIES

Description

The macroinvertebrate communities of lotic systems are commonly composed of mussels (mollusk), crayfish (crustaceans), worms (annelids) and insects (arthropods). Aquatic insects that live along the substrate are referred to as benthic macroinvertebrates, and this group is the most commonly evaluated in stream systems due to their higher diversity and abundance across stream types. Benthic macroinvertebrates generally have an aquatic immature stage and a terrestrial adult stage. They inhabit many different areas of a stream (Figure 10.3), and location often depends on their primary feeding mechanism. Functional feeding groups are often used to categorize aquatic insects and include predators, collectors, scrapers and shredders (Cummins, 1973; Voshell, 2002). A collector may feed by gathering detritus from the stream bed or by filtering detritus out of the water column, while a scraper scrapes periphyton off of the substrate. Shredders feed by shredding organic material, such as leaves, and can be found in leaf packs that accumulate along banks and woody debris in the channel.

Macroinvertebrate lifecycle demands and processing can have important influences on nutrient and carbon cycles and movement of energy in and around lotic systems. They are an important link in transferring energy up the aquatic food chain as an intermediate

trophic level. Benthic macroinvertebrates feed on periphyton, small bits of organic material, and other organisms and are in turn fed on by fish and terrestrial insectivores (Jackson and Resh, 1989; Wallace and Webster, 1996). Energy flows between terrestrial and aquatic environments, and between allochthonous and autochthonous sources (e.g., the export of autochthonous energy and a return of allochthonous energy contributed by the terrestrial system to the stream channel, and then a flow of energy back to the terrestrial system with the emergence of the adult aquatic insects).

Macroinvertebrates are influenced by water quality, habitat availability and food resources. Benthic macroinvertebrates have a range of sensitivities to changes in organic pollutants, sediments and toxicants, as well as habitat conditions. Macroinvertebrates are good indicators of water quality and stream condition. There are several reasons for this, including: 1) they have relatively short lifecycles that span multiple seasons; 2) species have different tolerances to water quality and stream condition; and 3) they are less mobile than fish and, therefore, cannot easily escape local perturbations (Kuehne, 1962; Bartsch and Ingram, 1966; Wilhm and Dorris, 1968; Warren, 1971; Cairns and Pratt, 1993). The sufficient availability of food resources, including plankton, periphyton and dissolved and particulate organic matter, can promote benthic macroinvertebrate productivity (Richardson, 1993).

Benthic macroinvertebrate communities can benefit from many stream restoration techniques, even in highly degraded systems. Floodplain connectivity and design of an appropriate bankfull channel reduce the impacts of large storm events on habitats and excessive scouring that removes food resources. Organic carbon can be carried from the floodplain to the stream during storm events, and fine sediment can be deposited on the floodplain instead of inundating stream habitats. Benthic macroinvertebrates are associated with the hyporheic zone, using it as physical habitat, as well as feeding on periphyton established at the groundwater-surface water interface where dissolved organic carbon is exchanged. Any stream restoration practice that increases available habitat will enhance communities. Bed form diversity and in-stream structures provide both habitat and enhance stream stability. Structures that are constructed using large woody debris, root wads and other woody material are particularly beneficial to macroinvertebrates because they provide resting and escape cover, increase surface area for feeding, capture additional organic material, and increase retention time of organic material that supports many macrobenthic invertebrate feeding groups. The addition of woody material has been shown to improve density and species diversity of macroinvertebrates (Gerhard and Reich, 2000). Restoration of the riparian plant community is usually a component of stream restoration projects and will significantly benefit aquatic macroinvertebrates by providing thermal regulations, as well as contributions of woody debris and leaf litter to support food chains.

A healthy functioning macroinvertebrate community occurs when the following conditions are present:

- Floodplain connectivity and bankfull channel, which dissipate energy of large storm events to prevent excessive scouring of substrate, provide access to organic carbon sources available on the floodplain and prevent sediment inundation of substrate habitat;
- Healthy hyporheic zones, which provide habitat for macroinvertebrates and facilitate exchange of dissolved constituents for healthy periphyton communities, a valuable food resource;
- Bed form diversity and complexity, create diverse habitats for feeding and reproduction, dissipate stormflow energy, provide opportunities for organic carbon storage and retention, provide substrates such as large woody debris, and provide scour holes and offer shelter;
- Channel stability, which prevents sediment inundation of habitat and the detrimental effects of turbidity on filter feeders; and
- Riparian community, which provides allochthonous carbon inputs for food resources; provides shade for cooler temperatures and provides vegetative roots for available habitat.

FIGURE 10.3 MACROINVERTEBRATES OCCUR IN A VARIETY OF HABITATS WITHIN THE STREAM CHANNEL, INCLUDING THE RIFFLES AND POOLS CREATED BY THE ROCKS AND WOODY DEBRIS IN THIS MOUNTAIN STREAM.

Source: Reproduced with permission from Stream Mechanics

Measurement Methods

Benthic macroinvertebrates sampling is mostly appropriate for perennial channels due to the physical size of the organisms and the higher diversity found in running waters. Assessments on the recovery of benthic macroinvertebrate populations based on reference stream communities are recommended. For the most rapid recolonization after restoration, reference conditions should ideally be present upstream of the restored reach.

The methods used to collect macroinvertebrates are fairly consistent across monitoring protocols. Visual observation along with various types of nets and sieves can be utilized in the different habitats to capture benthic species. Habitats include riffles, pools, leaf packs and woody debris, sediments, and macrophyte beds. Macroinvertebrate samples must be collected in proportion to the relative habitat abundance, and organisms must be collected in proportion to the species abundance in order to get a sample that truly represents the community structure. There are many assessment methods and protocols developed throughout the United States for benthic macroinvertebrates, including the EPA Rapid Bioassessment Protocol (RPB) method (Barbour et al., 1999), the EPA Environmental Monitoring and Assessment Program (EMAP) methods (Klemm et al., 2000), or the North Carolina Department of Natural Resources Division of Water Quality's Benthic Macroinvertebrate Monitoring Protocols (NCDENR, 2006), to name a few. In general, most macroinvertebrate sampling protocols involve a multi-habitat approach since macroinvertebrates occupy diverse habitats within the stream channel.

The three categories of measurement methods associated with biological macroinvertebrate communities are presented below, including the direct methods for taxonomic and non-taxonomic measurements, as well as the indirect method of the biological index measurement. The level of effort is considered intensive, except for certain biological indices that may require only moderate efforts. These methods are also complex because they require trained biologists to adequately collect the macroinvertebrates from different habitats, to determine characteristics of the community, and to effectively compare the community to reference condition assemblages. Again, certain biological index methods may be moderate in their level of complexity, depending on the variables and methods included (Appendix Ac).

1. Taxonomic Measurements

Benthic macroinvertebrate samples can be evaluated for taxonomic measures such as species composition, relative abundance and taxa richness. Mandaville (2002) provides an extensive review of population metrics that are commonly used to access macroinvertebrate populations. Species identification is performed using the many readily available taxonomic keys, including general keys (e.g., Peckarsky, 1990; Merritt and Cummins, 1996; Smith, 2001; Thorp et al., 2009). State or regional keys should be sought to limit the species to be considered and greatly aid the identification of macroinvertebrate samples. Often, abbreviated samples will just focus on three orders that are the most sensitive to stream condition: Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies). Sampling and identification of these three orders is referred to as an EPT assessment.

2. Non-Taxonomic Measurements

Measurements of biomass and secondary production allow for an assessment of how available energy is being utilized for macroinvertebrate growth. Benke (1984, 2010) provides an excellent discussion of the biological parameters that contribute to macrobenthic secondary production. There are many approaches to making secondary production measurements, depending on the application of the data (Benke and Huryn, 2010). Secondary production involves the measure of biomass over some period of time. Often these studies look at the production by a single age group or cohort. One sampling method that is often used for this purpose is the emergence trap. This is a trap placed over the stream that captures adult insects as they leave the water and can provide data for estimating abundance, biomass and production. Consideration should be given to trap placement in order to take a representative sample (Malison et al., 2010). While the emergence trap is relatively easy to use for this purpose, secondary production can also be determined at the aquatic life stage using established collection methods, quantifying biomass and establishing how this changes over a time (Jaynie et al., 2007).

3. Biological Indices

Benthic macroinvertebrates are widely used as a monitoring tool by many water resource agencies (Southerland and Stribling, 1995; USEPA, 2002). The change in populations and species assemblage composition over time can also reveal if the change has been positive or negative. Species have varying tolerances to pollutants, and a biologist experienced at identifying benthic macroinvertebrates should be able to look at a population sample and quickly determine whether or not it is from a stressed aquatic system.

Macroinvertebrate biotic indices generally include assessments of taxonomic and non-taxonomic metrics and include information on tolerances to stream condition and habitat measures. Many state agencies have developed biotic indices that are based on these metrics and data collected in various stream types, including reference reaches in different regions.

Performance Standards

Thresholds for determining if a stream is Functioning based on the macroinvertebrate community must be considered with stream type and the expected community type in mind. In general, it is always best to compare the condition of a project site with observations at stable reference streams. Performance standards for taxonomic and non-taxonomic measurements have generally not been developed. Biotic indices developed for specific stream types and regions that combine these measures with stream physicochemical and habitat conditions can, however, be used as performance standards. Several examples of biotic indices are listed in Table 10.4. Streams that fall into the Not Functioning category would most likely also have very low taxa richness and mostly very tolerant taxa, such as aquatic worms and snails. Engel and Voshell (2002) developed a quantitative multimetric index for volunteers with the Virginia Save Our Streams program to use, and found that it agreed very closely (96%) with the determinations made by professionals. In this study they found 15 candidate macrobenthic-based metrics that exhibited statistical properties

that would make them good measures of water quality. The process used in this study would be beneficial to use for developing a regionally specific biotic index if one does not exist. While these performance standards can be used anywhere, it is recommended that they be evaluated against a sample from a reference stream to ensure they provide the proper measure of performance.

TABLE 10.4 MACROINVERTEBRATE PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Hilsenhoff Biotic Index (HBI) (Hilsenhoff, 1988)	0.00-4.25 Excellent to Very Good	4.26-5.75 Good to Fair	5.76-10.00 Fairly Poor to Very Poor
WVSCI (Gerritsen et al., 2000; WVDEP)	68-100 Very Good to Good	45-61 Gray Area to Fair	0-45 Poor to Very Poor
Virginia Stream Condition Index (Burton and Gerritsen, 2003)	61-100 Exceptional to Similar to Ref.	40-60 Impaired Tier 1	0-40 Impaired Tier1 & 2
SOS Multimetric Index (Engel and Voshell, 2002)	7-12 Acceptable	N/A	0-6 Unacceptable

10.4 » PARAMETER: FISH COMMUNITIES

Description

Fish are the most ubiquitous vertebrate species found in rivers and streams. Fish are the top aquatic predators in most lotic systems and are utilized for food by many terrestrial species. Stream fishes have many adaptations for living in high velocity environments. They can use low-velocity microhabitats like pools, downstream sides of cover elements, or areas under and between substrate. Stream fishes have bodies that are fusiform and streamlined to reduce drag in high velocity, or they are adapted to living on the bottom with large pectoral fins that are aligned so that flow pushes the fish downward. Fish are often specialized feeders with anatomical adaptations for feeding on the bottom, scraping periphyton, picking macroinvertebrates off of rocks, or capturing other fishes. They have adapted reproductive approaches that protect their eggs and young, such as spawning on the undersides of exposed rocks, building clean pebble bounds in which to scatter their eggs, or burying the eggs in clean, well aerated gravel beds (Balon, 1975).

Fish communities include herbivores, insectivores, detritivores and piscivores. They serve as important links in aquatic food chains because they move the energy captured from lower trophic levels up to higher-level predators, such as terrestrial animals. Just as

with emerging macroinvertebrates, fish also act as the link for moving energy produced or captured in the aquatic environment to the terrestrial environment. One of the most dramatic examples of the importance of fish to aquatic food chains is the influence of anadromous salmon. These fish spend several years at sea feeding and growing and then move into rivers and streams to spawn. After spawning, they die, which provides an influx of nutrients during decomposition. This leads to an increase in food chain productivity, which in turn supports the young salmon as they grow to a size when they return to the ocean for the process to begin again. As top predators in stream systems, fish populations have been shown to affect the structure of prey populations, including the movement of prey from one habitat patch to another (Sih and Wooster, 1994), as well as the structure of the fish community itself through piscivory (Jackson et al., 2001). Given the importance of fish in structuring the populations of their food resources, they play a significant role in the population dynamics, nutrient cycling and energy flow in lotic ecosystems.

The ability of fish populations to fulfill their life history requirements normally depends on streamflow, water quality and habitat availability. Adequate flow in rivers and streams must be maintained to allow fish movement and survival. Impoundment structures can block fish passage and hold streamflow back to levels that will not support fish. Water withdrawals for human activities and consumption may prevent adequate flow during certain seasons where water tables are already low due to normal hydrology (Wootten, 1992). Changes in Physicochemical parameters can have a significant impact on fish. Fish can be highly sensitive to the amount of dissolved oxygen in the water column. When the oxygen levels drop below a certain threshold, this can have dramatic effects on fish populations and "fish kills" result (Hynes, 1960). Stream temperature not only affects fish metabolism between seasons, it also determines their distribution (Hynes, 1970). Warm-water streams and cold-water streams are distinguished as fish habitat based on the presence of certain fish species (Moyle and Cech, 1982). When restoring the functional ecology of a stream, the goal is typically to improve overall fish habitat. Good habitat includes creating riffle, run, pool and glide bed forms, as well as providing diverse cover elements within the channel. Diverse habitat will support different stages of a fish's life cycle and/or different species of fish over a varying spatial and temporal scale (Rohde et al., 1994). Diverse habitat also produces diverse food sources for fish. This may include patches within a stream that support algae or macrophytes for herbivores; riffles or woody debris that supports various benthic macroinvertebrates; or deep pools where piscivorous predators may ambush smaller fish. Habitat diversity is generally correlated with diversity in fish communities within streams.

Fish are often the primary connection between a water course and the human population that utilizes it. The devotion that these resources inspire is demonstrated by the creation of resource-based groups like BASS and Trout Unlimited. These groups invest significant resources in the preservation of habitats that supports the population in which they are interested. Because their efforts are directed at habitat preservation and restoration, the result often benefits all species using the habitat. This scenario demonstrates the importance that man places on aquatic resources supporting fisheries. It is for this reason

that the benefit of restoration projects on fish populations is important and should be considered as a potential parameter to be evaluated. Fish are good indicators of both short-term and long-term water quality and stream condition because they are relatively long-lived, mobile and many have a lifecycle that requires high water quality. Assessing stream fish populations provides important information for understanding the functioning of the biological community, for evaluating biological integrity and for protecting surface water resource quality (Barbour et al., 1999).

There are many stream restoration practices benefitting fish populations within all four underlying levels of the Stream Functions Pyramid that are similar for other biological communities. Hydrology and flow dynamics are very important for fish populations, particularly considering the essential requirement of adequate flow conditions throughout the seasons. Upstream impoundments and water withdrawals should be addressed prior to design to ensure continuous streamflow. If these upstream flow conditions cannot be addressed, then restoration of fish habitat may be futile. Assessment of reference condition is an important tool for determining if fish are present in the stream type, as well as size that will be restored. Upstream populations will also determine re-establishment of fish communities. If there is no upstream fish population, stocking may be required to introduce the fish into the newly created habitat. Species of special concern, including any threatened or endangered species designated by federal and state agencies, should always be considered first when designing habitat features of a restored stream channel. Hydraulic parameters, including floodplain connectivity and the provision of a bankfull channel, are effective at sustaining fish populations along with other biological communities. A healthy hyporheic zone and substrates that support prey populations will help sustain fish with food resources. Fish habitat created by in-stream structures, large woody debris, macrophyte beds and bed form diversity will allow for feeding, shelter and reproduction, including deep pools and scour holes (Figure 10.4). Established riparian buffers provide shade for temperature regulation and allochthonous inputs to sustain prey populations and the large woody debris. Good water quality is important, especially maintenance of dissolved oxygen levels that result from structures and flow dynamics providing turbulence for oxygen entrainment, and from habitats that provide primary production of algae and macrophytes.

A healthy, functioning fish community occurs when the following conditions are present:

- Continuous upstream streamflow sources, as removal of impoundments and excessive water consumption for human activities will provide adequate streamflow throughout the year;
- Floodplain connectivity and bankfull channel, dissipate energy of large storm events to prevent excessive scouring of substrates used for reproduction (pools), and prevent sediment inundation of substrate habitat;
- Healthy hyporheic zones, which provide habitat for food resources;
- Bed form diversity and in-stream structures, which create diverse habitats for feeding and reproduction, dissipate stormflow energy; provides opportunities for organic

carbon storage and retention, provide substrates such as large woody debris, and provide scour pools for reproduction, feeding and shelter;
- Channel stability, which prevents sediment inundation of habitat and excessive turbidity that is contributed from channel erosion;
- Riparian community, which provides allochthonous carbon inputs for food resources, provides shade for cooler temperatures and provides vegetative roots for available habitat; and
- Adequate dissolved oxygen, which is required for fish survival and health.

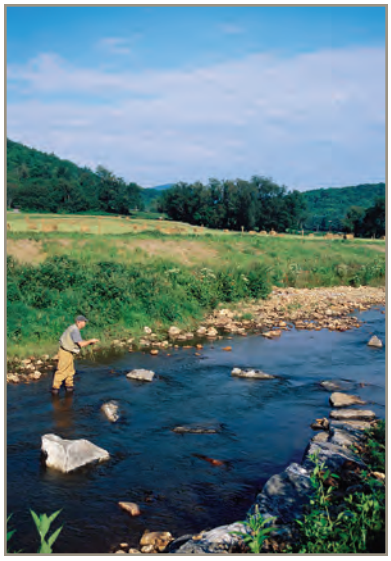

FIGURE 10.4 FISH HABITAT IN A SCOUR POOL CREATED BY AN IN-STREAM STRUCTURE, REFERRED TO AS A J-HOOK.
Source: Reproduced with permission from Michael Baker Corporation

Measurement Method

Fisheries resources can be sampled using a variety of approaches, and the sampling methodology selected should be chosen to provide quantifiable measurements for the parameter addressed (Bonar et al., 2009). The USEPA's RBP (Barbour et al., 1999) recommends using electrofishing to collect samples, a common method used by most state fishery departments and fisheries investigators to evaluate fish populations in designated reaches (Carle and Strub, 1978; Zippin, 1956). Snorkeling the study reach and recording observed species is a less intrusive method that some have used. This has been used as an alternative to electrofishing (Thurow and Schill, 1996; Mullner et al., 1998) for estimating abundance and population size structure. The National Park Service, in conjunction with George Mason University, compiled an Ecological Assessment Methods Database (2010). The database was originally created to provide park managers with a source for identifying and selecting assessment methods for various watershed management practices, including methods for assessing fisheries and their habitat. The database can be accessed at *http://assessmentmethods.nbii.gov*.

When evaluating fish communities, there are several factors that must be considered. Fish movement (passage) within the stream, and upstream water quality issues should be considered when interpreting data. Sample design often involves comparisons between restored areas and unrestored areas on the same stream, and should include pre- and post-restoration sampling.

The three categories of measurement methods associated with biological fish communities are presented below including the direct methods for taxonomic and non-taxonomic measurements, as well as the indirect method of the biological index measurement. The level of effort is considered intensive, except for certain biological indices that may require only moderate efforts. These methods are also complex because they require

trained biologists to adequately collect the macroinvertebrates from different habitats, determine characteristics of the community, and effectively compare the community to reference condition assemblages. Again, certain biological index methods may be moderate in their level of complexity, depending on the variables and methods included (Appendix Ac).

1. Taxonomic Measurements

Once a fish population sample is obtained, individuals should be identified to species and enumerated. Fish sample data can be expressed in species composition, relative abundance, species richness (or other taxon), percent similarity between sites, Simpson's Diversity Index (Simpson, 1949), or other similar indexes and metrics.

2. Non-Taxonomic Measurements

Data on population size or biomass will require length and weight data of fish collected within a sample, as well as a good measure of the area sampled. The growth rate, or change in biomass of fish over time, is an estimate of productivity. Growth rate data requires aging fish or estimating age and is a more complicated process than most restoration monitoring programs will undertake; but this process is still a good measure of fish community productivity. Details of both taxonomic and non-taxonomic methods can be found in Hauer and Lamberti (2006), Methods in Stream Ecology.

3. Biological Index

As with other taxa, fish population quality can also be expressed in an Index of Biotic Integrity. Karr et al. (1986) recommended 12 measures of fish assemblages that fall into three broad catagories: species composition, trophic composition, and fish abundance and condition. This methodology has been applied to evaluations of fish populations, and it has been adjusted by state and regional biologist to reflect regional stream conditions. Angermeier and Karr (1986) used an IBI for stream-fish communities to evaluate water and habitat quality. Roth et al. (1996) used a fish population IBI to demonstrate that habitat and fish assemblage quality was highly correlated.

Performance Standard

For the best results, performance standards should be based on data collected from reference reaches upstream of the restoration reach. A reference condition can be established using the upstream reference reach and/or other reference streams. Multiple samples that account for spatial and temporal variability should be collected before setting these standards. If species to be evaluated include populations that support a fishery, evaluators should consult state fishery agencies to see if they have already established the range of variation that these populations typically exhibit. This information can then help guide empirically establishing performance standards.

Performance standards for taxonomic and non-taxonomic measurements have generally not been developed. However, biotic indices developed for specific stream types, and regions that combine these measures with stream physicochemical and habitat conditions

can be used as performance standards. Several examples of biotic indices are listed in Table 10.5. Streams that fall into the Functioning category have high species diversity and relative abundance, which indicates good stream habitat. The Not Functioning category would most likely have very low taxa richness and mostly very tolerant taxa that indicates poor stream habitat.

TABLE 10.5 FISH COMMUNITY PERFORMANCE STANDARDS

MEASUREMENT METHOD	FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING
Mid-Atlantic Highlands IBI (McCormick et al., 2001)	IBI > 72 Good to Excellent	IBI = 56 to 71 Fair	IBI < 56 Poor
Mid-Western Fish Community IBI (Karr et al., 1986)	48-60 Good to Excellent	40-44 Fair	0-34 Poor to No Fish

10.5 » PARAMETER: LANDSCAPE CONNECTIVITY

Description

The importance of using a holistic landscape perspective for understanding stream ecosystem structure and function is well established. Recognition of the connection between the stream and surrounding terrestrial ecosystems was fundamental to the development of stream ecosystem theory (Hynes, 1975; Minshall et al., 1985). The landscape connectivity concept is defined as "the degree to which the landscape (physical structure) facilitates or impedes movement (organism behavior) among resource patches" (Taylor et al., 1993). It includes both structural and functional aspects of the landscape. Structural aspects are the physical relationships among habitat patches and the distance between them. The dimensions of a stream riparian buffer corridor are an example of structural connectivity. Functional aspects are what affect the movement behavior of organisms through the landscape. Most landscape connectivity evaluations include only structural assessment, which may not be at the appropriate spatial scale nor adequate to prevent loss of essential habitat. There is a critical threshold of landscape connectivity that must be maintained in order for the species of interest to persist (With et al., 1997).

In stream restoration projects, landscape connectivity represents the ability of a target aquatic or riparian species to move between habitats. Fish migrate upstream and downstream to feed and reproduce. Benthic macroinvertebrates migrate not only upstream and downstream, but also across the land-water interface between the larval and adult stages. Some benthic macroinvertebrate adults may even require different terrestrial landscape habitats surrounding water to persist. Stream restoration projects can contribute to landscape connectivity using practices at all levels of the Stream Functions Pyramid.

Hydrologic parameters create that link between landscape and lotic system through exchange of water resources, including surface runoff and groundwater inputs. Floodplain connectivity and establishment of riparian buffers are other important land-water connections for organism (plant and animal) movement between habitat patches. Microbial species, plant seeds and spores, and vertebrate eggs can be deposited in terrestrial habitats for migration to the lotic system during high-flow events. Any in-stream structure that promotes habitat diversity and allows passage of animal species or establishment of microbial and plant species is essential for landscape connectivity. Stream stability will protect both aquatic and terrestrial habitats and allow for movement of species. Good water quality and resource availability (carbon and nutrients) are essential for healthy biota that will move between habitats and persist through landscape connectivity.

Landscape connectivity is enhanced when the following conditions are present:

- Long reaches of restoration connected to other high-quality reaches, which provide healthy stream corridors;
- Surface runoff and groundwater inputs, which maintain the connection between land and water habitats and their shared resources;
- Floodplain connectivity and established riparian buffers, which maintain the connection between land and water habitats and their shared resources, and allow movement of species between habitats during life cycle;
- In-stream structures, which can promote organism passage and habitat and substrate for stream organisms;
- Stream stability, which protects aquatic and terrestrial habitats; and
- Good water quality and resource availability, provide the environmental conditions for biological movement and species persistence.

Measurement Method

Measurement methods used to assess landscape connectivity are all direct measures that require intensive level of effort due to the spatial aspects associated with the data required. The methods are all considered complex due to the tools required for assessment, e.g., GIS, GPS and models, as well as the expertise required for data collection and analyses. There are three measurement methods described below.

1. Spatial Analysis

In order to measure overall landscape connectivity effectively, both structural and functional pieces must be included. Structural landscape connectivity can be measured using linear features on the landscape, which are commonly measured with current spatial analysis technologies such as GIS. The length of a riparian corridor or forested wetland patch near a stream would be an example of a linear feature.

2. Species Tracking

Functional landscape connectivity measurements are not as readily available because they are specific to individual species or species groups with similar behaviors. Taylor (1993) details species parameters that can provide information on species movement in response to the landscape structure, including movement rates, dispersal range, mortality during dispersal, and boundary interactions. Species movement is not easy to measure, but knowledge of species behavior can be gathered from the literature and from on-the-ground tracking and satellite GPS technologies. In streams, invertebrates and vertebrates can be tagged for monitoring. Currently there are tracking products available for larger aquatic species (e.g., Pacific salmon; Eiler, 1995), but smaller species and canopy cover issues have not advanced. Consultation with biologists who are familiar with the species of interest, their habitat requirements throughout their life cycle, and their behaviors can help with landscape connectivity measurements.

3. Habitat Models

There are also various habitat models described in the literature that have been developed to provide landscape connectivity assessments specifically (With et al., 1997). There are also GIS-based models that have been developed to help with habitat assessments that can be found at the following websites:

Circuitscape: *www.circuitscape.org/Circuitscape/Welcome.html*
Conefor Sensinode: *www.conefor.org*
Funconn: *www.nrel.colostate.edu/projects/starmap/funconn_index.htm*
Pathmatrix: *cmpg.unibe.ch/software/pathmatrix*

Performance Standards

There are no performance standards developed for landscape connectivity at this time. The landscape matrix should be included in stream restoration planning, however, in order for the project to provide the greatest biological benefit. Although this matrix most often extends beyond the boundary (and scope) of stream projects, it is important to keep it in mind as a focal point during the planning process in order to establish the landscape connectivity needed for a healthy biological community. Landscape connectivity also relates to proper site selection for a stream restoration project. In order to see the most improvement in the other Biology parameters listed above, it is critical that the restoration reach be "connected" with a high-quality upstream reference reach. The restoration reach, in turn, begins to provide the necessary conditions for future downstream restoration efforts to continue progress towards landscape connectivity for species selected within the stream. Linking restoration projects together is a good way to increase landscape connectivity and work towards watershed scale restoration. This approach provides greater functional lift than restoring discrete stream reaches that are spread out across the watershed.

Chapter 11

Application of the Stream Functions Pyramid

This chapter provides three different examples of how the Stream Functions Pyramid can be applied. These applications include creating function-based goals and objectives, developing stream assessment methods, and establishing stream mitigation debit and credit determination methods.

Goal setting is critical to the success of a project because it communicates why the project is being done and sets expectations on how success will be measured. The goal-setting section provides several examples of goals that will improve stream functions when achieved. The assessment and mitigation sections provide a broad overview of how the Pyramid can be applied. It does not provide a "cookbook" approach to developing a functional assessment methodology or stream mitigation Standard Operating Procedures (SOPs). Rather, the examples and templates provided below are intended to provide a broad-level framework. Scientists and managers may choose to create more specific or quantitative functional assessments and debit/credit determination methods based on the examples provided in this chapter.

11.1 » ADDING PARAMETERS, MEASUREMENTS AND PERFORMANCE STANDARDS

The existing Stream Functions Pyramid Framework includes a wide range of function-based parameters that are applicable for a wide range of environmental settings. However, users may need to add a function-based parameter based on a unique project or assessment goal. This is most likely to occur at the Biology Level because not all forms of aquatic and riparian life are included, e.g., mussels and amphibians. To add a function-based parameter, users should follow the selection criteria outlined in Chapter 4.

11.2 » DEVELOPING GOALS AND OBJECTIVES

Developing goals and objectives is important for projects of all sizes. Well-articulated goals and objectives establish a foundation for project success. Vague, too broad, or poorly articulated goals and objectives often lead to project failure (worst case) and misunderstandings at best. The terms goals and objectives are often used interchangeably; however, there is a difference. Goals are statements about why the project or effort is needed. They are general intentions and often cannot be validated. Objectives are more specific. They help explain how the project will be completed. They are tangible and can be validated, typically by the performance standard.

Even with this differentiation, it can be challenging to develop well-formulated goals and objectives. Part of this difficulty relates to the scale and type of effort that is being undertaken. For example, watershed management plans require goals and objectives at a broad scale, i.e., to cover a large watershed. Stream restoration projects require goals and objectives that are typically formulated at a reach scale and after some type of assessment has been completed to determine the problem, i.e., what function(s) needs to be restored. This can be an iterative process as the project team tests the restoration needs against project and watershed constraints.

Goals are statements about why the project or effort is needed. They are general intentions and often cannot be validated. Objectives are more specific. They help explain how the project will be completed. They are tangible and can be validated, typically by the performance standard.

Regulatory and non-regulatory programs also have goals and objectives, but they may not be tied to a specific watershed or reach. For example, Trout Unlimited, a non-regulatory organization, has broad goals to improve the quality of trout streams, wherever trout streams exist. The Clean Water Act (FWPCA, 1972) has an overall goal for all waterways to be fishable and swimmable. Section 303 of the CWA includes provisions to have all streams, and rivers support the designated uses identified in their water quality standards (FWPCA, 1972). No net loss of wetland resources is a goal of the Section 404 of the CWA program and the fundamental objective of compensatory mitigation in the regulatory program is to offset environmental losses resulting from unavoidable impacts [33.C.F.R. § 332.3(a)(1)_/40 C.F.R. § 230.93(a)(1)].

Many existing stream SOPs associated with the CWA Section 404 program include references to restoring stream dimension, pattern and profile as a way to acquire restoration credits. This has resulted in many stream mitigation plans being created that state the goal of a project is to restore dimension, pattern, and profile, rather than stating goals that provide some type of functional lift to offset permitted losses and better align with the fundamental objective of the CWA Section 404 regulatory program.

The Stream Functions Pyramid can be used to help prepare better goals and objectives for watershed management plans, regulatory and non-regulatory programs, and stream restoration projects. Simply stated, the Pyramid can help link goals and objectives to stream functions. For example, the Pyramid can be used to help articulate goals that relate to the improvement or assessment of stream functions or even function-based parameters. The goal should relate to the primary function(s) of interest, e.g., life history of some type of aquatic life. This information is provided on the Pyramid Overview and the Pyramid Functions and Parameters. Objectives should help explain how the functional improvement will occur. Objectives can also be used to identify the supporting functions needed to meet the goal. The Pyramid Functions and Parameters, Measurement

Methods and Performance Standards are all helpful in formulating objectives. These figures and tables are provided in Appendix A. Other sources for developing stream restoration-related goals and objectives include the NRCS Stream Restoration Design Manual, Part 654, Chapter 2 (USDA NRCS 2007) and the USACE Technical Note, Ecosystem Restoration Objectives and Metrics (McKay et al., 2012).

Developing goals and objectives requires an understanding of how to "enter" the Pyramid, i.e. how to start using the Pyramid Framework. Examples for watershed management plans, regulatory/non-regulatory programs and project designs are provided below.

Watershed Management Plans

Watershed management plans typically include two major components, an inventory of water resource problems, followed by options/recommendations for improvement. These improvement options may include preservation, restoration, stormwater best management practices (BMPs), Low Impact Development (LID), etc. A key to success is to link the appropriate improvement option to the appropriate impairment. This is an area where the Stream Functions Pyramid Framework can help articulate specific goals and objectives by answering the following questions:

1. Look at Pyramid figures in Appendix A. What types of functional losses have occurred in the watershed? Try to relate the losses to function-based parameters, e.g., channelization and loss of floodplain connectivity, and/or population declines to native fish species.
2. Can these functions be restored? This requires an understanding of the stream functions and the cause of the impairment, along with the potential for their improvement.
3. Look at Pyramid figures again. What supporting function-based parameters are needed to assess improvement to the impaired functions listed in number 1?
4. What types of restoration activities are needed to improve those function-based parameters? This could include stream preservation of healthy headwater streams and restoration of degraded stream channels. It could also include stormwater BMPs and LID. An experienced multi-disciplinary team will be required to link the improvement activity to the functional lift.

Answering these questions will allow the team to develop goals and objectives that relate to functional impairments and their potential improvements in the watershed. For example, depending on how the questions were answered, an example goal and associated objectives may include the following.

Goal:
Improve the health of a smallmouth bass fishery. (Note that this relates to Level 5 on the broad-level overview Pyramid.)

Objectives:
1. Reduce stream temperature and improve dissolved oxygen to concentrations required

by smallmouth bass (Level 4).
2. Improve bed form diversity to meet smallmouth bass habitat requirements (Level 3).
3. Provide floodplain connectivity to provide the flow dynamics needed for smallmouth bass (Level 2).
4. Evaluate watershed runoff and flow duration to determine the suitability for supporting smallmouth bass (Level 1).

These objectives are specific function-based parameters that support the higher-level goal of restoring a smallmouth bass fishery. They are quantifiable, tangible and can be measured. In some cases, these parameters have measurement methods that include performance standards. The objectives provided above are just examples and could be changed or expanded for an actual watershed plan. In addition, a wide range of improvement options may be required to meet the watershed scale goals and objectives described above. These activities are discussed in item 4 of the Watershed Management Plans section above.

Regulatory and Non-Regulatory Programs

The same approach provided above for watershed management plans can be used in regulatory and non-regulatory stream improvement programs. For example, non-regulatory programs, such as watershed coalitions and non-profit organizations, set programmatic goals and objectives. As with watershed management plans, these goals are typically established at Level 5 since they relate to some type of aquatic life impairment. An example would be Trout Unlimited with the goal to restore a fishery. The advantage of the Pyramid is that once the aquatic life of interest is identified, the supporting functions can be established through quantifiable objectives. This will help the organization focus its resources by addressing activities that specifically affect the critical functions.

The same holds true for regulatory programs like Sections 303 and 404 of the Clean Water Act (FWPCA, 1972). Under Section 303, states are required to have water quality standards that support designated uses for waterways. Streams that do not meet these requirements are placed on the 303(d) list. For pollutant-impaired waters, Total Maximum Daily Loads (TMDLs) must then be established to address the pollutant(s) causing the impairment. Nationwide, sediment is the second-ranked pollutant causing streams and rivers to be placed on the 303(d)(USEPA, 2012). The causes of impairment are often inferred from results of biological monitoring, i.e., sediment is often identified as a reason that macroinvertebrate populations are negatively impacted.

The Pyramid could be used in impaired waters programs to establish more specific targeted load reduction alternatives based on cause-and-effect relationships shown on the Pyramid. For example, an initial assessment may show that the macroinvertebrate populations have lower abundance and more tolerant taxa than the reference conditions for a given area. Next, the Stream Functions Pyramid can be used to identify all the supporting functions that are required to support a healthy macroinvertebrate community. Third, further assessments can be conducted to determine if those functions (using function-

based parameters and a measurement method appropriate for the study) are Functioning, Functioning-at-Risk or Not-Functioning. Finally, objectives could be established that focus on the improvements needed to change the Not-Functioning and Functioning-at-Risk parameters to Functioning. This would likely include more parameters than just sediment, but would yield a plan with much more detail and potential for success.

The Pyramid can also be used to improve goals and objectives related to Section 404 of the Clean Water Act and compensatory mitigation. As was discussed above, many mitigation providers relate restoration goals to changes in channel dimension, pattern and profile. Mitigation credits are often provided based on these, among other, changes (USACE Wilmington District et al., 2003; USACE Norfolk District and VDEQ, 2007; and USACE Charleston District, 2010). The Pyramid can help practitioners develop goals and objectives that relate directly to stream functions. Over the last few years, attention to stream mitigation requirements associated with stream impacts from coalmining activities in Appalachia has increased. Practitioners and the regulatory community have grappled with how to assess functional lift through compensatory mitigation, especially for projects that include onsite mitigation. The process starts with setting appropriate goals and objectives. An example of how the Pyramid can be used to provide goals and objectives for on-site stream mitigation associated with large scale landscape modifications, such as mining, is provided below.

Example Goals:

1. Achieve replacement of aquatic functions (functions are defined in a function-based assessment) through onsite mitigation.
2. Use natural channel design techniques to re-establish a small headwater stream network after mining activities have ceased.

Example Objectives:

1. Water quality (pH and conductivity) will have similar or more suitable ranges compared to the pre-disturbance condition.
2. Bed form diversity, defined by pool-to-pool spacing and depth variability, will be improved compared to the pre-disturbance condition and will be characterized as Functioning using the Stream Functions Pyramid.
3. A 50-foot-wide riparian buffer composed of native grasses and trees will be established.
4. The restored channel will include large woody debris that meets a Functioning level.
5. The restored channel will have streambank erosion rates that are less than or equal to the existing condition and meet a Functioning level.
6. Floodplain connectivity in the restored channel will meet a Functioning level. Note: floodplain connectivity in v-shaped and colluvial valleys is characterized by a flood-prone area that can be very small.
7. Post-restoration flow duration will match pre-disturbance flow duration.
8. Post-restoration aquatic IBI scores will match or exceed pre-disturbance values.

These goals and objectives are just examples and would be modified based on the function-based assessment and local knowledge of the site. The value of using specific objectives, like the ones above, is that developing performance standards becomes much easier. The performance standards simply quantify the objectives.

Restoration Project Design Goals and Objectives

The Stream Functions Pyramid Framework may be the most useful in developing design goals and objectives, which are developed once a restoration site has been selected and some form of functional or existing condition assessment has been completed. Using the Pyramid to assist with functional assessments is discussed in the next section. More information about developing goals and objectives associated with natural channel designs is provided below.

Restoration projects generally occur at a reach scale and can have significant functional lift of Level 2 and 3 parameters. However, to achieve goals in Levels 4 and 5, a combination of reach scale restoration and adequate upstream watershed health are required. In other words, site selection becomes critically important to achieving Level 4 and 5 goals.

Developing design goals and objectives can be an iterative process. Typically, a broad goal is established early in the process, perhaps prior to the functional assessment. This goal could relate to a broad watershed goal, like restoring a smallmouth bass fishery as described above under Watershed Management Plans. After the assessment, other functional impairments may be identified that prohibit the restoration of a smallmouth bass fishery. These impairments may occur in the upstream watershed and cannot be addressed by the restoration project. In this case, the team would need to pick a different approach or establish new goals based on what can be achieved at the site (reach scale). Often the goal can be revised to improve function-based parameters in Levels 2 and 3, e.g., floodplain connectivity, bed form diversity, lateral stability and riparian vegetation. This will not directly restore a smallmouth bass fishery, but it can indirectly help smallmouth bass recovery by providing the channel form and habitats that they require.

This example illustrates the importance of setting project goals and objectives that are compatible with the health of the watershed. Restoration projects generally occur at a reach scale and can have significant functional lift of Level 2 and 3 parameters. However, to achieve goals in Levels 4 and 5, a combination of reach scale restoration and adequate upstream watershed health are required. In other words, site selection becomes critically important to achieving Level 4 and 5 goals.

Common Mistakes and Ideas for Improvement

A common stream restoration goal is simply to improve aquatic habitat (Fischenich, 2006). This is a poorly stated goal because it does not tell the reader what organism the habitat is for. Habitat requirements for mussels are different than habitat for a trout. If a habitat goal is going to be used, the goal, at a minimum, should state what species the habitat is for, e.g., "The goal of this project is to restore a southeastern native brook trout fishery." Now the reader knows why the project is proposed. Of course, the term "habitat" is still broad and could include many things. So an even better goal would be "To improve the abundance of native brook trout populations within the project reach." This is a goal that can be evaluated, and the measure of success is very specific. Objectives associated with this goal would identify the lower-level function-based parameters that must be Functioning in order to increase the abundance of native brook trout. And since this is a Level 5 goal, a thorough assessment of the watershed must be completed to determine if the upstream conditions will support brook trout, even after reach scale restoration. If not, another project reach, perhaps farther upstream, will need to be selected.

Another common and poorly stated goal is to improve water quality. Like habitat, water quality is a very broad concept and means different things to different people. For example, practitioners in West Virginia will typically equate water quality to pH and conductivity because of their work with the coalmining industry. Practitioners working in the eastern US Coastal Plain region will typically think of water quality as a nutrient (e.g., nitrogen and phosphorus) issue. Practitioners in the eastern US Piedmont and Mountain regions may think of water quality as a sediment or turbidity problem. Practitioners in the Pacific Northwest often think of water quality as a temperature problem. There are many other examples across the country, depending on the primary causes of water quality impairment. The key is to be specific. Use the goal to clearly establish why water quality is being addressed: to improve pH, conductivity, nutrients, sediment or other physicochemical properties. And, as with all of the goals, the next step is to develop objectives that identify the supporting, lower-level function-based parameters that must be Functioning in order to meet the goal. This also provides an opportunity to determine if stream restoration is the appropriate solution, or if other techniques are required. For example, stream restoration may have a minimal influence on conductivity and pH.

11.3 » FUNCTION-BASED STREAM ASSESSMENTS

The Pyramid is a framework that can be used as an aid in developing and reviewing function-based stream assessments. Somerville (2010) showed that stream assessments are often completed for a variety of regulatory and non-regulatory reasons, and range from broad assessments of stream condition to specific regulatory requirements. Three uses of function-based stream assessments will be discussed below and include:

- Determining restoration potential and functional lift;
- Determining stream functions lost and gained as part of a compensatory mitigation project; and
- Locating potential stream restoration projects as part of a watershed management plan.

A function-based assessment may include parameters from the Pyramid that are functions themselves; parameters that are not functions but help to describe the function from that category, e.g., bank height ratio from the Geomorphology category to help explain flow dynamics and floodplain connectivity. Parameter selection will be determined by the purpose of the assessment, the funding level and the geographic region. For example, flow duration is more limiting in some regions (and for some restoration types) than it is in others. Simple parameters may be selected for rapid-based assessments, and more complex parameters (that are also functions) may be selected for more intensive studies.

Regardless of the reason for completing function-based stream assessments, the following steps should be completed when using the Pyramid as a guide.

1. Determine the purpose of the assessment.
2. Select parameters from the Pyramid and/or other sources of information about parameters that describe stream functions relevant to the study. Include supporting functions.
3. Determine the appropriate methods for measuring the parameters, e.g., rapid versus intensive, and simple versus complex. This selection will also be dependent on the budget and purpose of the assessment.
4. Determine if the measurement methods need to be adapted based on unique regional characteristics, e.g., karst topography or endangered species.
5. Review the performance standards that are associated with the measurement methods, and determine if they are appropriate based on local environmental conditions and the purpose of the assessment. If possible, update performance standards with information from local reference streams.
6. If deemed necessary by the purpose, develop a scoring method to determine the overall functionality score of the stream reach, i.e., Overall Functioning, Functioning-at-Risk or Not Functioning. Consider having an overall score per functional category as well, e.g., Geomorphology, to help show where functional problems may exist.
7. Establish the length of the assessment (monitoring) period.
8. Implement function-based stream assessment, evaluate its effectiveness in assessing stream functions, and adapt method as necessary.

A description for each of the three general uses for stream assessment methods is provided below, along with examples of parameters from the Pyramid that could be included for that assessment.

Determining Restoration Potential and Functional Lift

The Stream Functions Pyramid Framework can be used to determine the restoration potential at a proposed project site. Restoration potential is the highest level of restoration or functional lift that can be achieved given the site constraints and health of the watershed. Once the restoration potential is known, specific design goals and objectives can be established, or original goals and objectives may need to be refined.

These assessments may include parameters from all five levels of the Pyramid that

quantify and describe the pre-restoration condition of the channel. Common Level 1 parameters include the precipitation/rainfall relationship, channel forming discharge and flood frequency. These parameters are used to quantify and describe the transport of water from the watershed to the channel, and they are needed in order to complete the Hydraulic and Geomorphology portions of the assessment. Common Level 2 parameters include both flow dynamics and floodplain connectivity, since these are critical for determining channel stability. Flow dynamics are typically assessed by measuring stream velocity, shear stress and stream power. Floodplain connectivity is most commonly assessed using the bank height ratio and entrenchment ratio. If the bankfull stage is unknown, stage-versus-discharge estimates using a hydraulic computer model can also be used to assess floodplain connectivity. However, to complete a proper hydraulic assessment to determine channel stability, field surveyed cross sections are required. A longitudinal profile is helpful for measuring bank height ratios along the reach. The profile can also be used for Level 3 assessment.

Restoration potential is the highest level of restoration or functional lift that can be achieved given the site constraints and health of the watershed. Once the restoration potential is known, specific design goals and objectives can be established, or original goals and objectives may need to be refined.

Level 3 parameters include sediment transport competency and capacity, channel evolution, streambank erosion rates, bed form diversity, large woody debris assessments, and riparian vegetation assessments. These parameters may be measured using rapid or more intensive approaches, based on the complexity of the project and funding level. However, the main purpose of the Level 3 assessment is to determine if the channel is vertically and laterally stable. Channel evolution assessments are used in combination with the above measures to estimate the future trend, i.e., whether the stream is evolving towards stability or instability. Of course, some stream types are naturally unstable; however, these streams should not be candidates for restoration. Common Level 4 parameters include basic water quality measures like pH, conductivity, temperature and dissolved oxygen. Assessments in the eastern US Coastal Plain region may also include nutrient assessments. Level 5 function-based parameters sometimes include macroinvertebrate and fish community assessments. Landscape connectivity is rarely used, but should be considered for providing watershed scale improvements.

The assessment results can then be used to determine the restoration potential. For example, the assessment may indicate that a stream reach is severely incised with extreme bank erosion, low bed form diversity, and no riparian vegetation. If this site is in a rural setting (low lateral constraints) with a healthy watershed, then the restoration potential is high because functional lift can likely be achieved through Level 5. However, if this same site is in an urban area or a setting with lateral constraints — like a road or

even cropland — that cannot be removed from production, then the restoration potential is lower because the functional lift may only occur in Levels 2 and 3.

Table 11.1 can be used to illustrate the baseline functions at the project site along with the proposed functional lift; the examples provided above are shown in the table. The values are arbitrary and not associated with a project. The purpose is simply to show how the function-based parameters, measurement methods and performance standards may be used as part of an assessment. The function-based parameters and measurement methods are selected based on the restoration potential, and the performance standards are used to quantify the functional lift.

Determining Stream Functions Lost and Gained as Part of a Compensatory Mitigation Project

The 2008 Mitigation Rule recommends that some type of functional assessment be completed at the permitted impact site and the mitigation site. The purpose of the functional assessment is to determine the functional loss at the permitted impact site and the functional lift at the mitigation site. Functional lift is defined as the difference between the pre-restoration and post-restoration condition. This process is intended to result in replacement of aquatic resources, in this case, the stream ecosystem.

Developing a function-based assessment for this purpose would be very similar to the one used to determine restoration potential and functional lift (described above). One difference is that the assessment would need to be applied at the permitted impact site and the mitigation site. The level of assessment will vary at the impact site, as the level of impact varies from minor (e.g., a culvert replacement or utility crossing) to major (e.g. surface mining or new road construction). For example, if only a few parameters are being affected, then only a few parameters need to be included in the assessment. If all five levels are being affected, the assessment should include parameters from all five levels. For the mitigation sites, the assessment can be more consistent with, and will be similar to, what is described in the restoration potential and functional lift section above. These parameters would then be assessed as part of the monitoring phase, and the data used to determine if performance standards are being achieved.

Locating Potential Stream Restoration Projects Using a Watershed Management Plan

Watershed management plans are becoming common among non-regulatory and regulatory programs. These plans are typically used to (1) identify the sources of stream and water quality impairments; (2) identify stream reaches and sub-watersheds that are relatively un-impacted, and (3) develop management plans to improve stream health and water quality. Federal programs that support watershed management plans include grants provided by Section 319 of the Clean Water Act (FWPCA, 1972), Total Maximum Daily Loads (TMDL), 2008 Mitgation Rule, and others.

Function-based stream assessments fit well with watershed management plans. They are often used as the method for differentiating between impaired and unimpaired

TABLE 11.1 FUNCTIONAL LIFT DETERMINATION

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Channel-Forming Discharge	Regional Curves	200 cfs	N/A	200 cfs	N/A Used as an input parameter for Level 2 and 3
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	3.0	Not Functioning	1.0	Functioning
		Entrenchment Ratio	1.1	Not Functioning	3.0	Functioning
3 – Geomorphology	Bed Form diversity	Pool-to-pool spacing	> 7	Not Functioning	4 to 5	Functioning
	Channel Evolution	Simon	Stage 2 to 3	Not Functioning	Stage 6	Functioning
	Riparian Vegetation	RBP	Width is 12 meters with some human activity	Functioning-At-Risk	Width is > 18 meters and no human activity	Functioning
	Lateral Stability	BEHI/NBS	High/High	Not Functioning	Low/Low	Functioning
4 – Physicochemical	Water quality	Temperature	Higher than upstream reference reach; does not meet species requirements	Not Functioning	Same as upstream reach and meets species requirements	Functioning
5 – Biology	Macroinvertebrate Communities	Virginia Stream Condition Index	7	Not Functioning	4	Functioning

stream reaches. To complete this task, these assessment methods are often implemented differently at the watershed scale and the reach scale. At the watershed scale, GIS, remote sensing and aerial photography are used to broadly assess parameters that would indicate stable, healthy streams versus unstable streams. These parameters from the Pyramid might include riparian vegetation, lateral stability and landscape pathways, all of which can be assessed with GIS and aerial photography. Some watersheds may be included in FEMA-regulated floodplains and contain Hydrology and Hydraulic characterizations that can be used to estimate floodplain connectivity and flow dynamics.

From this initial screening, on-the-ground, rapid-based assessments can be used to further determine channel stability, channel evolution, restoration potential, basic water chemistry and biological health. Rapid methods are needed so that long reaches of channel can be assessed in a relatively short period of time. The result is a map showing the location of impaired stream reaches, their proximity to other land uses, and a priority ranking for restoration. For example, an impaired stream downstream of a high quality sub-watershed, or an impaired reach between two stable reaches, would be high priorities because the functional lift would transcend the project reach length. Conversely, an impaired reach downsteam of multiple point source discharges, or areas of rapid development, may receive a lower priority; therefore, other techniques like stormwater BMPs and Low Impact Development may be recommended instead. Once reaches are selected for a project, a more intensive assessment method to determine channel stability and restoration potential can be implemented.

Additional information about conducting watershed assessments can be found at *http://water.epa.gov/type/watersheds*. There is a wealth of information on this website, but one tool that my be particularly helpfulfor evaluating potential stream restoration sites is the Recovery Potential Project, a landscape screening tool for assessing the restorability of impaired waters.

11.4 » KEY PARAMETERS

The Stream Functions Pyramid includes over 30 parameters, but it is unlikely that a project would ever need to assess them all. However, there are core or key parameters that can be listed for a variety of common projects, such as restoring channelized streams in alluvial valleys back into meandering streams, restoring small headwater streams associated with mining, and improving salmonid fish habitat. Examples of key function-based parameters that should be evaluated before and after restoration are provided below. A variety of rapid and more intensive measurement methods are also provided.

The Stream Functions Pyramid includes over 30 parameters, but it is unlikely that a project would ever need to assess them all.

Restoring Channelized Streams in Alluvial Valleys to Meandering Streams

Many projects in the eastern US attempt to restore streams that were enlarged and

deepened through channelization and incision. These projects occur in alluvial valleys, in both urban and rural settings, and with a variety of substrate compositions. The Rosgen Priority Levels are often used as an approach for restoring these streams. Figures 11.1a and 11.1b show before and after photos of a stream restoration project in the Coastal Plain of North Carolina. Figure 11.1a shows a channelized, incised stream that lacks bed form diversity due to low sinuosity and dredging. There is minimal riparian vegetation and nutrient runoff that can easily enter the stream from the adjacent cropland causing eutrophication. Figure 11.1b shows the same project site approximately one growing season after restoration construction was completed. The stream is shallower than the pre-restoration condition, creating enhanced floodplain connectivity and an elevated water table that supports the development of riparian wetlands. The meandering pattern carries both baseflow and bankfull flows effectively, providing longer retention times and opportunities for denitrification. The biggest driver of denitrification is the increased floodplain access by stormflows, water storage on the floodplain, shallow depth to the water table, and establishment of a woody riparian buffer over time.

FIGURE 11.1A PRE-RESTORATION

FIGURE 11.1B POST-RESTORATION

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This project, like most other restoration projects where channelized streams are converted back into meandering systems, highlights four key parameters that must be addressed to achieve project success. The key parameters include: floodplain connectivity, bed form diversity, lateral stability and riparian vegetation. These function-based parameters are shown below in Table 11.2. The second column provides measurement methods that can rapidly be assessed with minimal field measurements. The third column provides measurement methods that provide a more detailed assessment of the stream reach; however, they also require more effort. These more intensive measurement methods require more time in the field to collect data and, in some cases, require repeated monitor-

The key parameters include: floodplain connectivity, bed form diversity, lateral stability and riparian vegetation.

ing over several years, e.g., developing rating curves, establishing erosion rates and measuring vegetation growth.

If these four function-based parameters are addressed properly along with proper site selection, then there is a high probability of achieving success by improving the physical, chemical and biological integrity of the stream. This table should not be used to assume that parameters in other levels of the Pyramid are not important (these all come from Levels 2 and 3). Rather, the intent is to show that these parameters are generally the critical foundation to a healthy stream in most alluvial valleys.

TABLE 11.2 KEY PARAMETERS FOR ASSESSING STREAM FUNCTIONS ASSOCIATED WITH RESTORING MEANDERING STREAMS

PARAMETER	SIMPLE MEASUREMENT METHOD	MORE INTENSIVE MEASUREMENT METHOD
Floodplain Connectivity	Bank Height Ratio, Entrenchment Ratio,	Rating curves (discharge vs. stage)
Bed Form Diversity	Percent Riffle and Pool	Depth Variability
Lateral Stability	Streambank Erosion Rates using BANCS model	Measuring Streambank Erosion Rates with permanent cross sections
Riparian Vegetation	Riparian Buffer Width	Riparian Vegetation Density and Composition-Vegetation Plots

Restoring Small Headwater Streams

The key parameters listed in Table 11.2 would need to be modified slightly for assessing stream functions associated with the restoration of small headwater streams, such as those commonly found in the Appalachian Mountains. The restoration of high-gradient, very small intermittent and ephemeral channels as part of stream mitigation projects is common in coalmining regions. In other areas of the Appalachian Mountains, Trout Unlimited and resource agencies work to restore native brook trout populations in headwater perennial mountain streams that are typically located in colluvial and v-shaped valleys. Unlike the lateral meandering streams discussed above, these streams dissipate energy through vertical meandering of the stream bed, i.e., through a step-pool bed form sequence (Wohl, 2000). These streams do not have floodplains that are built by river meandering processes, but rather have floodprone areas that often extend the width of the bowl- or v-shaped valley. Figures 11.2a and 11.2b show an example of a small headwater mountain stream restoration project. Figure 11.2a shows the stream before restoration. The bed form is devoid of pools due to past cattle trampling and channel widening. Figure 11.2b shows the project after restoration construction. Boulder and wood structures were used to create a step-pool bed form, re-establishing the vertical meandering processes. A bowl-shaped floodprone area provides energy dissipation during flood

events, and a riparian buffer was established to provide lateral stability.

FIGURE 11.2A PRE-RESTORATION
Cows are periodically allowed to graze.

FIGURE 11.2B POST-RESTORATION

Source: Reproduced with permission from Michael Baker Corporation

The same key function-based parameters associated with a natural channel design and listed in Table 11.2 are included here in Table 11.3, with one minor exception. Since these channels do not have floodplains, the function-based parameter is changed to floodprone area connectivity, as it is still important for the channel to only carry the amount of water necessary for sediment transport requirements. Flood flows should be transported in the floodprone area. The simple measurement method for bed form diversity also changes, from percent riffle-pool to pool-to-pool spacing, which is a better measure of vertical meandering and has better performance standards (Leopold, 1994; Gregory et al., 1994; Whittaker, 1987; Chin, 1989, and Grant et al., 1990).

TABLE 11.3 CRITICAL CATEGORIES FOR ASSESSING FUNCTIONS BEFORE AND AFTER STREAM RESTORATION PROJECTS

PARAMETER	SIMPLE MEASUREMENT METHOD	MORE INTENSIVE MEASUREMENT METHOD
Floodplain Connectivity (Floodprone Area Connectivity)	Bank Height Ratio, Entrenchment Ratio,	Rating Curves (discharge vs. stage)
Bed Form Diversity	Pool-to-Pool Spacing	Depth Variability
Lateral Stability	Streambank Erosion Rates using BANCS Model	Measuring Streambank Erosion Rates with Permanent Cross Sections
Riparian Vegetation	Riparian Buffer Width	Riparian Vegetation Density and Composition-Vegetation Plots

Table 11.3 is primarily for natural channel design, i.e., these parameters are key design parameters that can have a major effect on creating higher-order functional improvements. Additional function-based parameters may be selected when evaluating headwater mountain stream restoration projects for functional lift that is associated with mining activities. Table 11.4 provides an example of the minimum function-based parameters per functional category that are recommended. Measurement method examples are provided that would be appropriate for a mitigation project; some are rapid and others are more intensive.

TABLE 11.4 POSSIBLE FUNCTION-BASED PARAMETERS AND MEASUREMENT METHODS FOR EVALUATING FUNCTIONAL LIFT IN SMALL, HIGH GRADIENT STREAMS

FUNCTIONAL CATEGORY	FUNCTION-BASED PARAMETER	MEASUREMENT METHOD
Hydrology	Rainfall / Runoff	Rationale Method
Hydrology	Flow Duration	Rapid Indicators
Hydraulics	Floodplain (Floodprone area) Connectivity	Bank Height Ratio Entrenchment Ratio
Geomorphology	Large Woody Debris	Large Woody Debris Index
Geomorphology	Bed Form Diversity	Pool-to-Pool Spacing Depth Variability
Geomorphology	Lateral Stability	BEHI/NBS
Geomorphology	Riparian Vegetation	Buffer Width Buffer Composition Buffer Density
Physicochemical	Water Quality	pH Conductivity
Biological	Macroinvertebrate Communities	State Protocol, if available

There are exceptions to the key parameters listed above. It is likely that many small, headwater ephemeral stream channels in the mountain regions are the product of erosion and channel formation due to land clearing practices during post-European settlement. In some of these systems, forest regeneration has occurred over the decades, and the channel that formed is stable. However, from a functional standpoint, it would be better to have valley bottoms rather than channels that provide greater storage capacity for water, wood, and other forms of organic matter. Restoration would typically not be recommended in stable environments; however, small-channel and no-channel approaches for restoring disturbed systems are being investigated by various researchers and practitioners. Examples of natural channel design in small headwater channels can be reviewed at *https://louisville.edu/speed/civil/si*.

Key Parameters for other Types of Restoration

The key parameters listed above are applicable to many full-scale restoration projects. However, some forms of restoration do not require aggressive changes to channel form, and different key parameters may be required for restoration success. Water removal impacts in the arid West are an example where the key parameters listed above would not apply. In these environments, the channel form may include floodplain connectivity, bed form diversity, laterally stability, and have riparian vegetation common for arid regions; however, historically perennial streams can become ephemeral due to excessive water withdrawals. In these cases, flow duration is the key parameter and the restoration activities may include policy/management changes rather than natural channel designs.

Other examples of restorations that may require minimal or no adjustments to channel form include removal of fish passage impediments and eliminating water quality impairments associated with point-source discharges and stormwater runoff. However, these key parameters listed above should still be assessed, or at least considered, before moving forward with other forms of restoration, especially for perennial streams in alluvial valleys. More likely, additional function-based parameters would be added to the list, rather than removing them.

11.5 » REVIEWING EXISTING STREAM ASSESSMENTS

Government agencies often want to evaluate existing stream assessment protocols before making the decision to develop a new one. Somerville and Pruitt (2004) and Somerville (2010) provide a good starting point for evaluating existing stream assessment protocols. New protocols continue to be developed, especially related to stream mitigation. The draft Regional Guidebook for High-gradient Ephemeral and Intermittent Headwater Streams, USACE (2010), is an example of a functional assessment methodology that has been developed in response to mitigation requirements in coalmining regions of West Virginia and Kentucky. Given the volume of existing assessment methodologies, it is important to have criteria for selecting an existing methodology or for making the decision to develop a new methodology. The following checklist may help with this decision.

Checklist for Selecting Existing Stream Assessment Methodologies

1. Determine why a stream assessment is needed. What is the purpose?
2. Is the assessment needed to meet regulatory requirements?
3. Is the existing stream assessment protocol appropriate for your region? In other words, some protocols are developed for very specific environmental settings and conditions, e.g., high gradient or arid.
4. Has the existing stream assessment protocol been peer reviewed, validated, or otherwise assessed for accuracy and precision in relation to direct functional measures?
5. How much is already known about the functional impairments of the watershed? Some understanding of existing impairments is helpful when selecting an existing protocol because the impairments can be related to the function-based parameters from the Pyramid. Then these parameters can be compared to the parameters as-

sessed in the protocol. If there is a good match, then the existing protocol may be selected. Otherwise, other protocols should be reviewed and potentially new protocols may needed to be developed.

6. Are lower-level functional categories included, e.g., Hydrology, Hydraulics, and Geomorphology? Generally, existing protocols are weak in these categories. Review the protocol to ensure that the supporting/"driver" parameters are included.
7. Are the key parameters described in the above sections included? If not, is there a good reason?

11.6 » DEVELOPING DEBITS AND CREDITS

The development of stream debit and credit determination methods continues to evolve as USACE Districts implement the 2008 Mitigation Rule. The Rule does not provide a formula for developing debit or credits. It simply states that a description of the debits or credits will be provided, including the rationale used. In some regions, IRTs have incorporated credit determination methods into SOPs; however, in other areas, the credit determination method is left up to the mitigation provider. The Rule defines debits as a unit of measure that accounts for the functional loss at a permitted impact site. Some mitigation SOPs, like the Unified Stream Methodology (USACE Norfolk District and VDEQ, 2007) and the Charleston, SC SOP (USACE Charleston District, 2010) provide debit calculations based on a stream condition assessment, similar to a function-based assessment. However, some of the techniques described in the Function-based Assessment section above could be used to better link the functions lost at a permitted impact site to the functions gained at a mitigation site.

The Stream Functions Pyramid can also be used to separate restoration efforts that improve Level 2 and 3 functions, and those that restore through Level 5. As such, IRTs may choose to consider creating two levels of restoration: Restoration 1 and Restoration 2.

Stream mitigation credits are units of measure that represent the accrual or attainment of stream functions at a compensatory mitigation site (33.C.F.R. § 332/40 C.F.R. § 230). The accrual or attainment of stream function occurs through a variety of approaches, including restoration, enhancement, re-establishment and preservation. The Pyramid Framework can be used to help show the functional lift, especially with stream restoration approaches. Stream restoration is defined in the 2008 Mitigation Rule as the "manipulation of the physical, chemical and biological characteristics of a site with the goal of returning natural/historic functions to a former or degraded aquatic resource." Most stream mitigation SOPs cite this definition; however, functional lift is often tied to the Priority Levels of Restoration (Rosgen, 1997) and/or changes to stream dimension, pattern and profile (Somerville, 2010).

This has led to several problems, including: (1) incentivizing maximum channel manipulation to show changes in dimension, pattern and profile to receive the maximum amount of credits; (2) focusing the objectives and performance standards on dimension, pattern and profile changes instead of stream functions or function-based parameters, making the communication of functional lift difficult; and (3) removing evidence of functional lift from the evaluation of project success. This credit determination method has resulted in many projects being evaluated simply on visual observations of channel stability, in-stream structure integrity, and condition of the riparian buffer. The Stream Functions Pyramid, and the forms shown in the assessment section, can help articulate function-based goals, develop function-based assessments, and then develop credit determination methods based on the potential functional lift. Examples of how to do this are provided in the next section.

The Stream Functions Pyramid can also be used to separate restoration efforts that improve Level 2 and 3 functions, and those that restore through Level 5. As such, IRTs may choose to consider creating two levels of restoration: Restoration 1 and Restoration 2. Restoration 1 would restore functions through Level 5 and represent the highest level of restoration achievable. This would require reach-scale restoration and an upstream watershed that supports aquatic life identified in Level 5. It could also include watershed-scale restoration for small headwater systems. More details are provided below about credits; however, 1 credit per foot is proposed as the maximum number attainable, essentially representing 100% restoration. Restoration 2 is also defined as the restoration of reach-scale functions; however, the upstream watershed may not be suitable for supporting species of interest in Level 5. The restoration project may still be worthwhile (based on the function-based assessment); however, functions are only restored through Level 3. Therefore, the maximum achievable credits for Restoration 2 would be less than for Restoration 1; perhaps the maximum is 0.8 credits per foot for the example. However, if a mitigation provider continued to work in the watershed and showed appropriate levels of functional improvement in Level 5, the IRT may want to allow the provider to request the additional 0.2 credits per foot to achieve the full 1.0 credit per foot. This would offer incentive for the mitigation providers to perform watershed-scale restoration.

One value in this restoration level approach is that it clearly identifies function-based parameters that a mitigation provider can control (Restoration 2) versus function-based parameters that are more dependent on upstream watershed condition (Restoration 1).

One value in this restoration level approach is that it clearly identifies function-based parameters that a mitigation provider can control (Restoration 2) versus function-based parameters that are more dependent on upstream watershed condition (Restoration 1). For a Restoration 2 example, projects that restore meandering pattern to channelized

streams would show functional improvement in the key parameters shown in Table 11.2 (floodplain connectivity, bed form diversity, lateral stability, riparian vegetation). The mitigation provider has a lot of control over the design and functionality of these parameters. This should improve communication between the provider and the IRT, making the development of performance standards much more specific and quantitative than many current approaches that simply deal with channel form (dimension, pattern and profile). However, further improvements in Levels 4 and 5 are dependent on upstream watershed conditions. To achieve Restoration 1 and receive full restoration credit, the upstream watershed condition combined with reach-scale restoration creates a Functioning ecosystem through Level 5. The mitigation provider does not have control of the upstream watershed condition; however, they do have control over how the project site is selected.

Debit and Credit Templates Overview

The purpose of this section is to show how the Stream Functions Pyramid Framework can be used as an aid in developing stream debit and credit determination methods. Example debit and credit determination templates will be provided, along with examples and case scenarios to illustrate how the Pyramid Framework can be used — at least at a broad level. The main goal of this section is simply to illustrate how the Pyramid might be used to develop debits and credits. It is not intended to be a policy recommendation, but rather "food for thought". It is a tool, not a rule; however, the approach does try to address requirements in the 2008 Mitigation Rule.

Example templates are provided below to aid IRTs in developing debits and credits. The templates are meant to provide IRTs with ideas on how they can create an SOP that utilizes the Stream Functions Pyramid to help show functional lift. They should be modified to fit local needs and conditions. The SOP template does not address credit release schedules, land protection measures, monitoring designs, service area delineation or other elements of a stream mitigation plan. Rather, the SOP templates focus on how to show appropriate compensation by matching the functions lost at the impact site to the functions gained at the mitigation site by comparing the difference between pre- and post-conditions. These conditions are assessed using the function-based parameters, measurement methods and performance standards from the Pyramid Framework.

Example applications of the template for several impact scenarios (debits) and mitigation scenarios (credits), representing a wide range of conditions from across the country, are provided in Appendix B. The debit scenarios include:

1. Culvert installations,
2. Channelization and bank hardening, and
3. Surface mining of high gradient streams.

The credit scenarios include:

1. Restoration of incised streams;
2. Restoration of stream flow for channels that have excessive water withdrawal;

3. Salmonid fish passage and habitat restoration; and
4. Restoration of high gradient, headwater streams.

Debit and Credit Templates Structure

There are three sample debit and three sample credit templates provided below, along with a description of each. Template 1 for debits and credits shows the functional loss and lift, respectively. Template 2 provides a place where the user can write notes about the rationale used to complete Template 1. There is a Debit Template 2 and a Credit Template 2. Template 3 provides a method for calculating debits (Debit Template 3) and credits (Credit Template 3). A detailed description of each is provided below.

The main goal of this section is simply to illustrate how the Pyramid might be used to develop debits and credits. It is not intended to be a policy recommendation, but rather "food for thought". It is a tool, not a rule; however, the approach does try to address requirements in the 2008 Mitigation Rule.

The *Debit Template 1: Functional Loss Determination* (Table 11.5) shows the Pyramid level number and category name. For each category (Hydrology, Hydraulics, etc.) the table shows the parameter selected from the Pyramid, the measurement method, the pre-disturbance condition and the post-disturbance condition. The key parameters are selected based on the type of impact and whether or not the impact is expected to affect the parameter. For example, if a culvert is going to be installed in a stream with a mature bottomland hardwood forest, the riparian vegetation parameter would be selected. This would show that the buffer is Functioning before the permitted impact and is Not Functioning after the impact. All the information needed to complete this table is provided in Chapters 5-9. A summary is provided in Appendix A.

The *Credit Template 1: Functional Lift Determination* (Table 11.6) is identical to the Debit Template 1 (Table 11.5) with two exceptions. The pre-disturbance condition and post-disturbance condition have been changed to pre-restoration condition and post-restoration condition. Parameters and measurement methods are selected to best represent the potential improvement in stream functions.

TABLE 11.5 DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Insert key parameter from the Pyramid. Refer to Chapters 5-9.	Choose the appropriate measurement method for the selected parameter.	Enter the actual value determined using the measurement method.	Enter Functioning, Functioning-at-Risk or Not Functioning based on the performance standard value.	Enter the predicted or measured value determined using the measurement method.	Enter Functioning, Functioning-at-Risk or Not Functioning based on the performance standard value.
2 – Hydraulics	Example	Example	Example	Example	Example	Example
	Floodplain Connectivity	Bank Height Ratio	1.0	Functioning	2.5	Not Functioning
		Entrenchment Ratio	3.0	Functioning	1.1	Not Functioning
3 – Geomorphology						
4 – Physicochemical						
5 – Biology						

TABLE 11.6 CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Insert key parameter from the Pyramid. Refer to Chapters 5-9.	Choose the appropriate measurement method for the selected parameter.	Enter the actual value determined using the measurement method.	Enter Functioning, Functioning-at-Risk or Not Functioning based on the performance standard value.	Enter the measured value determined using the measurement method.	Enter Functioning, Functioning-at-Risk or Not Functioning based on the performance standard value.
2 – Hydraulics	Example	Example	Example	Example	Example	Example
	Floodplain Connectivity	Bank Height Ratio	3.0	Not Functioning	1.0	Functioning
		Entrenchment Ratio	1.1	Not Functioning	3.0	Functioning
3 – Geomorphology						
4 – Physicochemical						
5 – Biology						

The next tables (Table 11.7 and 11.8) are templates that can be used to provide supporting text about the above pre- and post-condition tables. On the debit side, the table is used to describe the pre-disturbance condition and the rationale for selecting the parameters and measurement methods. The rationale used to predict the post-impact condition should also be provided. The approach is similar on the credit side. For this template, a description of the pre- and post-restoration condition is provided, along with the rationale for selecting key parameters and measurement methods.

TABLE 11.7 DEBIT TEMPLATE 2: PRE- AND POST-DISTURBANCE CONDITIONS AND RATIONALE

Describe Pre-and Post-Disturbance Condition and Rationale for Selecting Parameters
Enter a short description of the pre- and post-disturbance condition for each functional category. Explain why the selected parameters and their measurement method were used. Also include the rationale for the expected outcome. An abbreviated example is provided below for a ***permitted culvert installation****. The remainder of this example is provided in Appendix B.*
Hydrology: The watershed hydrology is stable and is not expected to change. Therefore, Hydrology parameters were not selected.
Hydraulic: The existing channel is not incised and has access to a wide alluvial floodplain, i.e., there is floodplain connectivity. In this example, the culvert will likely cause channel incision downstream of the culvert, and bank height ratios are likely to increase, causing a Not Functioning score. The culvert will provide grade control for the upstream channel and the bank height ratio may decrease because of aggradation.
Geomorphology: see Appendix B, Table B2a
Physicochemical: see Appendix B, Table B2a
Biological: see Appendix B, Table B2a

TABLE 11.8 CREDIT TEMPLATE 2: PRE- AND POST-RESTORATION CONDITIONS AND RATIONALE

Describe Pre-and Post-Restoration Condition and Rationale for Selecting Parameters
Enter a short description of the pre-and post-restoration condition for each functional category. Explain why the selected parameters and their measurement method were used, along with the rationale for the expected improvement. An abbreviated example is provided below for the ***restoration of an incised channel****. The remainder of this example is provided in Appendix B.*
Hydrology: The watershed hydrology is stable and is not expected to change. Therefore, Hydrology parameters were not selected.
Hydraulic: The existing channel is severely incised (Bank Height Ratio of 3) and does not have access to a wide alluvial floodplain. The channel will be reconnected to the floodplain through a Rosgen Priority 1 Restoration. The Bank Height Ratio will be reduced to 1.0, and all flows greater than bankfull will spread onto a floodplain that is 50 times wider than the channel, making the entrenchment ratio well over 2.2.
Geomorphology: see Appendix B, Table B11a
Physicochemical: see Appendix B, Table B11a
Biological: see Appendix B, Table B11a

The third set of templates (Tables 11.9 and 11.10) provides debit and credit ratios based on the results from Template 1. The ratios used to create debits and credits can be modified. The ones used in this template are for demonstration purposes and were chosen to encourage mitigation providers to select projects that have the potential for the greatest functional lift. Credits range from 0 to 1 credit-per-foot of restored channel. Debits range from 1 to 2 debits-per-foot. Therefore, an impact that creates maximum functional loss would be assigned 2 debits-per-foot. Since the maximum credit ratio is 1 credit-per-foot, they will have to perform mitigation on twice the stream length that was impacted. Since a portion of credits is released before a site reaches maturity, a greater amount of mitigation is necessary to address this temporal loss as well as the risk of project failure.

Table 11.9 provides example debit ratios. The first column shows the functionality of the stream reach before an impact occurs. Functionality ranges from Low to High and is based on the pre-disturbance condition from Debit Template 1. The remaining columns show the predicted functional loss from the permitted impact, ranging from no functional loss to high functional loss, based on the predicted functional loss from Debit Template 1. Debit ratios are then assigned to the different levels of functional loss. Therefore, high-quality streams that are more severely impacted would yield more debits than degraded streams that were minimally impacted. A debit adjustment factor is provided for scenarios that may need to be modified based on unique site conditions or because the result fits between two categories.

TABLE 11.9 DEBIT TEMPLATE 3: DEBIT CALCULATIONS

PRE-DISTURBANCE CONDITION	POST-DISTURBANCE CONDITION			
	No Functional Loss	Low to Moderate Functional Loss	Moderate to High Functional Loss	Debit Adjustment (+/-)
Low (Mix of Functioning-at-Risk and Not Functioning)	**(Post-disturbance condition matches pre-disturbance condition)** **No mitigation required**	Greater number of Functioning-at-Risk and Not Functioning Scores 1.1 to 1.2	Mostly Not-Functioning Scores 1.2 to 1.3	0.1
Moderate (Mix of Functioning, Functioning-at-Risk, and Not Functioning)		Loss of Functioning scores and/or greater number of Functioning-at-Risk and Not Functioning Scores 1.3 to 1.5	Mix of Functioning-at-Risk and Not Functioning Scores 1.5 to 1.7	0.1
High (Functioning)		Mix of Functioning, Functioning-at-Risk, and Not Functioning Scores 1.7 to 1.9	Mix of Functioning-at-Risk and Not Functioning Scores 2.0	0.2

Tables 11.10 and 11.11, provide examples of credit determination method templates for Restoration 1 and Restoration 2 projects. Specific examples are provided in Appendix B. The table below includes four columns: Credit Category, Pre-Restoration Condition, Post-Restoration Condition and Credit Ratio. The credit ratio is expressed as credit-per-foot with the highest ratio set at 1.0 credit–per-foot for a Restoration 1 project with a Maximum Lift score. Maximum Lift is the first row under the Credit Category. So if a project was 5,000 feet long, the maximum number of credits that could be attained is 5,000. The other categories are Moderate and Low lift. So a project that has several Functioning scores in the baseline condition would have a Low lift and would be given less credit. Note that the post-restoration condition is the same for Maximum, Moderate and Low lift. The difference is in the baseline condition. This reflects a goal of achieving the highest restoration or enhancement possible, but acknowledges that some sites start in a more degraded condition; thus, more lift is created and more credit is given. Again, these ratios are provided only as a guide. Appendix B provides other examples of credit determination methods for other scenarios.

TABLE 11.10 CREDIT TEMPLATE 3: CREDIT CALCULATIONS FOR RESTORATION 1

RESTORATION 1 CREDIT CATEGORIES	PRE-RESTORATION CONDITION	POST-RESTORATION CONDITION	CREDITS PER FOOT
Maximum Lift	All parameters in Pyramid Levels 2 and 3 have Not Functioning scores. Parameters in Levels 4 and 5 are Not Functioning or Functioning-at-Risk.	Functioning scores for Levels 1-5	0.8 to 1.0
Moderate Lift	Mix of Not-Functioning and Functioning-at-Risk scores for parameter Levels 2 through 5.	Functioning scores for Levels 1-5	0.6 to 0.8
Low Lift	Mix of Not-Functioning, Functioning-at-Risk and Functioning scores for parameter Levels 2 through 5.	Functioning scores for Levels 1-5	0.4 to 0.6

Credits = Credit Ratio (in Credits/Ft) times the restored stream length (ft).

TABLE 11.11 CREDIT TEMPLATE 3: CREDIT CALCULATIONS FOR RESTORATION 2

RESTORATION 2 CREDIT CATEGORIES	PRE-RESTORATION CONDITION	POST-RESTORATION CONDITION	CREDITS PER FOOT
Maximum Lift	All parameters in Pyramid Levels 2 and 3 have Not Functioning scores.	Functioning scores for Levels 1-3	0.6 to 0.8
Moderate Lift	Mix of Not-Functioning and Functioning-at-Risk scores for parameter Levels 2 through 3.	Functioning scores for Levels 1-3	0.4 to 0.6
Low Lift	Mostly Functioning-at-Risk and Functioning scores for parameter Levels 2 through 3. May include some Not-Functioning scores.	Functioning scores for Levels 1-3	0.2 to 0.4

Credits = Credit Ratio (in Credits/Ft) times the restored stream length (ft).

Enhancement Credits

The Pyramid Framework can be used to help develop enhancement credits, although less emphasis is placed on these projects within this document. The 2008 Mitigation Rule defines enhancement as the manipulation of the physical, chemical and biological characteristics of an aquatic resource to heighten, intensify or improve a specific aquatic resource function(s). Enhancement may lead to a gain in certain functions, but could also lead to a decline in other functions. Enhancement does not increase the aquatic resource area, e.g., stream length. An appropriate way to develop stream enhancement credits using the Stream Functions Pyramid Framework as a guide is to complete a function-based assessment before making the determination of whether restoration or enhancement is the better solution. The assessment may be rapid or intensive depending on the project; however, information about which function-based parameters are Functioning and Not Functioning must be determined before the practitioner can know what needs to be enhanced.

Enhancement can lead to projects that achieve the same level of functionality as a Restoration 1 approach above; however, they can also lead to projects that still have several function-based parameters with a Functioning-at-Risk or Not Functioning score. Therefore, the key difference between restoration and enhancement, as described here, is the level of functional lift. Restoration 1 includes changes to many function-based parameters, along with proper site selection, to achieve a fully functioning score. Enhancement may include a change to only one parameter to achieve a fully functioning score, if all other key parameters are functioning, e.g., the riparian buffer. In this example, the product is the same but the amount of functional lift is much less with an enhancement approach. Enhancement can also improve one function-based parameter like lateral stability, but not improve other key parameters like floodplain connectivity or bed form diversity. This would lead to a stream that has some improvement in stream function, but the change is not necessarily significant. And because the stream is not connected to the floodplain, the channel could lose other functions in the future.

A table is not provided for calculating enhancement credits. Rather, some examples of enhancement scenarios are provided below. These examples show how to focus on enhancements to function-based parameters rather than practices like benching or in-stream structures. These practices will likely be used; however, the credits should be based on changes to function-based parameters and not the number of structures. Of course, enhancement credits should also be less than restoration credits on a per, foot basis.

Example Enhancement Scenarios:

1. Projects in non-incised, rural streams within alluvial valleys. The stream is well connected to a floodplain and there are diverse bed forms created from the appropriate plan form geometry and bed form complexity. Streambanks are not eroding at levels above reference conditions, i.e., banks are stable. However, the riparian buffer is thin with only a single row of trees along the streambank.

Enhancement credits could be provided for expanding the buffer. In this case, higher order functions like de-nitrification and even improvements to benthics and fish may occur — if supported by the upstream watershed.

2. Same setting as number 1 and same conditions, except in addition to having a narrow riparian buffer, the bed form diversity is also low, e.g., mostly riffle bed forms due to straightening and vegetation/debris removal.

   Enhancement would include improving the bed form diversity, e.g., percent riffle and pool, depth variability, and improving the buffer width and composition. This would be a higher level of enhancement because more than one function-based parameter is being improved.

3. Urban setting, flood control channel. A channelized, trapezoidal channel with streambanks stabilized by rip rap and some vegetation.

   High level of enhancement would include providing limited floodplain connectivity by excavating bankfull benches, providing bed form diversity through the installation of in-stream structures, and planting a narrow buffer. Lower-level enhancement would be bank stabilization using vegetation, e.g., bioengineering and perhaps bed form diversity with in-stream structures; however, significant benching and vegetation beyond the top of the streambank would be limited.

Example of Calculating Debits and Credits

The following is an example of how the templates can be used to calculate debits and credits from a hypothetical permitted impact site and a mitigation site.

Impact Site

- 500 feet of culvert with 200 feet of downstream impact and 100 feet of upstream impact. Total impact length is 800 feet.
- The functional condition before disturbance shows a mix of Not-Functioning, Functioning-at-Risk and Functioning scores for Level 2 through 5 parameters. This equals a Functionality Before Impact score of Moderate (Table 11.9).
- A standard installation approach is used instead of an arch culvert or bridge, so post-construction functions will include a greater number of Not-Functioning and Functioning-at-Risk scores for Level 2 through 5 parameters. This equals a Moderate Functional Loss from Table 11.9.
- A Moderate/Moderate score yields a ratio range of 1.3 to 1.5 debits per foot. For this example, a ratio of 1.5 is used.
- The total debits equal 1.5 X 800 = 1,200 debits. In other words, 1,200 credits are needed to compensate for the impacts.
- This example could have been broken into three reaches, including upstream of the culvert, through the culvert, and downstream of the culvert, since the impacts will likely vary. An example of calculating debits by reach for a culvert installation is shown in Appendix B.

Off-Site Mitigation

- A 10,000-foot stream restoration site is located that meets the Restoration 1 criteria. A Restoration 1 site includes full restoration of Level 2 and 3 functions and the watershed supports Level 4 and 5 functions.
- The pre-restoration condition shows that all parameters in Pyramid Levels 2 and 3 have Not Functioning scores. Parameters in Levels 4 and 5 are Not Functioning or Functioning-at-Risk.
- The post-restoration condition is predicted to show Functioning scores for Levels 1-5. The stream is well connected to the floodplain with diverse and complex bed forms that are representative of the stream type. Riparian buffer is diverse and has sufficient width to support Level 4 and 5 functions. Since the upstream watershed supports Level 4 and 5 functions, it is predicted that the project reach will achieve Functioning scores for Levels 4 and 5 as well.
- This results in a Maximum Lift score, with a credit ratio range of 0.8 to 1.0 credits per foot.
- For this example, a credit ratio of 1.0 is selected.
- The total credits available at this site are 10,000 ft X 1.0 credits/ft = 10,000 credits.

As was mentioned previously, the debits and credits can be modified to meet local conditions and requirements. The debit and credit range selected for these examples was based on two important factors. First, more credits were provided for scenarios that improved more functions, i.e., the more functions that are restored, the more credits. Second, a multiplier is applied to the debits to ensure that debits are never less than the length of impact. The maximum is 2.2:1, meaning that 2.2 times the amount of impacted length may be required for mitigation. The multiplier acknowledges the fact that impacts occur immediately during construction and that mitigation sites take years to reach functional maturity. Since a portion of credits is released before the site reaches maturity, a greater amount of mitigation is warranted for temporal losses to stream functions.

11.7 » STEPS TO DEVELOPING DEBITS AND CREDITS

The following provides general steps for using the Pyramid to develop unique debit and credit determination methods. These steps also provide guidance on how to collect the information necessary to complete the templates described above. Actual steps and tasks will vary based on local needs and conditions, and additional steps will be needed to meet other 2008 Mitigation Rule requirements. For example, the steps below do not address how to develop the Prospectus or the Mitigation Banking Instrument.

Steps to Develop Debits Using the Pyramid

1. List types of impacts for the service area, i.e., culvert crossings, channelization, etc.
2. Select key function-based parameters from the Pyramid that are typically associated with each type of impact. The selected parameters should be based on some form of function-based assessment.

3. Select the appropriate measurement method for each parameter, e.g., simple and rapid-based or more complex and time intensive. This selection should be based on the severity of the impact and difficulty in predicting functional loss.
4. Perform function-based assessment on stream reach proposed to be impacted.
5. Record values for each measurement method and use the performance standards to determine if the function-based parameter is Functioning, Functioning-at-Risk and Not Functioning. Record values on Debit Template 1 (Table 11.5).
6. Provide justification for the selection of function-based parameters and measurement methods in Debit Template 2 (Table 11.6).
7. Develop overall scoring method (optional). Note: This document does not provide a scoring method that combines parameters, their measurement method and performance standard into an overall index of stream function. The document does show a method for calculating debits without this overall score; however, a function index might be a helpful tool for future use.
8. Determine overall baseline condition using scoring method developed in step 6, or refer to the debit calculation method shown in Debit Template 3 (Table 11.9).
9. Calculate overall debits for site. The formula used in this document is the debit ratio multiplied by the impacted stream length.

Steps to Develop Credits Using the Pyramid

1. Develop or use existing watershed management plans for each service area. Locate areas of water quality impairment and stream degradation. Determine the causes of impairment. Also locate areas of high water quality and healthy stream channels. Use the plan to identify stream reaches that can produce high-quality mitigation and, if possible, support the overall improvement of the watershed.
2. Based on the watershed management plan, determine the different types of techniques required to improve watershed health, e.g., stormwater BMPs, stream restoration, stream enhancement, riparian corridor preservation.
3. Perform a function-based assessment of the potential project reach.
4. Determine the restoration potential based on the assessment, watershed condition and constraints.
5. Establish function-based design goals and objectives.
6. Select key parameters from the Pyramid based on the assessment and restoration potential. Select parameters that are expected to change as a result of the restoration or enhancement activity.
7. Select the appropriate measurement method for each parameter, e.g., simple and rapid-based or more complex and time intensive. This selection should be based on the level of effort required to show functional lift.
8. Record the function-based parameter, measurement method and scores using the performance standards on Credit Template 1 (Table 11.6).
9. Provide justification for selecting the parameters and measurement methods on Credit Template 2 (Table 11.8).

10. Develop overall scoring method (optional). Note: This document does not provide a scoring method that combines parameters, their measurement method and performance standard into an overall index of stream function. The document does show a method for calculating credits without this overall score; however, a function index would be a helpful tool for future use.
11. Determine overall baseline condition using scoring method developed in step 10, or refer to the credit calculation method shown in Tables 11.10 and 11.11.
12. Calculate overall credits predicted for the site. The formula used in this document is the credit ratio multiplied by the restored or enhanced stream length.
13. Develop a monitoring plan to verify that the functional lift meets or exceeds the performance standards.

References

33 CFR Part 332.3, 2008. Compensatory Mitigation For Losses of Aquatic Resources. *www.nap.usace.army.mil/cenap-op/regulatory/documents/mitigation/33cfr332_final_mitig_rule.pdf*

Abbe, T.B., A.P. Brooks, and D.R. Montgomery, 2003. Wood in River Rehabilitation and Management.
In: The Ecology and Management of Wood in World Rivers, S.V. Gregory, K.L. Boyer, and A.M. Gurnell (Editors). American Fisheries Society, Bethesda, Maryland, pp. 367-389.

Abbe, T.B. and D.R. Montgomery, 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. Regulated Rivers: Research and Management 12:201-221.

Adams, E.A., S.A. Monroe, A.E. Springer, K.W. Blasch, and D.J. Bills, 2006. Electrical Resistance Sensors Record Spring Flow Timing, Grand Canyon, Arizona. Ground Water 44:630–641. doi: 10.1111/j.1745-6584.2006.00223.x.

Albright, L.J. and J.W. Wentworth, 1973. Use of the Heterotrophic Technique as a Measure of Eutrophication. Environmental Pollution 5:59-72.

Allan, J.D., 2004. Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-284.

Allan, J.D. and M.M. Castillo, 2007. Stream Ecology: Structure and Function of Running Waters, Second Edition. Springer, Dordrecht, The Netherlands.

Allen, W., T. Weber, E. McLaughlin, and R. Starr, 1999. US 301 Environmental Stewardship Methodologies and Results. The Conservation Fund, Maryland Department of Natural Resources, and US Fish and Wildlife Service, Annapolis, Maryland.

Anderson, K.R., 2011. The Road to Trout Recovery. Presentation, 2011 Mid-Atlantic Stream Restoration Conference, Rocky Gap Resort, Flintstone, Maryland. *www.fws.gov/chesapeakebay/Masrc/AbstractPDFs.html#anderson2*

Andrews, E.D., 1983. Entrainment of Gravel from Naturally Sorted Riverbed Material. Geological Society of America Bulletin 94:1225-1231.

Andrews, E.D., 1984. Bed-Material Entrainment and Hydraulic Geometry of Gravel-Bed Rivers in Colorado. Geological Society of America Bulletin 95:371-378.

Andrews, E.D. and D.C. Erman, 1986. Persistence in the Size Distribution of Surficial Bed Material During an Extreme Snowmelt Flood. Water Resources Research 22(2):191-197.

Angermeier P.L. and J.R. Karr, 1986. Applying an Index of Biotic Integrity Based on Stream-Fish Communities: Considerations in Sampling and Interpretation. North American Journal of Fisheries Management 6:418-429.

Baattrup-Pedersen, A. and T. Riis, 1999. Macrophyte Diversity and Composition in Relation to Substratum Characteristics in Regulated and Unregulated Danish Streams. Freshwater Biology 42:375–385.

Baattrup-Pedersen, A., K. Szoszkiewicz, R. Nijboer, M. O'Hare and T. Ferreira, 2006. Macrophyte Communities in Unimpacted European Streams: Variability in Assemblage Patterns, Abundance and Diversity. Hydrobiologia 566:179–196.

Bagnold, R.A., 1980. An Empirical Correlation of Bedload Transport Rates in Flumes and Natural Rivers. Proceedings of the Royal Society (London) 372:452-473.

Balon, E.K., 1975. Reproductive Guilds of Fish: A Proposal and Definition. Journal of the Fisheries Research Board of Canada 32:821-864.

Barbour, M.T., J. Gerritsen, B.D. Snyder and J.B. Stribling, 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish, Second Edition, EPA 841-B-99-002. US Environmental Protection Agency, Washington, DC. *http://www.epa.gov/owow/monitoring/rbp/ch07main.html*.

Barton D.R., W.D. Trylor and R.M. Bierre, 1985. Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams. North American Journal of Fishery Management 5:364-378.

Bartsch, A.F. and W.M. Ingram, 1966. Biological Analysis of Water Pollution in North America. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte 16:786-800.

Benke, A.C., 1984. Secondary Production of Aquatic Insects. In: Ecology of Aquatic Insects, V.H. Resh and D.M. Rosenberg (Editors). Praeger, New York, New York, pp. 289-322.

Benke, A., 2010. Secondary Production. Nature Education Knowledge 1(8):5.

Benke, A.C. and C.E. Cushing, 2005. Rivers of North America. Elsevier Academic Press, Burlington, Massachusetts. ISBN-0-12-088254-1.

Benke A.C. and A.D. Huryn, 2010. Benthic Invertebrate Production — Facilitating Answers to Ecological Riddles in Freshwater Ecosystems. Journal of the North American Benthological Society 29(1):264-285.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Baranas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S.G. Loss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powerll, and E. Sudduth, 2005. Synthesizing US River Restoration Efforts. Science 308:636-637.

Bernot, M.J. and W.K. Dodds, 2005. Nitrogen Retention, Removal and Saturation in Lotic Ecosystems. Ecosystems 8:442-453.

Bevenger, G.S., and R.M. King, 1995. A Pebble Count Procedure for Assessing Watershed Cumulative Effects. US Department of Agriculture Forest Service Research Paper RM-RP-319. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Biggs, B.J.F., 1996. Patterns in Periphyton of Streams. In: Algal Ecology: Freshwater Benthic Ecosystems, R.J. Stevenson, M.L. Bothwell, and R.L. Lowe (Editors). Academic Press, San Diego, California, pp. 31–56.

Blasch, P.A., T. Ferre, A.H. Christensen and J.P. Hoffman, 2002. New Field Method to Determine Streamflow Timing Using Electrical Resistance Sensors. Vadose Zone Journal 1(2):289-299.

Bonar, S., W. Hubert and D. Willis, 2009. Standard Methods for Sampling North American Freshwater Fishes. American Fisheries Society, Bethesda, Maryland.

Bond, N.R. and P.S. Lake, 2005. Ecological Restoration and Large-scale Ecological Disturbance: The Effects of Drought on the Response by Fish to a Habitat Restoration Experiment. Restoration Ecology 13:39–48.

Bott, T., 1973. Bacteria and the Assessment of Water Quality. In: Biological Methods for the Assessment of Water Quality, J. Cairns and K.L. Dickson (Editors). American Society for Testing and Materials, Los Angeles, California.

Bott, T.L., J.T. Brock, C.E. Cushing, S.V. Gregory, D. King, and R.C. Peterson, 1978. A Comparison of Methods for Measuring Primary Productivity and Community Respiration in Streams. Hydrobiologia 60:3-12.

Boulton, A.J., T. Datry, T. Kasahara, M. Mutz and J.A. Stanford, 2010. Ecology and Management of the Hyporheic Zone: Stream-Groundwater Interactions of Running Waters and Their Floodplains. Journal of North American Benthological Society 29(1):26-40. doi 10.1899/08-017.1.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett, 1998. The Functional Significance of the Hyporheic Zone in Streams and Rivers. Annual Review of Ecology and Systematics 29:59-81.

Bowden, W.B., J.M. Glime, and T. Riis, 2006. Macrophytes and Bryophytes. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp.381-414.

Bridge, J.S., 2003. Rivers and Floodplains: Forms, Processes, and Sedimentary Record. Blackwell Publishing, Oxford, United Kingdom.

Brunner, G.W., 2010. HEC-RAS Version 4.1 River Analysis System User's Manual. US Army Corps of Engineers Hydrologic Engineering Center, Davis, California. *www.hec.usace.army.mil/software/hec-ras/hecras-document.html*

Bryce S.A., G.A. Lomnicky, P.R. Kaufmann, 2010. Protecting Sediment Sensitive Aquatic Species in Mountain Streams Through the Application of Biologically Based Streambed Sediment Criteria. Journal of the North American Benthological Society 29(2):657-672.

Bunte, K. and S.R. Abt, 2001. Sampling Surface and Subsurface Particle-Size Distributions in Wadeable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Stream-Bed Monitoring. General Technical Report RMRS-GTR-74, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Cairns, J. and J.R. Pratt, 1993. A History of Biological Monitoring Using Benthic Macroinvertebrates. In: Freshwater Biomonitoring and Benthic Macroinvertebrates, D.M. Rosenberg and V.H. Resh (Editors). Routledge, Chapman, and Hall, New York, New York.

Carle, F.L. and M.R. Strub, 1978. A New Method for Estimating Population Size from Removal Data. Biometrics 34:621-630.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W Howarth, A.N. Sharpley and V.H. Smith, 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications 8:559-568.

Castelle, A.J., A.W. Johnson and C. Conolly, 1994. Wetland and Stream Buffer Size Requirements — A Review. Journal of Environmental Quality 23:878-882.

Castro, J.M. and P.L. Jackson, 2001. Bankfull Discharge Recurrence Intervals and Regional Hydraulic Geometry Relationships: Patterns in the Pacific Northwest, USA. Journal of the American Water Resources Association 37(5):1249-1262.

Chaplin, J.J., 2005. Development of Regional Curves Relating Bankfull-Channel Geometry and Discharge to Drainage Area for Streams in Pennsylvania and Selected Areas of Maryland. US Geological Survey Water-Resources Investigation Report 2005-5147, US Geological Survey, Reston, Virginia.

Chin, A., 1989. Step Pools in Stream Channels. Progress in Physical Geography 13:391-407.

Clarke, S.J., 2002. Vegetation Growth in Rivers: Influences Upon Sediment and Nutrient Dynamics. Progress in Physical Geography 26:159-172.

Claussen, J.C., K. Guillard, C.M. Sigmund and K.M. Dors, 2000. Water Quality Changes From Riparian Buffer Restoration in Connecticut. Journal of Environmental Quality 29:1751-1761.

Clean Water Act (CWA), 2002. 33 U.S.C. 1251 et seq. http://epw.senate.gov/water.pdf

Cinotto, P.J., 2003. Development of Regional Curves of Bankfull-Channel Geometry and Discharge for Streams in Non-Urban, Piedmont Physiographic Province, Pennsylvania and Marlyand. US Geological Survey Investigation Report 03-4014, US Geological Survey, Reston, Virginia.

Cooper, J.R., J.W. Gilliam, R.B. Daniels and W.P. Robarge, 1987. Riparian Areas as Filters in Agricultural Sediment. Soil Science Society of America Journal 51:416-420.

Cronk, J.K. and M.S. Fennessy, 2001. Wetland Plants: Biology and Ecology. CRC Press/ Lewis Publishers, Boca Raton, Florida.

Cummins, K.W., 1973. Trophic Relations of Aquatic Insects. Annual Review of Entomology 18:183-206.

Cummins, K.W. and M.J. Klug, 1979. Feeding Ecology of Stream Invertebrates. Annual Review of Ecology and Systematics 10:147-172.

Cummins, K.W., J.R. Sedell, F.J. Swanson, G.W. Minshall, S.G. Fisher, C.E. Cushing, R.C. Peterson and R.L. Vannote, 1983. Organic Matter Budgets for Stream Ecosystems. In: Stream Ecology: Application and Testing of General Ecological Theory, J.R. Barnes and G.W. Minshall (Editors). Plenum Press, New York, New York, pp. 299-253.

Dahm, C.N., M.A. Baker, D.I. Moore and J.R. Thibault, 2003. Coupled Biogeochemical and Hydrological Responses of Streams and Rivers to Drought. Freshwater Biology 48:1219-1231.

Daniels, R.B. and J.W. Gilliam, 1996. Sediment and Chemical Load Reduction by Grass and Riparian Filters. Soil Science Society of America Journal 60(1):246-251.

Darby, S.E. and C.R. Thornes, 1992. Impact of Channelisation on the Mimmshall Brook, Hertfordshire, UK. Regulated Rivers 7:193-204.

Davis, W.M., 1899. The Geographical Cycle. Geographical Journal 14:481-504.

Davis, J.C., W.G. Minshall, C.T. Robinson and P. Landres, 2001. Monitoring Wilderness Stream Ecosystems. General Technical Report RMRS-GTR-70. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Dawson, H., 2002. Guidance for the Field Assessment of Macrophytes of Rivers within the STAR Project. National Environment Research Council, Centre for Ecology and Hydrology, Dorset, United Kingdom.

Dingman. L.S., 2008. Physical Hydrology, Second Edition. Prentice Hall, New York, New York.

Dodds, W.K., and J. Brock, 1998. A Portable Flow Chamber for In Situ Determination of Benthic Metabolism. Freshwater Biology 39:49-59.

Doll, B.A., D.E. Wise-Frederick, C.M. Buckner, S.D. Wilkerson, W.A. Harman, R.E. Smith, and J. Spooner, 2002. Hydraulic Geometry Relationships for Urban Streams throughout the Piedmont of North Carolina. Journal of the American Water Resources Association 38:641-651.

Dolloff, C.A. and M.L.Warren, Jr., 2003. Fish Relationships with Large Wood in Small Streams. American Fisheries Society Symposium 37:179–193.

Downing, J., and F.H. Rigler, 1984. Secondary Productivity in Fresh Waters. Blackwell, New York, New York.

Dudley, R.W., 2004. Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine. US Geological Survey Water-Resources Investigation Report 2004-5042, US Geological Survey, Reston, Virginia.

Dunne, T. and L.B. Leopold, 1978. Water in Environmental Planning. W.H. Freeman Co., San Francisco, California.

Dutnell, R.C., 2000. Development of Bankfull Discharge and Channel Geometry Relationships for Natural Channel Design in Oklahoma Using a Fluvial Geomorphic Approach. Master's Thesis, University of Oklahoma, Norman, Oklahoma.

Easterbrook, D.J., 1999. Surface Processes and Landforms, Second Edition. Prentice-Hall, Inc., Upper Saddle Brook, New Jersey.

Eaton, A.D., L.S. Clesceri, E.W. Rice and A.E. Greenberg, 2005. Standard Methods for the Examination of Water and Wastewater, 21st Edition. American Public Health Association, Washington, D.C.

Edwards, R.T., J.L. Meyer, and S.E.G. Findlay, 1990. The Relative Contribution of Benthic and Suspended Bacteria to System Biomass, Production, and Metabolism in a Low-Gradient Blackwater River. Journal of the North American Benthological Society 9(3):216-228.

Ehrman, T.P. and G.A. Lamberti, 1992. Hydraulic and Particulate Matter Retention in a 3rd Order Indiana Stream. Journal of the North American Benthological Society 11:341-349.

Eiler, J.H., 1995. A Remote Satellite-Linked Tracking System for Studying Pacific Salmon with Radio Telemetry. Transactions of the American Fisheries Society 124(2):184-193.

Endreny, T.A., 2003. Fluvial Geomorphology Module. University Corporation for Atmospheric Research (UCAR) COMET Program and National Oceanic and Atmospheric Administration (NOAA) River Forecast Center, Syracuse, New York. *www.fgmorph.com*.

Engel, S.R. and J.R. Voshell, 2002. Volunteer Biological Monitoring: Can It Accurately Assess the Ecological Condition of Streams? American Entomologist 48:164-177.

Essington, M.E., 2004. Soil and Water Chemistry: An Integrative Approach. CRC Press, LLC, Boca Raton, Florida.

European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council — Establishing a Framework for Community Action in the Field of Water Policy. Brussels, Belgium.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes and Practices. National Technical Information Service, Springfield, Virginia.

Federal Water Pollution Control Act of 1972 (FWPCA, 1972) Public Law 92-500, 86 Stat. 816. Amended in 1977 and 1987, referred to as the Clean Water Act, codified at 33 U.S.C. 1251-1387 (1988)

Ferreira, M.T., A. Albuquerque, F.C. Aguiar and N. Sidorkewicz, 2002. Assessing Reference Sites and Ecological Quality of River Plant Assemblages from an Iberian Basin Using a Multivariate Approach. Archive fur Hydrobiologie 155:121-145.

Fetter, C.W., 1994. Applied Hydrogeology. Macmillan College Publishing Company. New York, New York.

Finlay J.C., 2001. Stable-Carbon-Isotope Ratios of River Biota: Implications for Energy Flow in Lotic Food Webs. Ecology 82:1052-1064.

Fischenich, C. and R. Seal, 1999. Boulder Clusters. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-11), US Army Engineer Research and Development Center, Vicksburg, Mississippi. *http://libweb.erdc.usace.army.mil/Archimages/7431.PDF*.

Fischenich, J.C., 2006. Functional Objectives for Stream Restoration, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-52), US Army Engineer Research and Development Center, Vicksburg, Mississippi. *http://el.erdc.usace.army.mil/elpubs/pdf/sr52.pdf*.

Fischer, R.A., C.O. Martin, J.T. Ratti and J. Guidice, 2000. Riparian Terminology: Confusion and Clarification. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-25), US Army Engineer Research and Development Center, Vicksburg, Mississippi. *http://www.wes.army.mil/el/emrrp.*

Fischer, R.A. and J.C. Fischenich, 2000. Design Recommendations for Riparian Corridors and Vegetated Buffer Strips. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-24), US Army Engineer Research and Development Center, Vicksburg, Mississippi. *http://www.wes.army.mil/el/emrrp*.

Fisher, S.G., N.B. Grimm, E. Martı´, R.M. Holmes and J.B. Jones, Jr., 1998. Material Spiraling in Stream Corridors: A Telescoping Ecosystem Model. Ecosystems 1:19-34.

Fore, L.S., 2003. Response of Diatom Assemblages to Human Disturbance: Development and Testing of a Multimetric Index for the Mid-Atlantic Region (USA). In: Biological Response Signatures, Indicator Patterns Using Aquatic Communities, T.P. Simon (Editor). CRC Press, Boca Raton, Florida, pp. 445-471.

Fore, L.S. and C. Grafe, 2002. Using Diatoms to Assess the Biological Condition of Large Rivers in Idaho (USA). Freshwater Biology 47:2015-2037.

Flores, H., D. McMonigle, and K. Underwood, 2011. Regenerative Step Pool Storm Conveyance (SPSC) Design Guidelines, Revision 4. Department of Public Works, Anne Arundel County Government, Maryland. http://www.aacounty.org/DPW/Watershed/SPSCdesignguidelinesJan2012rev4.pdf

Fritz, K.M., B.R. Johnson and D.M. Walters, 2006. Field Operations Manual for Assessing the Hydrologic Permanence and Ecological Condition of Headwater Streams. EPA 600/R-06/126, US Environmental Protection Agency, Washington, DC 20460..

Georgia Department of Transportation (GDOT), 2004. Final Report: Regional Curve Development for the Coastal Plain of Georgia. Buck Engineering, Cary, North Carolina.

Gerhard, M. and M. Reich, 2000. Restoration of Streams with Large Wood: Effects of Accumulated and Built-In Wood on Channel Morphology, Habitat Diversity and Aquatic Fauna. International Revue of Hydrobiology 85:123-137.

Gomez, B., 1991. Bedload Transport. Earth-Science Reviews 31(2):89-132.

Gordon, N.D., T.A. McMahon, B.L. Finlayson, C.J. Gippel, R.J. Nathan, 2004. Stream Hydrology: An Introduction for Ecologists, Second Edition. John Wiley and Sons, Hoboken, New Jersey.

Goulsbra, C.S., J.B. Lindsay and M.G. Evans, 2009. A New Approach to the Application of Electrical Resistance Sensors to Measuring the Onset of Ephemeral Streamflow in Wetland Environments. Water Resources Research 45(W09501):1-7.

Grant, G.E., F.J. Swanson and M.G. Wolman, 1990. Pattern and Origin of Stepped-Bed Morphology in High Gradient Streams, Western Cascades, Oregon. Geological Society of America Bulletin 102: 340-352.

Gregory, K.J., A.M. Gurnell, C.T. Hill and S. Tooth, 1994. Stability of the Pool-riffle Sequence in Changing River Channels. Regulated Rivers: Research and Management 9:35-43.

Gregory, S.V., F.J. Swanson, W.A. McKee and K.W. Cummins, 1991. An Ecosystem Perspective of Riparian Zones: Focus on Links between Land and Water. Bioscience 41:540-551.

Gücker, B. and M.T. Pusch, 2006. Regulation of Nutrient Uptake in Eutrophic Lowland Streams. Limnology and Oceanography 51(3):1443-1453.

Hack, J.T., 1960. Interpretations of Erosional Topography in Humid Temperate Regions. American Journal of Science 258A:80-97.

Hammer, T., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8(6):1530-1540.

Harman, W.A., 2008. Design Improvements of Meander Bend Protection Using Root Wads. Southeastern Regional Conference on Stream Restoration, Winston-Salem, NC

Harman, W.A., 2009. The Functional Lift Pyramid (Presentation). Mid-Atlantic Stream Restoration Conference, Morgantown, WV. *www.canaanvi.org/canaanvi_web/uploadedFiles/Events/Past_Events/masrcl_harman_will.pdf*.

Harman, W.A., G.D. Jennings, J.M. Patterson, D.R. Clinton, L.O. Slate, A.G. Jessup, J.R. Everhart and R.E. Smith, 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. In: American Water Resources Association Wildland Hydrology Proceedings, TPS-99-3, D.S. Olsen and J.P. Potyondy (Editors). American Water Resources Association, Middleburg, Virginia, pp. 401-408.

Harman, W.A. and R. Starr, 2011. Natural Channel Design Review Checklist. US Fish and Wildlife Service, Chesapeake Field Office, Annapolis, MD. US Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds, Wetlands Division, Washington, DC. EPA 843-B-12-005.

Harman, W.A., D.E. Wise, M.A. Walker, R. Morris, M.A. Cantrell, M. Clemmons, G.D. Jennings, D. Clinton and J. Patterson, 2000. Bankfull Regional Curves for North Carolina Mountain Streams. In: Proceedings of the American Water Resources Association Conference Water Resources in Extreme Environments, Anchorage, Alaska, D.L. Kane (Editor). American Water Resources Association, Middleburg, Virginia, pp. 185-190.

Harrelson, C.C., C.L. Rawlins and J.P. Potyondy, 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Harvey, J.W. and K.E. Bencala, 1993. The Effect of Streambed Topography on Surface-Subsurface Water Exchange in Mountain Catchments. Water Resources Research 29:89-98.

Haslam, S., 1987. River Plants of Western Europe. Cambridge University Press, Cambridge, United Kingdom.

Hauer, F.R. and W.R. Hill, 2006. Temperature, Light and Oxygen. In: Methods in Stream Ecology, Second Edition, F.R. Hauer and G.A. Lamberti (Editors). Elsevier, Amsterdam, The Netherlands, pp. 103-117.

Haury, J., M.C., Peltre, M. Tremolieres and J. Barbe, G. Thiébaut, I. Bernez, H. Daniel, P. Chatenet, G. Haan-Archipof, S. Muller, A. Dutartre, C. Laplace-Treyture, A. Cazaubon, E. Lambert-Servien, 2006. A New Method Involving Macrophytes to Assess Water Trophy and Organic Pollution: The Macrophyte Biological Index for Rivers (IBMR) — Application to Different Types of Rivers and Pollutions. Hydrobiologia 570(1):153-158.

Hendricks, S.P., 1993. Microbial Ecology of the Hyporheic Zone: A Perspective Integrating Hydrology and Biology. Journal of the North American Benthological Society 12:70-78.

Hession, W.C., T.E. Johnson, D.F. Charles, D.D. Hart, R.J. Horwitz, D.A. Kreeger, J.E. Pizutto, D.J. Velinsky, J.D. Newbold, C. Cianfrani, T. Clason, A.M. Compton, N. Coulter, L. Fuselier,B.D. Marshall, and J. Reed, 2000. Ecological Benefits of Riparian Reforestation in Urban Watersheds: Study Design and Preliminary Results. Environmental Monitoring and Assessment63:211-222.

Hey, R.D., 2006. Fluvial Geomorphological Methodology for Natural Stable Channel Design. Journal of American Water Resources Association 42(2):357-374.

Hill, B.H. and A.T. Herlihy, 2000. Periphyton (Section 7). In: Environmental Monitoring and Assessment Program—Surface Waters: Field Operations and Methods Manual for Measuring the Ecological Condition of Wadeable Streams, J.M. Lazorchak, B.H. Hill, D.K. Averill, D.V. Peck, and D.J. Klemm (Editors). US Environmental Protection Service, Cincinnati, Ohio. *http://www.epa.gov/emap/html/pubs/docs/groupdocs/surfwatr/field/R5_remap.pdf*

Hill, B.H., A.T. Herlihy, P.R. Kaufmann, J.R. Stevenson, F.H. McCormick, and C.B. Johnson, 2000. Use of Periphyton Assemblage Data as an Index of Biotic Integrity. Journal of the North American Benthological Society 19:50-67.

Hilsenhoff, W.L., 1988. Rapid Field Assessment of Organic Pollution with a Family-Level Biotic Index. Journal of the North American Benthological Society 7:65-68.

Hobbie, J.E. and R.T. Wright, 1965. Bioassay with Bacterial Uptake Kinetics: Glucose in Freshwater. Limnology and Oceanography 10:471-474.

Hoffman, J.C., 2006. Do American Shad Grow on Trees? Linking Forests with the Life History of a Marine Fish. Fisheries 31(2):94.

Holmes, N., T.H., J. R. Newman, S. Chadd, K.J. Rouen, L. Saint, and F.H. Dawson, 1999. Mean Trophic Rank: A Users Manual, R&D Technical Report E38. Environment Agency of England and Wales, Bristol, United Kingdom.

Hughes, R.M., A.T. Herlihy, and P.R. Kaufmann, 2010. An Evaluation of Qualitative Indexes of Physical Habitat Applied to Agricultural Streams in Ten US States. Journal of the American Water Resources Association 46(4):792-806.

Humphries, P. and D.S. Baldwin, 2003. Drought and Aquatic Ecosystems: An Introduction. Freshwater Biology 48:1141-1146.

Hupp, C.R., 1992. Riparian Vegetation Recovery Patterns Following Stream Channelization: A Geomorphic Perspective. Ecology 73:1209-1226.

Hynes, H.B.N., 1960. Biology of Polluted Waters. Liverpool University Press, Liverpool, United Kingdom.

Hynes, H.B.N., 1970. The Ecology of Running Water. University of Toronto Press, Toronto, Canada.

Inglis, C.C., 1947. Meanders and their Bearing on River Training. Institution of Civil Engineers, Maritime and Waterways Engineering Division, Paper No. 7, London, England.

Jackson D.A., P.R. Peres-Neto, and J.D. Olden, 2001. What Controls Who is Where in Freshwater Fish Communities — The Roles of Biotic, Abiotic, and Spatial Factors. Canadian Journal of Fisheries and Aquatic Sciences 58:157-170.

Jackson J.K. and V.H. Resh, 1989. Activities and Ecological Role of Adult Aquatic Insects in the Riparian Zone of Streams. In: Proceedings of the California Riparian Systems Conference: protection, management, and restoration for the 1990s, Davis, California, D.L. Abell (Editor). General Technical Report PSW-110, US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, pp. 342-346.

James, A.B.W. and I.M. Henderson, 2005. Comparison of Coarse Particulate Organic Matter Retention in Meandering and Straightened Sections of a Third-order New Zealand Stream. River Research and Applications 21:641-650.

Janauer, G. and M. Dokulil, 2006. Macrophytes and Algae in Running Waters. In: Biological Monitoring of Rivers: Applications and Perspectives, G.M. Ziglio, M. Siligardi and G. Flaim (Editors). John Wiley & Sons, Ltd, Chichester, United Kingdom, pp. 89-109.

Kalbus, E., F. Reinstorf and M. Schirmer, 2006. Measuring Methods for Groundwater, Surface Water and Their Interactions: A Review. Hydrology and Earth System Sciences Discussion 3(4):1809-1850.

Kappesser, G.B., 2002. A Riffle Stability Index to Evaluate Sediment Loading to Streams. Journal of the American Water Resources Association 38(4):1069-1081.

Karr, J.R., 1993. Defining and Assessing Ecological Integrity Beyond Water Quality. Environmental Toxicology and Chemistry 12(9):1521-1531.

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser, 1986. Assessing Biological Integrity of Running Waters: A Method and its Rationale. Illinois Natural History Survey, Special Publication #5, Champaign, Illinois.

Kasahara, T. and A.R. Hill, 2006. Hyporheic Exchange Flows Induced by Constructed Riffles and Steps in Lowland Streams in Southern Ontario, Canada. Hydrological Processes 20(20):4287-4305.

Kasahara, T. and A.R. Hill, 2007. Instream Restoration: Its Effects on Lateral Stream-Subsurface Water Exchange in Urban and Agricultural Streams in Southern Ontario. River Research and Applications 23:801-814.

Keaton, J.N., T. Messinger and E.J. Doheny, 2005. Development and Analysis of Regional Curves for Streams in the Non-Urban Valley and Ridge Physiographic Province, Maryland, Virginia, and West Virginia. US Geological Survey Water-Resources Investigation Report 2005-5076, US Geological Survey, Reston, Virginia.

Kilpatrick, F.A. and H.H. Barnes Jr., 1964. Channel Geometry of Piedmont Streams as Related to Frequency of Floods. US Geological Survey Professional Paper 422-E, US Geological Survey, Reston, VA.

Klemm, D.J., J. M. Lazorchak and D.V. Peck, 2000. Benthic Macroinvertebrates (Section 9). In: Environmental Monitoring and Assessment Program—Surface Waters: Field Operations and Methods Manual for Measuring the Ecological Condition of Wadeable Streams, J.M. Lazorchak, B.H. Hill, D.K. Averill, D.V. Peck, and D.J. Klemm (Editors). US Environmental Protection Service, Cincinnati, Ohio, pp. 146-160. *www.epa.gov/emap/html/pubs/docs/groupdocs/surfwatr/field/R5_remap.pdf*

Klocker, C.A., S.S. Kaushal, P.M. Groffman, P.M. Mayer and R.P. Morgan, 2009. Nitrogen Uptake and Denitrification in Restored and Unrestored Streams in Urban Maryland, USA. Aquatic Science 71:411-424.

Knight, A.W. and R.L. Bottorff, 1984. The Importance of Riparian Vegetation to Stream Ecosystems. In: California Riparian Systems, Ecology, Conservation, and Productive Management, R.E. Warner and K.M. Hendrix (Editors). Univeristy of California Press, Berkeley, California, pp. 160-167.

Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Oxford University Press Inc., New York, New York.

Kroes, D.E. and C.R. Hupp, 2010. The Effect of Channelization on Floodplain Sediment Deposition and Subsidence Along the Pocomoke River, Maryland. Journal of the American Water Resources Association 46(4):686-699.

Kuehne, R.A., 1962. A Classification of Streams, Illustrated by Fish Distribution in an Eastern Kentucky Creek. Ecology 43(4):608-614.

Lake, P.S., N. Bond and P. Reich, 2007. Linking Ecological Theory with Stream Restoration. Freshwater Biology, 52:597-615.

Lamberti, G.A., 1996. The Role of Periphyton in Benthic Food Webs. In: Algal Ecology: Freshwater Benthic Ecosystems, R.J. Stevenson, M.L. Bothwell, and R.L. Lowe (Editors). Academic Press, San Diego, California, pp. 533-572.

Lamberti, G.A., J.W. Feminella, and C.M. Pringle, 2006. Primary Producer-Consumer Interactions. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp. 537-559.

Lamberti, G.A. and S.V. Gregory, 2006. CPOM Transport, Retention, and Measurement. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp. 273-289.

Langbein, W.B. and L.B. Leopold, 1966. River Meanders — Theory of Minimum Variance. United States Geological Survey Professional Paper 422H, US Geological Survey, Reston, VA.

Lane, E.W., 1955. Design of Stable Channels. Transactions of the American Society of Civil Engineers Paper No. 2776:1234-1279.

Lane, E.W., 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. Proceedings of the American Society of Civil Engineering 81(745):1-17.

Lee, M.T., R.K. Peet, S.D. Roberts, and T.R. Wentworth, 2008. CVS-EEP Protocol for Recording Vegetation, Version 4.2. North Carolina Department of Environment and Natural Resources, Ecosystem Enhancement Program, Raleigh, North Carolina.

Lee, K.H., T.M. Isenhart, and R.C. Schultz, 2003. Sediment and Nutrient Removal in an Established Multi-Species Riparian Buffer. Soil and Water Conservation Journal 58(1):1-8.

Leopold, L.B., 1994. A View of the River. Harvard University Press, Cambridge, Massachusetts.

Leopold, L.B. and M.G. Wolman, 1957. River Channel Patterns: Braided, Meandering and Straight. US Geological Survey Professional Paper 282B:39-103.

Leopold, L.B., M.G. Wolman and J.P. Miller, 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co., San Francisco, California.

Leopold, L.B., M.G. Wolman and J.P. Miller, 1992. Fluvial Processes in Geomorphology. Dover Publications, Inc., New York, New York.

Lowe, R.L., and G.D. LaLiberte, 2006. Benthic Stream Algae: Distribution and Structure. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp. 327-356.

Lowrance, R. and J.M. Sheridan, 2005. Surface Runoff Quality in a Managed Three Zone Riparian Buffer. Journal of Environmental Quality 34(5):1851-1859.

Lowrance, R.R., R.L. Todd, J. Fail, O. Hendrickson, R. Leonard, and L.E. Asmussen, 1984. Riparian Forests as Nutrient Filters in Agricultural Watersheds. Bioscience 34:374-377.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood, 1989. Nutrient and Sediment Removal by Vegetated Filter Strips. Transactions, American Society of Agricultural Engineers 32:663–667.

Malison, R.L., J.R. Benjamin, and C.V. Baxter, 2010. Measuring Adult Insect Emergence from Streams: The Influence of Trap Placement and a Comparison with Benthic Sampling. Journal of the North American Benthological Society 29(2):647-656.

Mandaville, S.M., 2002. Benthic Macroinvertebrates in Freshwaters— Taxa Tolerance Values, Metrics, and Protocols, Project H-1. Soil & Water Conservation Society of Metro Halifax, Nova Scotia.

Matthews, R.A., A.L. Buikema, Jr., J. Cairns, Jr., and J.H. Rodgers, Jr., 1982. Biological Monitoring Part IIA — Receiving System Functional Methods, Relationships, and Indices. Water Resources 16: 129-139.

Mayer, P.M., S.K. Reynolds, M.D. McCutchen, and T.J. Canfield, 2006. Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations. US Environmental Protection Agency EPA/600/R-05/118, Washington, D.C. *http://www.epa.gov/nrml/pubs/600R05118*

McCafferty, P.W., 1981. Aquatic Entomonology The Fishermen's and Ecologists' Illustrated Guide to Insects and their Relatives. Jones and Bartlett Publishers, Boston, Massachusetts.

McCandless, T.L. and R.A. Everett, 2002. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region. US Fish and Wildlife Service Technical Report CBFO-S02-01, US Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, Maryland.

McCandless, T.L., 2003a. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Allegheny Plateau and the Valley and Ridge Hydrologic Regions. US Fish and Wildlife Service Technical Report CBFO-S03-01, US Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, Maryland.

McCandless, T.L., 2003b. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics in the Coastal Plain Hydrologic Region. US Fish and Wildlife Service Technical Report CBFO-S03-02, US Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, Maryland.

McCormick, F.H., R.M. Hughes, P.R. Kaufmann, A.T. Herlihy, and D.V. Peck, 2001. Development of an Index of Biotic Integrity for the Mid-Atlantic Highlands Region. Transactions of the American Fisheries Society 130:857–877.

McKay, K., I. Linkov, C. Fischenich, S. Miller, and J. Valverde, 2012. Ecosystem Restoration Objectives and Metrics (In Progress). EBA Technical Notes Collection, ERDC TN-EMRRP-EBA-12-##. US Army Engineer Research and Development Center, Vicksburg, Mississippi.

Meilinger, P., S. Schneider, and A. Melzer, 2005. The Reference Index Method for the Macrophyte-Based Assessment of Rivers — a Contribution to the Implementation of the European Water Framework Directive in Germany. International Review of Hydrobiology 90(3):322-342.

Merigliano, M.F., 1997. Hydraulic Geometry and Stream Channel Behavior: An Uncertain Link. Journal of the American Water Resources Association 33(6):1327-1336.

Merritt, R.W. and K.W. Cummins, 1996. An Introduction to the Aquatic Insects of North America, Third Edition. Kendall/Hunt Publishing Company, Dubuque, Iowa. ISBN-13: 978-0787232412.

Messinger, T., 2003. Comparison of Storm Response of Streams in Small, Unmined and Valley-Filled Watersheds, 1999–2001, Ballard Fork, West Virginia. US Geological Survey Water-Resource Investigations Report 02-4303, US Geological Survey, Reston, Virginia.

Metcalf, C.K., 2004. Regional Channel Charateristics for Maintaining Natural Fluvial Geomorphology in Florida Streams. US Fish and Wildlife Service Technical Report, US Fish and Wildlife Service Panama City Fisheries Resource Office, Panama City, Florida.

Meybeck, M., 1982. Carbon, Nitrogen and Phosphorus Transport by World Rivers. American Journal of Science 282:401-450.

Miller, S.J. and D. Davis, 2003. Identifying and Optimizing Regional Relationships for Bankfull Discharge and Hydraulic Geometry at USGS Stream Gage Sites in the Catskill Mountains, New York. Technical Report, New York City Department of Environmental Protection, New York, New York.

Miller, S.J., B.A. Pruitt, C.H. Theiling , J.C. Fischenich and S.B. Komlos, 2011. Reference Concepts in Ecosystem Restoration and EBA: Principles and Practices, EBA Technical Notes Collection, ERDC TN-EMRRP-EBA-11-##. US Army Engineer Research and Development Center, Vicksburg, Mississippi. *cw-environment.usace.army.mil/eba*

Minshall, G.W., K.W. Cummins, R.C. Peterson, C.E. Cushing, D.A. Bruns, J.R. Sedell, and R.L. Vannote, 1985. Developments in Stream Ecosystem Theory. Canadian Journal Fisheries and Aquatic Sciences 42:1045-1055.

Moerke, A.H. and G.A. Lamberti, 2003. Response in Fish Community Structure to Restoration of Two Indiana Streams. North American Journal of Fisheries Management 23:748-759.

Montgomery, D.R. and J.M. Buffington, 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition, TFW-SH10-93-002, Timber, Fish, and Wildlife Agreement. Washington Department of Natural Resources, Olympia, Washington.

Montgomery, D.R., B.D. Collins, J.M Buffington, and T.B. Abbe, 2003. Geomorphic effects of wood in rivers, In: The Ecology and Management of Wood in World Rivers, S.V. Gregory, K.L. Boyer, and A.M. Gurnell (Editors). American Fisheries Society Symposium, Bethesda, Maryland, pp. 21-47.

Mortimer, C.H., 1981. The Oxygen Content of Air-Saturated Fresh Waters over Ranges of Temperature and Atmospheric Pressure of Limnological Interest. Mitteilungen der IVL 22:1-23.

Moyle, P.B. and J.J. Cech, Jr., 1982. Fishes: An Introduction to Ichthyology. Prentice Hall, Englewood Cliffs, New Jersey.

Mullner, S.A., W.A. Hubert, and T.A. Wesche, 1998. Snorkeling as an Alternative to Depletion Electrofishing for Estimating Abundance and Length-class Frequencies of Trout in Small Streams. North American Journal of Fisheries Management 18:947-953.

Mulvihill, C.I., A.G. Ernst and B.P. Baldigo, 2006. Regionalized Equations for Bankfull Discharge and Channel Characteristics of Streams in New York State: Hydrologic Region 6 in the Southern Tier of New York. US Geological Survey Water-Resources Investigation Report 2004-5100, US Geological Survey, Reston, Virginia.

Murphy, M.L., C.P. Hawkins, and N.H. Anderson, 1981. Effects of Canopy Modification and Accumulated Sediment on Stream Communities. Transactions of the American Fisheries Society 110(4):469-478.

Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph, 1992. General Principles of Classification and the Assessment of Conservation Potential in Rivers. In: River Conservation and Management, P. Boon, P. Calow, and G. Petts, (Editors). John Wiley and Sons, Chichester, United Kingdom, pp. 93-123.

Naiman, R.J. and H. Décamps, 1997. The Ecology of Interfaces — Riparian Zones. Annual Review of Ecology and Systematics 28:621-658.

Nanson, G.C. and J.C. Croke, 1992. A Genetic Classification of Floodplains. Geomorphology 4:459- 486.

National Park Service (NPS) and George Mason University, 2010. Ecological Assessment Methods Database. National Biological Information Infrastructure (NBII), Center for Biological Informatics of the US Geological Survey. *assessmentmethods.nbii.gov*

New Mexico Environment Department/Surface of Water Quality Bureau (NMED/SWQB), 2009. Hydrology Protocol for the Determination of Ephemeral, Intermittent, and Perennial Waters — DRAFT. *ftp.nmenv.state.nm.us/www/swqb/MAS/Hydrology/NMHydroProtocol-PublicCommentDraft08-2009.pdf*

Newbold, J.D., 1992. Cycles and Spirals of Nutrients. In: The Rivers Handbook. I. Hydrological and Ecological Principles, P. Calow and G.E. Petts (Editors). Blackwell Scientific Publishers, Oxford, United Kingdom, pp. 379-408.

Newbold, J.D., P.S. Mulholland, J.W. Elwood, and R.J. O'Neill, 1982. Organic Carbon Spiraling in Stream Ecosystems. Oikos 38:266-272.

Newbold, J.D., J.W. Elwood, R.V. O'Neill, and W. Van Winkle, 1981. Measuring Nutrient Spiraling in Streams. Canadian Journal of Fisheries and Aquatic Sciences 38:860-863.

Nixon, M., 1959. A Study of Bankfull Discharges of Rivers in England and Wales. Institution of Civil Engineers Proceedings, 12(2):157-174.

North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality (DWQ), 2005. Methodology for Identification of Intermittent and Perennial Streams and Their Origins, V.3.1. Raleigh, North Carolina. *portal.ncdenr.org/c/document_library/get_file?uuid=6b6a0403-d445-43de-8e29-83bc549fdf88&groupId=38364*

NCDENR, DWQ, 2006. Standard Operating Procedures for Macroinvertebrates. NCDENR Biological Assessment Unit, Raleigh, North Carolina.

NCDENR, DWQ, 2010. Methodology for Identification of Intermittent and Perennial Streams and Their Origins, V.4.0. Raleigh, North Carolina. *portal.ncdenr.org/c/document_library/get_file?uuid=59f76e1a-9c9f-43e3-a764-a2703239fe36&groupId=38364*

O'Hare M.T., A. Baattrup-Pedersen, R. Nijboer, K. Szoszkiewicz, and T. Ferreira, 2006. Macrophyte Communities of European Streams with Altered Physical Habitat. Hydrobiologia 566:197-210.

Opperman, J.J. and A.M. Merenlender, 2004. The Effectiveness of Riparian Restoration for Improving Instream Fish Habitat in Four Hardwood-dominated California Streams. North American Journal of Fisheries Management 24:822-834.

Orzetti, L.L., R.C. Jones, and R.F. Murphy, 2010. Stream Condition in Piedmont Streams with Restored Riparian Buffers in the Chesapeake Bay Watershed. Journal of the American Water Resources Association 46(3):474-485.

Passauer, B., P. Meilinger, A. Melzer, and S. Schneider, 2002. Does the Structural Quality of Running Waters Affect the Occurrence of Macrophytes? Acta Hydrochimica et Hydrobiologica 30:197-206.

Payn, R.A., J.R. Webster, P.J. Mulholland, H.M. Valett, and W.K. Dodds, 2005. Estimation of Stream Nutrient Uptake from Nutrient Addition Experiments. Limnology and Oceanography: Methods 3:174-182.

Peckarsky, B.L., 1990. Freshwater Macroinvertebrates of Northeastern North America. Comstock Publishing, Sacramento, California. ISBN-13: 978-0801496882.

Penn State-Westmoreland Conservation District, 2003. Macroinvertebrate Identification Workshop, Virginia Save-Our-Streams Protocol. Stroud Water Research Center, Donohoe Center, Greensburg, Virginia.

Peterson B.J. and B. Fry, 1987. Stable Isotopes in Ecosystem Studies. Annual Review of Ecology and Systematics 18:293-320.

Phillips, J.D., 1989. Hillslope and Channel Sediment Delivery and Impacts of Soil Erosion on Water Resources. Sediment and the Environment, Proceedings of the Baltimore Symposium. International Association of Hydrological Sciences Publication 184.

Pitlick, J., Y.T. Cui, and P.R. Wilcock, 2009. Manual for Computing Bed Load Transport Using BAGS (Bedload Assessment for Gravel-bed Streams) Software, General Technical Report RMRS–GTR–223. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. *www.fs.fed.us/rm/pubs/rmrs_gtr223.pdf*

Pizzuto, J.E., 1987. Sediment Diffusion During Overbank Flows. Sedimentology 34:301-317.

Prichard, D., J. Anderson, C. Correll, J. Fogg, K. Gebhardt, R. Krapf, S. Leonard, B. Mitchell, and J. Staats, 1998. Riparian Area Management: A User Guide to Assessing Proper Functioning Condition and the Supporting Science for Lotic Areas, Technical Report 1737-15. US Department of the Interior, Bureau of Land Management, US Department of Agriculture Forest Service, and Natural Resources Conservation Service. *ftp.blm.gov/pub/nstc/techrefs/Final%20TR%201737-15.pdf*

Pruitt, B.A., S.J. Miller, C.H. Theiling, and J.C. Fischenich, 2012. The Use of Reference Ecosystems as a Basis for Assessing Restoration Benefits, EBA Technical Notes Collection, ERDC TN-EMRRP-EBA-12-##. US Army Engineer Research and Development Center, Vicksburg, Mississippi. *cw-environment.usace.army.mil/eba*

Quinn, J.M., N.R. Phillips, and S.M. Parkyn, 2007. Factors Influencing Retention of Coarse Particulate Organic Matter in Streams. Earth Surface Processes and Landforms 32:1186-1203.

Richardson, J.S., 1993. Limits to Productivity in Streams: Evidence from Studies of Macroinvertebrates. In: Production of Juvenile Atlantic salmon, Salmo salar, in Natural Waters, R.J. Gibson and R.E. Cutting (Editors). Canadian Special Publication of Fisheries and Aquatic Sciences 118:9-15.

Richardson, J.S., R.E. Bilby, and C.A. Bondar, 2005. Organic Matter Dynamics in Small Streams of the Pacific Northwest. Journal of the American Water Resources Association 41(4):921-934.

Rohde, F.C., R.G. Arndt, D.G. Lindquist, and J.F. Parnell, 1994. Fishes of the Carolinas, Virginia, Maryland, and Delaware. University of North Carolina Press, Chapel Hill, North Carolina.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22:169-199.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, Colorado.

Rosgen, D.L., 1997. A Geomorphological Approach to Restoration of Incised Rivers. In: Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, S.S.Y. Wang, E.J. Langendoen, and F.D. Shields (Editors). University of Mississippi, Oxford, Mississippi.

Rosgen, D.L., 1998. The Reference Reach — A Blueprint for Natural Channel Design. Proceedings from Wetlands and Restoration Conference, American Society of Civil Engineers, Denver, Colorado.

Rosgen, D.L., 2001. A Practical Method of Computing Streambank Erosion Rate. Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, NV. II: 9-15.

Rosgen, D.L. 2001(a). A Stream Channel Stability Assessment Methodology. Proceedings of the Federal Interagency Sediment Conference, Reno, Nevada, II:18-26.

Rosgen, D.L., 2009. A Watershed Assessment for River Stability and Sediment Supply (WARSSS). Wildland Hydrology Books, Fort Collins, Colorado. *www.epa.gov/warsss*

Rosgen, D.L., 2010. The Toe Wood Structure. Conference Workshop, Stream Restoration in the Southeast, Connecting Communities with Ecosystems. North Carolina State University, Raleigh, North Carolina.

Rosgen, D.L. and L. Silvey, 1998. Field Guide for Stream Classification. Wildland Hydrology Books, Pagosa Springs, Colorado.

Roth, N.E., J.D. Allan, and D.L. Erickson, 1996. Landscape Influences on Stream Biotic Integrity Assessed at Multiple Spatial Scales. Landscape Ecology 11:141-156.

Scharffenberg, W.A. and M.J. Fleming, 2010. Hydrologic Modeling System HEC-HMS Version 3.5 User's Manual. US Army Corps of Engineers Hydrologic Engineering Center, Davis, California. http://www.hec.usace.army.mil/software/hec-hms/documentation.html

Schaumburg, J., C. Schranz, J. Foerster, A. Gutowski, G. Hofmann, P. Meilinger, S. Schneider, and U. Schmedtje, 2004. Ecological Classification of Macrophytes and Phytobenthos for Rivers in Germany According to the Water Framework Directive. Limnologica 34:283–301.

Schneider, S., T. Krumpholz, and A. Melzer, 2000. Tropha¨ eindikation in Fliessgewa¨ ssern mit Hilfe des TIM (Tropha¨ e-Index Macrophyten) — Erprobung eines neu entwickelten Index im Inniger Bach. Acta Hydrochimica et Hydrobiologica 28:241–249.

Schoof, R., 1980. Environmental Impact of Channel Modification. Water Resources Bulletin 16(4): 697-701.

Schoonover, J.E. and K.W.J. Williard, 2005. Ground Water Nitrate Reduction in Giant Cane and Forest Riparian Buffer Zones. Journal of the American Water Resources Association 39(2):347-354.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York.

Sculthorpe, C.D., 1967. The Biology of Aquatic Vascular Plants. Edward Arnold, London, United Kingdom.

Shields, Jr., F.D., R.E. Lizotte, Jr., S.S. Knight, C.M. Cooper, and D. Wilcox, 2010. The Stream Channel Incision Syndrome and Water Quality. Ecological Engineering 36:78-90.

Sih A. and D.E.Wooster, 1994. Prey Behavior, Prey Dispersal, and Predator Impacts on Stream Prey. Ecology 75(5):1199-1207.

Simpson, E.H. 1949. Measurement of Diversity. Nature, 163: 688.

Simon, A., 1989. A Model of Channel Response in Disturbed Alluvial Channels. Earth Surface Processes and Landforms 14:11-26.

Simon, A. and E. Langendoen, 2006. A Deterministic Bank-Stability and Toe Erosion Model for Stream Restoration. Proceedings of the Environmental and Water Resources Council 2006 Meeting, Omaha, Nebraska, R. Graham (Editor). Environmental and Water Resources Institute, American Society of Civil Engineers, Reston, Virginia. *www.ars.usda.gov/Research/docs.htm?docid=5044*

Smith, D.G., 2001. Pennak's Freshwater Invertebrates of the United States, Fourth Edition. John Wiley & Sons, New York, New York. ISBN0-471-35837-1.

Smith, J.W.N., 2005. Groundwater—Surface Water Interactions in the Hyporheic Zone. Environment Agency, Science Report SC030155/SR1, Bristol, United Kingdom. *publications.environment-agency.gov.uk/pdf/SCHO0605BJCQ-e-e.pdf*

Somerville, D.E., 2010. Stream Assessment and Mitigation Protocols: A Review of Commonalities and Differences. Contract No. GS-00F-0032M, US Environmental Protection Agency, Washington, D.C.

Somerville, D.E. and B.A. Pruitt, 2004. Physical Stream Assessment: A Review of Selected Protocols for Use in the Clean Water Act Section 404 Program. US Environmental Protection Agency, Washington, D.C.

Southerland, M.T. and J.B. Stribling, 1995. Status of Biological Criteria Development and Implementation. In: Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making, W.S. Davis and T.P. Simon (Editors). Lewis Publishers, Boca Raton, Florida, pp. 81-96.

Stanford, J.A. and J.V. Ward, 1988. The Hyporheic Habitat of River Ecosystems. Nature 335:64-66.

Stevenson, R.J., 1996. An Introduction to Algal Ecology in Freshwater Benthic Habitats. In: Algal Ecology: Freshwater Benthic Ecosystems, R.J. Stevenson, M.L. Bothwell, and R.L. Lowe (Editors). Academic Press, San Diego, California, pp. 3-30.

Stevenson, R.J. and L.L. Bahls, 1999. Chapter 6: Periphyton Protocols. In: Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition, M.T. Barbour, J. Gerritsen, B.D. Snyder, and J.B. Stribling (Editors). EPA 841-B-99-002, US Environmental Protection Agency, Washington, D.C.

Stevenson, R.J. and Y. Pan. 1999. Assessing Ecological Conditions in Rivers and Streams with Diatoms. In: The Diatoms: Applications to the Environmental and Earth Sciences, E. F. Stoermer and J. P. Smol (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 11-40.

Stevenson, R. J. and J.P. Smol, 2003. Use of Algae in Environmental Assessments. In: Freshwater Algae in North America: Classification and Ecology, J.D. Wehr and R.G. Sheath (Editors). Academic Press, San Diego, California, pp. 775-804.

Stoddard, J.L., D.P. Larsen, C.P. Hawkins, R.K. Johnson, and R.H. Norris, 2006. Setting Expectations for the Ecological Condition of Streams: The Concept of Reference Condition. Ecological Applications 16(4):1267-1276.

Stream Solute Workshop, 1990. Concepts and Methods for Accessing Solute Dynamics in Stream Ecosystems. Journal of the North American Benthological Society 9:95-119.

Stromberg, J.C., V.B. Beauchamp, M.D. Dixon, S.J. Lite, and C. Paradzick, 2007. Importance of Low-flow and High-flow Characteristics to Restoration of Riparian Vegetation along Rivers in Arid South-western United States. Freshwater Biology 52:651-679.

Stumm, W. and J.J. Morgan, 1996. Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters, Third Edition. John Wiley & Sons, Inc., New York, New York.

Sweeney, B.W., 1993. Streamside Forests and the Physical, Chemical, and Trophic Characteristics of Piedmont Streams in Eastern North America. Water Science and Technology 26:2653-2673.

Sweeney, B.W. and J.G. Blaine, 2007. Resurrecting the In-Stream Side of Riparian Forests. Journal of Contemporary Water Research and Education 136:17-27.

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Standley, W.C. Hession and R.J. Horwitz, 2004. Riparian Deforestation, Stream Narrowing, and Loss of Stream Ecosystem Services. Proceedings of the National Academy of Sciences 101(39):14132-14137.

Sweet, W.V. and J.W. Geratz, 2003. Bankfull Hydraulic Geometry Relationships and Recurrence Intervals for the North Carolina's Coastal Plain. Journal of the American Water Resources Association 39(4): 861-871.

Taylor, P.D., L. Fahrig, K. Henein, and G. Merriam, 1993. Connectivity is a Vital Element of Landscape Structure. Oikos 68(3):571-572.

Thomas, W.A., R.R. Copeland, and D.N. McComas, 2002. SAM Hydraulic Design Package for Channels. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. *www.ayresassociates.com/Web_SAMwin/docs.htm*

Thorp, J.H. and A.P. Covich, 2009. Ecology and Classification of North American Freshwater Invertebrates, Third Edition. Academic Press, London, United Kingdom. ISBN-13: 978-0123748553.

Thompson, P.D. and F.J. Rahel, 1996. Evaluation of Depletion-Removal Electrofishing of Brook Trout in Small Rocky Mountain Streams. North American Journal of Fisheries Management 16:332-339.

Thurman, E.M., 1985. Organic Geochemistry of Natural Waters. Martinus Nijhoff, Dordrecht, The Netherlands.

Thurow, R.F. and D.J. Schill, 1996. Comparison of Day Snorkeling, Night Snorkeling, and Electrofishing to Estimate Bull Trout Abundance and Size Structure in a Second-order Idaho Stream. North American Journal of Fisheries Management 16:314-323.

Tomer, M.D., T.B. Moorman, J.L. Kovar, D.E. James, and M.R. Burkart, 2007. Spatial Patterns of Sediment and Phosphorus in a Riparian Buffer in Western Iowa. Soil and Water Conservation Journal 62(5):329-338.

Topping, B.J.D., T. Nadeau, and M.R. Turaski, 2009. Oregon Streamflow Duration Assessment Method Interim Version. Public Notice release date, 6 March 2009. *www.oregonstatelands.us/DSL/PERMITS/docs/osdam_march_2009.pdf?ga=t*

Tremp, H. and A. Kohler, 1995. The Usefulness of Macrophyte Monitoring-Systems, Exemplified on Eutrophication and Acidification of Running Waters. Acta Botanica Gallica 142:541-550.

Tweedy, K., 2010. Personal Communication about the Flowline Products Flow Measurement Device. Michael Baker Engineering, Inc., Cary, NC.

US Army Corps of Engineers (USACE), 2010. Operational Draft Regional Guidebook for the Functional Assessment of High-gradient Ephemeral and Intermittent Headwater Streams in Western West Virginia and Eastern Kentucky, ERDC/EL TR-10-11. US Army Engineer Research and Development Center, Vicksburg, Mississippi.

USACE Charleston District, 2010. Guidelines for Preparing a Compensatory Mitigation Plan. *www.sac.usace.army.mil/?action=mitigation.home*

USACE Galveston District, 2011. Interim Galveston District Stream Condition Assessment Standard Operating Procedure for Compensatory Stream Mitigation. *www.swg.usace.army.mil/reg/documents/Stream_SOP.pdf*

USACE Norfolk District and Virginia Department of Environmental Quality (VDEQ), 2007.Unified Stream Methodology for use in Virginia. *www.nao.usace.army.mil/technical%20services/Regulatory%20branch/USM/USM_Final_Draft.pdf*

USACE Savannah District, 2004. Standard Operating Procedure for Compensatory Mitigation. *www.sas.usace.army.mil/regulatory/documents/SOP.04.pdf*

USACE Wilmington District and North Carolina Department of Environment and Natural Resources (NCDENR), 2005. Information Regarding Stream Restoration in the Outer Coastal Plain of North Carolina. *www.saw.usace.army.mil/wetlands/Policies/HWM12_1_05.pdf*

USACE Wilmington District, US Environmental Protection Agency (USEPA), North Carolina Wildlife Resource Commission (NCWRC), and NCDENR, 2003. Stream Mitigation Guidelines. *www.saw.usace.army.mil/WETLANDS/Mitigation/Documents/Stream/STREAM%20MITIGATION%20GUIDELINE%20TEXT.pdf*

US Department of Agriculture (USDA), National Resources Conservation Service (NRCS), 1998. Stream Visual Assessment Protocol. National Water and Climate Center Technical Note 99–1. *www.nrcs.usda.gov/technical/ecs/aquatic/svapfnl.pdf*

USDA, NRCS, 2007. Part 654 — Stream Restoration Design. In: NRCS National Engineering Handbook Part 654 — Stream Restoration Design, H.210.NEH.654. *www.nrcs.usda.gov/technical/ENG*

USDA, NRCS, 2009a. The Computer Program for Project Formulation Hydrology WinTR-20. ver 1.11. *http://www.wsi.nrcs.usda.gov/products/w2q/h&h/tools_models/WinTR20.html*

USDA, NRCS. 2009b. Urban Hydrology for Small Watersheds WinTR-55. Technical Release 210-VI-TR-55 Second edition, Version 1.00.09. Washington, D.C. *www.wsi.nrcs.usda.gov/products/w2q/h&h/tools_models/wintr55.html*.

US Environmental Protection Agency (USEPA). 1997a. Monitoring Guidance for Determining the Effectiveness of Nonpoint Source Controls. EPA/841-B-96-004, US Environmental Protection Agency, Nonpoint Source Control Branch, Washington, D.C.

USEPA, 1997b. Volunteer Stream Monitoring: A Methods Manual. EPA 841-B-97-003, US Environmental Protection Agency, Washington, D.C. *www.epa.gov/volunteer/stream/stream.pdf*

USEPA 2000. Nutrient Criteria Technical Guidance Manual Rivers and Streams. EPA 822-B-00-002, US Environmental Protection Agency, Washington, D.C. *www.epa.gov/waterscience/criteria/nutrient/guidance/rivers/rivers-streams-full.pdf*

USEPA, 2002. Standard Operating Procedure for Benthic Invertebrate Field Sampling Procedure. LG406, 7:1-5, US Environmental Protection Agency, Washington, D.C. *www.epa.gov/glnpo/monitoring/sop/chapter_4/LG406.pdf*

USEPA, 2003a. National Management Measures to Control Nonpoint Source Pollution from Agriculture. EPA 841-B-03-004, US Environmental Protection Agency, Washington, D.C. *water.epa.gov/polwaste/nps/agriculture/agmm_index.cfm*

USEPA, 2003b. Elements of a State Water Monitoring and Assessment Program. EPA 841-B-03-003, US Environmental Protection Agency, Washington, D.C. *www.epa.gov/owow/monitoring/repguid.html*

USEPA, 2007. The National Water Quality Standards Database (WQSDB), Release 9. US Environmental Protection Agency, Washington, D.C. *www.epa.gov/waterscience/standards/wqslibrary*

USEPA, 2008. Acid Rain. Available at *www.epa.gov/acidrain*

USEPA, 2009. National Water Quality Inventory: Report to Congress for the 2004 Reporting Cycle. US Environmental Protection Agency, Washington, D.C. *water.epa.gov/lawsregs/guidance/cwa/305b/upload/2009_01_22_305b_2004report_2004_305Breport.pdf*

USEPA, 2011. United States Code of Federal Regulations Title 40 Part 131, Subpart B: Establishment of Water Quality Standards. *water.epa.gov/scitech/swguidance/waterquality/standards/Laws-and-Regulations.cfm*

USEPA, 2012. EPA, 2012. National Summary of State Information: causes of impairment in assessed rivers and streams. URL: *iaspub.epa.gov/waters10/attains_index.control* last updated 3/7/2012, accessed 3/7/2012.

US Geological Survey (USGS). 1981. Guidelines for Determining Flood Flow Frequency, Bulletin 17b of the Hydrology Subcommittee. US Geological Survey, Reston, Virginia. *water.usgs.gov/osw/bulletin17b/bulletin_17B.html*

USGS, 2010. National Field Manual for the Collection of Water-Quality Data: US Geological Survey Techniques of Water-Resources Investigations, Book 9, Chapters. A1-A9. US Geological Survey, Reston, Virginia. ***pubs.water.usgs.gov/twri9A***.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing, 1980. The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Vervier, P., J. Gibert, P. Marmonier and M.J. Dole-Oliver, 1992. A Perspective on the Permeability of the Surface Freshwater-Groundwater Ecotone. Journal of the North American Benthological Society 11:93-102.

Voshell, J.R., 2002. A Guide to Common Freshwater Invertebrates of North America. The McDonald & Woodward Publishing Co., Blacksburg, Virginia.

Wagner, R.J., R.W. Boulger, Jr., C.J Oblinger, and B.A. Smith, 2006. Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation and Data Reporting. Techniques and Methods 1D-3, US Geological Survey, Reston, Virginia. ***pubs.water.usgs.gov/tm1d3***

Wallace, J.B., J.J. Hutchens, Jr., and J.W. Grubaugh, 2006. Transport and Storage of FPOM. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp. 249-271.

Wallace J.B. and J.R. Webster, 1996. The Role of Macroinvertebrates in Stream Ecosystem Function. Annual Review of Entomology 41:115-139.

Walling, D.E., 1984. Dissolved Loads and Their Measurement. In: Erosion and Sediment Yield: Some Methods of Measurement and Modeling, R.F. Hadley and D.E. Walling (Editors). Geo Books, Regency House, Norwich, United Kingdom, pp. 111-177.

Warren, C.E., 1971. Biology and Water Pollution Control. W.B. Saunders, Philadelphia, Pennsylvania.

Watson, I. and A.D. Burnett, 1993. Hydrology: An Environmental Approach. Buchanan Books, Fort Lauderdale, Florida.

Webster, J.R. and E.F. Benfield, 1986. Vascular Plant Breakdown in Freshwater Ecosystems. Annual Review of Ecological System 17: 567-594.

Webster, J.R., E.F. Benfield, T.P. Ehrman, M.A. Schaeffer, J.L. Tank, J.J. Hutchens, and D.J. D'Angelo, 1999. What Happens to Allochthonous Material that Falls into Sttreams? A Synthesis of New and Published Information from Coweeta. Freshwater Biology 41:684-705.

Webster, J.R. and J.L. Meyer, 1997. Stream Organic Matter Budgets—A Synthesis. Journal of the North American Benthological Society 16:141-161.

Webster, J.R. and H.M. Valett, 2006. Solute Dynamics. In: Methods in Stream Ecology, Second Edition, R.F. Hauer and G.A. Lamberti (Editors). Elsevier, Oxford, United Kingdom, pp. 169-185.

Weitzel, R.L., 1979. Methods and Measurements of Periphyton Communities: A Review. American Society for Testing and Materials, Committee D-19 on Water.

Westlake, D.F., 1974. Macrophytes. In: A Manual on Methods for Measuring Primary Production in Aquatic Environments, IBP Handbook 12, R.A. Vollenweider (Editor), Blackwell Scientific Publications, Oxford, United Kingdom, pp 32-42.

Wetzel, R.G., 1983. Periphyton of Aquatic Ecosystems. B.V. Junk Publishers, The Hague.

Wetzel, R.G., 2001. Limnology, Lake and River Ecosystems, Third Edition. Academic Press, London, United Kingdom.

Wetzel, R.G. and G.E. Likens, 2000. Limnological Analyses, Third Edition. Springer-Verlag, Inc., New York, New York.

Whipple, W., J. DiLouie, and J. Pytlar, 1981. Erosion Potential of Streams in Urbanizing Areas. Water Resources Bulletin 17(1):36-45.

White, D.S. and S.P. Hendricks, 2000. Lotic Macrophytes and Surface-Subsurface Exchange Processes. In: Streams and Ground Waters, J.B. Jones and P.J. Mulholland (Editors). Academic Press, San Diego, California, pp. 363-379.

Whittaker, J.G., 1987. Sediment Transport in Step-pool Streams. In: Sediment Transport in Gravel-Bed Rivers, C.R. Thorne, J.C. Bathurst, and R.D. Hey (Editors). John Wiley, New York, New York, pp. 545-579.

Wiegner, T.N. and S.P. Seitzinger, 2001. Photochemical and Microbial Degradation of External Dissolved Organic Matter Inputs to Rivers. Aquatic Microbial Ecology 24:27-40.

Wilcock, P., J. Pitlick and Y. Cui, 2009. Sediment Transport Primer: Estimating Bed-Material Transport in Gravel-bed Rivers. General Technical Report RMRS-GTR-226, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. *www.fs.fed.us/rm/pubs/rmrs_gtr226.pdf*

Wiley, J.B., J.T. Atkins,Jr., and D.A. Newell, 2002. Estimating the Magnitude of Annual Peak Discharges with Recurrence Intervals between 1.1 and 3.0 Years for Rural, Unregulated Streams in West Virginia. US Geological Survey Water Resources Investigations Report 02-4164, US Geological Survey, Reston, Virginia.

Wilhm, J.L. and T.C. Dorris, 1968. Biological Parameters for Water Quality Criteria. Bioscience 18:477-481.

Winter, T.C., W.H. Judson, O.L Franke, and W.M. Alley, 1998. Groundwater and Surface Water a Single Resource. Circular 1139, US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/circ/circ1139

With, K.A., R.H. Gardner, and M.G. Turner, 1997. Landscape Connectivity and Population Distributions in Heterogeneous Environments. Oikos 78:151-169.

Wohl, E.E., 2004. Disconnected Rivers, Linking Rivers to Landscapes. Yale University, New Haven, Connecticutt. ISBN-0-300-I0332-8.

Wohl, E.E., 2000. Mountain Rivers. Water Resources Monographs 14, American Geophysical Union, Washington, D.C.

Wohl, E.E. and D.M. Thompson, 2000. Velocity Characteristics Along a Small Step-Pool Channel. Earth Surface Processes and Landforms, 25(4):353-367.

Wohl, E.E., D.A. Cenderelli, K.A. Dwire, S.E. Ryan-Burkett, M.K. Young, and K.D. Fausch, 2009. Large In-Stream Wood Studies: A Call for Common Metrics. Earth Surface Processes and Landforms 35:618-625.

Wolman, M.G., 1954. A Method of Sampling Coarse River-bed Material. Transactions of the American Geophysical Union 35(6):951-956.

Wolman, M.G. and J.P. Miller, 1960. Magnitude and Frequency of Forces in Geomorphic Process. Journal of Geology 68:54-74.

Wootten, R.J., 1992. Fish Ecology, Tertiary Level Biology. Chapman & Hall, New York, New York.

Wroblicky, G.J., M.E. Campana, H.M. Valett and D.C.N. Dahm, 1998. Seasonal Variation in Surface-Subsurface Water Exchange and Lateral Hyporheic Area of Two Stream-aquifer Systems. Water Resources Research 34:317-328.

Wynn, T., S. Mostaghimi, J.A. Burger, A.A. Harpold, M.B. Henderson, and L. Henry, 2004. Variation in Root Density along Stream Banks. Journal of Environmental Quality 33:2030-2039.

Zippin, C., 1956. An Evaluation of the Removal Method of Estimating Animal Populations. Biometrics 12:163-169.

WEB REFERENCES

Chapter 1

Training Resources
training.fws.gov
www.stream-mechanics.com

Technical Resources for Stream Mitigation
water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm

Chapter 2

EPA Stream and Wetland Mitigation Resources
water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm

Chapter 3

Guidelines for Preparing a Compensatory Mitigation Plan, Charleston District, USACE
www.sac.usace.army.mil/?action=mitigation.home

Compensatory Stream Mitigation Standard Operating Procedures and Guidelines (Draft), Mobile District, USACE *www.sam.usace.army.mil/RD/reg/docs/2011 Draft Stream SOP.pdf*

Standard Operating Procedure for Compensatory Mitigation, Savannah District, USACE
http://www.sas.usace.army.mil/regulatory/documents/SOP.04.pdf

Stream Mitigation Guidelines, Wilmington District, USACE, *www.saw.usace.army.mil/WETLANDS/Mitigation/Documents/Stream/STREAM MITIGATION GUIDELINE TEXT.pdf*

Unified Stream Methodology, Norfolk District USACE, *www.nao.usace.army.mil/technical services/Regulatory branch/USM/USM_Final_Draft.pdf*

Stream Corridor Restoration: Principles, Processes and Practices
www.nrcs.usda.gov/technical/stream_restoration

Watershed Scale Restoration
http://water.epa.gov/type/watersheds/approach.cfm

Natural Resources Conservation Service National Engineering Handbook Part 654 — Stream Restoration Design
www.nrcs.usda.gov/technical/ENG

Chapter 5

Natural Resources Conservation Service, National Engineering Handbook
directives.sc.egov.usda.gov/viewerFS.aspx?id=3491

Somerville (additional assessment methodologies)
water.epa.gov/lawsregs/guidance/wetlands/upload/Stream-Protocols_2010.pdf

Stream Channel Reference Sites: An Illustrated Guide to Field Technique
www.stream.fs.fed.us/publications/PDFs/RM245E.PDF

The Reference Reach — A Blueprint for Natural Channel Design
www.wildlandhydrology.com/assets/The_Reference_Reach_II.pdf

Proper Functioning Condition
ftp.blm.gov/pub/nstc/techrefs/Final TR 1737-9.pdf

Watershed Assessment of River Stability and Sediment Supply
water.epa.gov/scitech/datait/tools/warsss/index.cfm

Size Class Pebble Count Analyzer
www.stream.fs.fed.us/publications/software.html

Channel Evolution Models/Stream Type Succession Scenarios
www.nrcs.usda.gov/technical/stream_restoration/

Rosgen Stream Type Succession Scenarios
water.epa.gov/scitech/datait/tools/warsss/successn.cfm

Regional Curves
water.epa.gov/lawsregs/guidance/wetlands/upload/Appendix-A_Regional_Curves.pdf

EPA Rapid Bio-assessment Protocol (RBP)
water.epa.gov/scitech/monitoring/rsl/bioassessment/index.cfm

Index of Biotic Integrity (IB)
www.epa.gov/bioiweb1/html/ibi_history.html

NRCS Stream Visual Assessment Protocol
www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/alphabetical/water/restoration/?&cid=stelprdb1043249

Monitoring Wilderness Stream Ecosystems
www.fs.fed.us/rm/pubs/rmrs_gtr70.pdf

EPA Statistical Primer
www.epa.gov/bioindicators/statprimer/statistical_testing.html

Chapter 6
Watershed Assessment of River Stability and Sediment Supply (WARSSS)
www.epa.gov/warsss

Methods for Identifying Bankfull
www.stream.fs.fed.us/publications/PDFs/RM245E.PDF

Methods for Identifying Bankfull in North Carolina Streams
www.bae.ncsu.edu/programs/extension/wqg/srp/rv-crs-3.pdf

Hydrologic Modeling System (HEC-HMS)
www.hec.usace.army.mil/software/hec-hms

Regional Regression Equations
water.usgs.gov/software/NFF

FEMA Regulated Floodplains Information
www.msc.fema.gov

USGS Bulletin 17b
water.usgs.gov/osw/bulletin17b/bulletin_17B.html

NC Department of Environment and Natural Resources, Division of Water Quality V. 3.1
portal.ncdenr.org/c/document_library/get_file?uuid=6b6a0403-d445-43de-8e29-83bc549fdf88&groupId=38364

V.4.0: *portal.ncdenr.org/c/document_library/get_file?uuid=59f76e1a-9c9f-43e3-a764-a2703239fe36&groupId=38364*

Oregon Streamflow Duration Assessment Method Interim Version
www.oregonstatelands.us/DSL/PERMITS/docs/osdam_march_2009.pdf?ga=t

Hydrology Protocol for the Determination of Ephemeral, Intermittent and Perennial Waters (DRAFT 8/09)
ftp.nmenv.state.nm.us/www/swqb/MAS/Hydrology/NMHydroProtocol-PublicComment-Draft08-2009.pdf

Chapter 7
FishXing Website
www.stream.fs.fed.us/fishxing/index.html

Chapter 8
SAMWin
chl.erdc.usace.army.mil/chl.aspx?p=s&a=SOFTWARE;2

2-D Models with Hydraulic and Sediment Transport Modeling Capabilities
RiverFLO-2D: *www.flo-2d.com/products*
Mike 21: *www.mikebydhi.com*

RIVERMorph Software Program
www.rivermorph.com

BAGS Program
www.stream.fs.fed.us/publications/bags.html

Technical Resources for Mitigation
water.epa.gov/lawsregs/guidance/wetlands/wetlandsmitigation_index.cfm

Parameters and Methods of Measurement
stream.fs.fed.us/publications/documentsStream.html

Assessing Proper Functioning Condition for Lotic Areas
ftp.blm.gov/pub/nstc/techrefs/Final%20TR%201737-15.pdf

NRCS Stream Visual Assessment Protocol (SVAP)
www.nrcs.usda.gov/technical/ecs/aquatic/svapfnl.pdf

Watershed Assessment of River Stability and Sediment Supply (WARSSS) Prediction Level Assessment (PLA) Index
water.epa.gov/scitech/datait/tools/warsss/pla_box07.cfm

US 301 Environmental Stewardship Study
Link: *www.fws.gov/chesapeakebay/streampub.html*

Sampling and Analyzing Surface and Subsurface Particles
www.stream.fs.fed.us/publications/documentsStream.html

Spreadsheet Tools and Instructions for Managing Pebble Count Data
www.stream.fs.fed.us/publications/software.html

Chapter 9
EPA Database of State Water Quality Standards
www.epa.gov/waterscience/standards/wqslibrary

EPA Water Quality Monitoring Information
www.epa.gov/storet

Chapter 10
Ecological Assessment Methods Database
assessmentmethods.nbii.gov

Landscape Connectivity
Circuitscape: *www.circuitscape.org/Circuitscape/Welcome.html*
Conefor Sensinode: *www.conefor.org*
Funconn: *www.nrel.colostate.edu/projects/starmap/funconn_index.htm*
Pathmatrix: *cmpg.unibe.ch/software/pathmatrix*

Chapter 11
Conducting Watershed Assessments
water.epa.gov/type/watersheds

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Appendices

A. STREAM FUNCTIONS PYRAMID

A. Overview Graphic
B. Functions & Parameters Graphic
C. Parameter & Measurement Method Table
D. Performance Standard Table

B. APPLICATION SCENARIOS

PERMITTED IMPACT SCENARIOS (DEBITS)

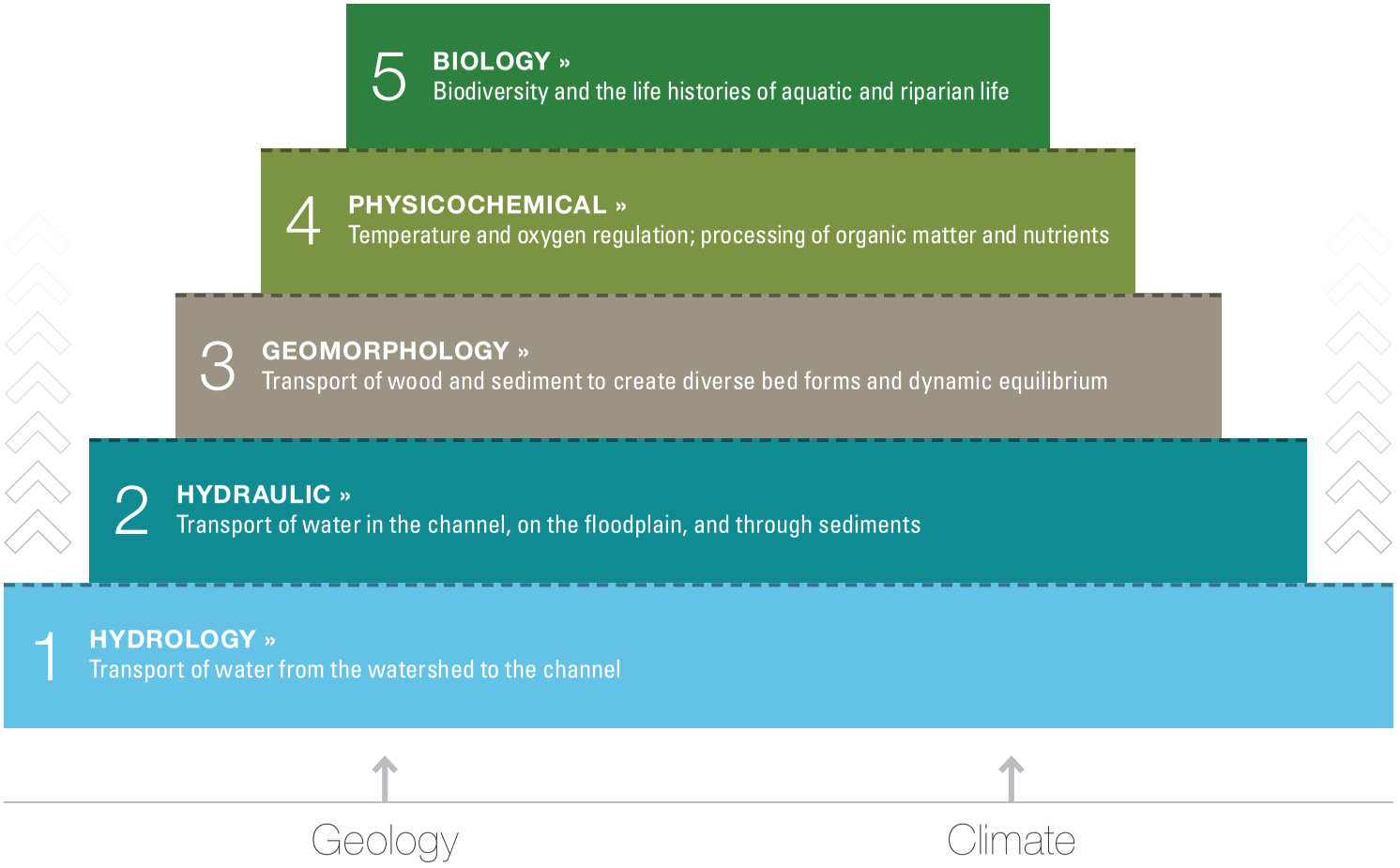
1. Culvert installations
2. Channelization and Bank Hardening
3. Surface Mining of High-Gradient Streams

STREAM MITIGATION SCENARIOS (CREDITS)

1. Restoration of Incised Channels in Alluvial Valleys
2. Restoration of Stream Flow for Channels That Have Excessive Water Withdrawal
3. Salmonid Fish Passage and Habitat Restoration
4. Restoration of High-Gradient, Headwater Streams

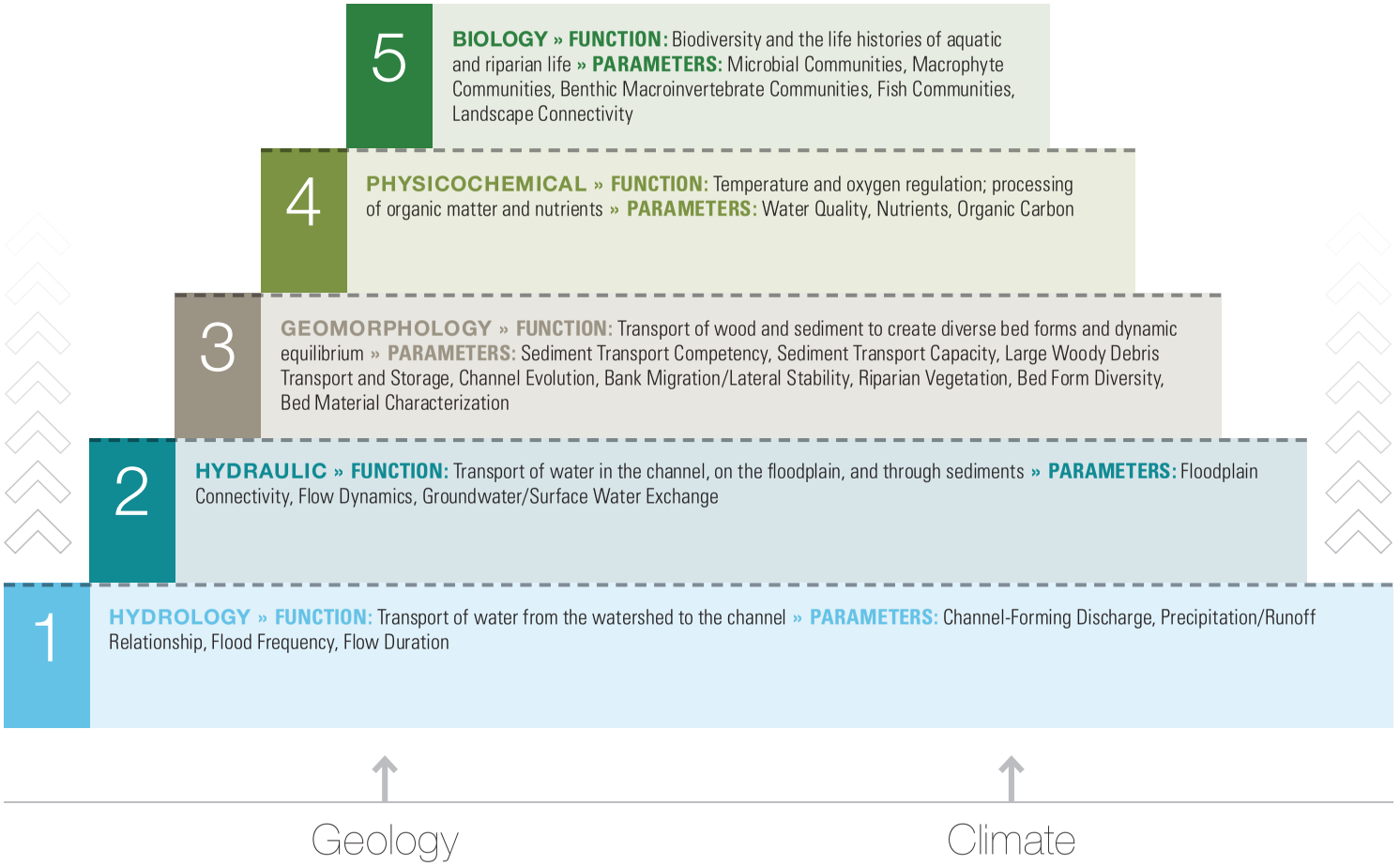
APPENDIX A: STREAM FUNCTIONS PYRAMID

a. OVERVIEW GRAPHIC



APPENDIX A: STREAM FUNCTIONS PYRAMID

b. STREAM FUNCTIONS PYRAMID: FUNCTIONS & PARAMETERS



APPENDIX A: STREAM FUNCTIONS PYRAMID

c. PARAMETER & MEASUREMENT METHOD TABLE

(Details about the categories for the measurement methods, including type, level of effort, level of complexity, and direct/indirect assessment , are provided in Chapter 4. The parameters and measurement methods shown here are examples. Additional parameters and measurement methods can be added based on user needs. Refer to Chapter 4 for instructions on how to add parameters and measurement methods.)

HYDROLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Channel-Forming Discharge	1. Regional Curves	1. Technique	1. Rapid to Intensive, dependent on curve	1. Simple to Complex, dependent on curve	1. Indirect
Precipitation/ Runoff Relationship	1. Rational Method 2. HEC-HMS 3. USGS Regional Regression Equations	1. Tool 2. Tool 3. Technique	1. Rapid 2. Moderate 3. Rapid	1. Moderate 2. Complex 3. Moderate	1. Indirect 2. Indirect 3. Indirect
Flood Frequency	1. Bulletin 17b	1. Technique	1. Moderate	3. Complex	1. Direct
Flow Duration	1. Flow Duration Curve 2. Crest Gauge 3. Monitoring Devices 4. Rapid Indicators	1. Technique 2. Tool 3. Tool 4. Assessment approach	1. Moderate to Intensive, dependent on data source 2. Rapid 3. Intensive 4. Rapid	1. Moderate/ Complex 2. Simple 3. Moderate 4. Simple	1. Direct/ Indirect 2. Indirect 3. Direct 4. Indirect

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

HYDRAULICS					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Floodplain Connectivity	1. Bank Height Ratio 2. Entrenchment Ratio 3. Stage Versus Discharge	1. Technique 2. Technique 3. Technique	1. Rapid/Moderate 2. Rapid/Moderate 3. Intensive	1. Simple/Moderate 2. Simple/Moderate 3. Complex	1. Direct 2. Direct 3. Indirect
Flow Dynamics	1. Stream Velocity 2. Shear Stress 3. Stream Power	1. Metric 2. Metric 3. Metric	1. Moderate/ Intensive 2. Moderate/ Intensive 3. Moderate/ Intensive	1. Moderate/ Complex 2. Moderate/ Complex 3. Moderate/ Complex	1. Direct 2. Direct 3. Direct
Groundwater/ SurfaceWater Exchange	1. Piezometers 2. Tracers 3. Seepage Meters	1. Tool 2. Tool 3. Tool	1. Intensive 2. Intensive 3. Intensive	1. Complex 2. Complex 3. Complex	1. Direct 2. Direct 3. Direct

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Sediment Transport Competency	1. Shear Stress Curve	1. Technique	1. Rapid to Intensive, dependent on curve availability	1. Simple to Complex, dependent on curve availability	1. Indirect
	2. Required Depth and Slope	2. Technique/ Tool	2. Moderate	2. Moderate	2. Indirect
	3. Spreadsheets and Computer Models	3. Tool	3. Moderate/ Intensive	3. Moderate/ Complex	3. Indirect
Sediment Transport Capacity	1. Computer Models	1. Tool	1. Moderate/ Intensive	1. Moderate/ Complex	1. Indirect
	2. FLOWSED and POWERSED	2. Tool	2. Intensive	2. Complex	2. Indirect
	3. BAGS	3. Tool	3. Rapid/Moderate	3. Simple/Moderate	3. Indirect
Large Woody Debris Transport and Storage	1. Wohl LWD Assessment	1. Assessment approach	1. Rapid/Moderate	1. Simple/Moderate	1. Direct for storage and Indirect for transport
	2. Large Woody Debris Index	2. Assessment approach	2. Moderate	2. Moderate	2. Direct for storage and Indirect for transport

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Channel Evolution	1. Simon Channel Evolution Model 2. Rosgen Stream Type Succession Scenarios	1. Technique 2. Technique	1. Rapid/Moderate 2. Moderate	1. Simple/Moderate 2. Moderate	1. Indirect 2. Indirect
Bank Migration/ Lateral Stability	1. Meander Width Ratio 2. BEHI / NBS 3. Bank Pins 4. Bank Profiles 5. Cross-Sectional Surveys 6. Bank Stability and Toe Erosion Model	1. Technique 2. Technique/ Tool 3. Technique 4. Technique 5. Technique 6. Tool	1. Rapid/Moderate 2. Moderate/ Intensive 3. Intensive 4. Intensive 5. Intensive 6. Intensive	1. Simple 2. Moderate 3. Moderate 4. Moderate 5. Moderate 6. Complex	1. Indirect 2. Indirect 3. Direct 4. Direct 5. Direct 6. Indirect

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Riparian Vegetation	1. Buffer Width	1. Technique	1. Rapid	1. Simple	1. Indirect
	2. Buffer Density	2. Technique	2. Moderate/ Intensive	2. Moderate	2. Direct
	3. Buffer Composition	3. Technique	3. Moderate/ Intensive	3. Moderate	3. Direct
	4. Buffer Age	4. Technique	4. Intensive	4. Moderate	4. Direct
	5. Buffer Growth	5. Technique	5. Intensive	5. Moderate	5. Direct
	6. Canopy Density	6. Technique	6. Moderate/ Intensive	6. Moderate	6. Direct
	7. Proper Functioning Condition (PFC)	7. Assessment approach	7. Rapid	7. Simple	7. Indirect
	8. NRCS Visual Assessment Protocol	8. Assessment approach	8. Rapid	8. Simple	8. Indirect
	9. Rapid Bioassessment Protocol	9. Assessment approach	9. Rapid	9. Simple	9. Indirect
	10. Watershed Assessment of River Stability and Sediment Supply (WARSSS)	10. Assessment approach	10. Intensive	10. Complex	10. Indirect
	11. USFWS Stream Assessment Ranking Protocol (SAR)	11. Assessment approach	11. Rapid	11. Simple	11. Indirect

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Bed Form Diversity	1. Percent Riffle and Pool	1. Technique	1. Rapid/Moderate	1. Moderate	1. Direct
	2. Facet Slope	2. Technique	2. Moderate	2. Moderate	2. Indirect
	3. Pool-to-Pool Spacing	3. Technique	3. Rapid/Moderate	3. Moderate	3. Indirect
	4. Depth Variability	4. Technique	4. Moderate	4. Moderate	4. Direct
Bed Material Characterization	1. Size Class Pebble Count Analyzer	1. Tool	1. Moderate/ Intensive	1. Moderate	1. Direct
	2. Riffle Stability Index (RSI)	2. Technique	2. Moderate/ Intensive	2. Moderate	2. Indirect
PHYSICOCHEMICAL					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Water Quality	1. Temperature	1. Metric	1. Rapid/Intensive	1. Simple/Moderate	1. Direct
	2. Dissolved Oxygen	2. Metric	2. Rapid/Intensive	2. Simple/Moderate	2. Direct
				3. Simple/Moderate	
				4. Simple/Moderate	
	3. Conductivity	3. Metric	3. Rapid/ Intensive	5. Simple/Moderate	3. Direct
	4. pH	4. Metric	4. Rapid /Intensive		4. Direct
	5. Turbidity	5. Metric	5. Rapid/Intensive		5. Direct
Nutrients	1. Field test kits using reagents reactions	1. Technique	1. Rapid for screening	1. Simple	1. Direct
	2. Laboratory analysis	2. Technique	2. Intensive	2. Complex	2. Direct

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

c. PARAMETER & MEASUREMENT METHOD TABLE

BIOLOGY					
PARAMETER	MEASUREMENT METHOD	TYPE	LEVEL OF EFFORT	LEVEL OF COMPLEXITY	ASSESSMENT OF PARAMETER
Organic Carbon	1. Laboratory analysis	1. Technique	1. Intensive	1. Complex	1. Direct
Microbial Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	1. Technique 2. Technique 3. Assessment approach	1. Intensive 2. Intensive 3. Moderate/ Intensive	1. Complex 2. Complex 3. Moderate/ Complex	1. Direct 2. Direct 3. Indirect
Macrophyte Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	1. Technique 2. Technique 3. Assessment approach	1. Intensive 2. Intensive 3. Moderate/ Intensive	1. Complex 2. Complex 3. Moderate/ Complex	1. Direct 2. Direct 3. Indirect
Benthic Macroinvertebrate Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	1. Technique 2. Technique 3. Assessment approach	1. Intensive 2. Intensive 3. Moderate/ Intensive	1. Complex 2. Complex 3. Moderate/ Complex	1. Direct 2. Direct 3. Indirect
Fish Communities	1. Taxonomic Methods 2. Non-Taxonomic Methods 3. Biological Indices	1. Technique 2. Technique 3. Assessment approach	1. Intensive 2. Intensive 3. Moderate/ Intensive	1. Complex 2. Complex 3. Moderate/ Complex	1. Direct 2. Direct 3. Indirect
Landscape Connectivity	1. Spatial Analysis 2. Species Tracking 3. Habitat Models	1. Technique 2. Technique 3. Technique	1. Intensive 2. Intensive 3. Intensive	1. Complex 2. Complex 3. Complex	1. Direct 2. Direct 3. Direct

APPENDIX A: STREAM FUNCTIONS PYRAMID

d. PERFORMANCE STANDARDS TABLE

Notes:

1. Since there are no Hydrology Performance Standards, there is not a Hydology Summary Table
2. Many of the performance standard values, especially the dimensionless ratios, should be considered as examples that can be modified based on regional differences in reference conditions.
3. Great care should be taken when selecting measurement methods and performance standards. Refer to Chapters 6-10 and the associated references before selecting measurement methods and performance standards.

HYDRAULIC					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Floodplain Connectivity	Bank Height Ratio (BHR)	1.0 to 1.2	1.3 to 1.5	> 1.5	Rosgen, 2001 (proceedings) and 1994 (book)
	Entrenchment Ratio (ER) for C and E Stream Types	> 2.2	2.0 to 2.2	< 2.0	
	Entrenchment Ratio (ER) for B and Bc Stream Types	> 1.4	1.2 to 1.4	< 1.2	
	Dimensionless rating curve	Project site Q/Q_{bkf} plots on the curve	Project site Q/Q_{bkf} plots above the curve	Project site Q/Qbkf of 2.0 plots above 1.6 for $d/_{dbkf}$	Dunne and Leopold 1978 (book)
Flow Dynamics	Bankfull Velocity for C and E stream types (ft/s)	3 to 6	6 to 7	> 7	Dunne and Leopold 1978 (book)
	Bankfull Velocity for Cc (ft/s)	< 3	3 to 4	> 5	
	Bankfull Velocity for B stream types (ft/s)	4 to 6	6 to 7	> 7	

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Large Woody Debris	Large Woody Debris Index (LWDI)	LWDI of project reach equals LWDI of reference reach.	LWDI of project reach does not equal LWDI of reference reach, but is trending in that direction.	LWDI of project reach does not equal LWDI of reference reach and is not trending in that direction.	Davis et al., 2001 (USFS Technical Report)
Channel Evolution	**Rosgen's Stream Type Succession Scenarios**				
	1. E→C→Gc→F→C→E	E, C	C→Gc and F→C	Gc, F	Rosgen 2010 (conference workshop)
	2. C→D→C	C	C→D and D→C	D	
	3. C→D→Gc→F→C	C	C→D and F→C	D, Gc, F	
	4. C→G→F→Bc	C, Bc	C→G and F→Bc	G, F	
	5. E→Gc→F→C→E	E, C	E→Gc and F→C	Gc, F	
	6. B→G→Fb→B	B	B→G and Fb→B	G, Fb	
	7. Eb→G→B	Eb, B	Eb→G and G→B	G	
	8. C→G→F→D→C	C	C→G and D→C	G, F, D	
	9. C→G→F→C	C	C→G and F→C	G, F	
	10. E→A→G→F→C→E	E	E→A and F→C	A,G, F	
	11. C→F→C→F→C	First and last C	C→F	F	
	12. C→G→F→C→C→C	First and last C	C→G and C→C	G,F, Fourth C	
	Simon Channel Evolution Model Stages				
	1. Sinuous, pre-modified	✓			Simon 1989 (journal)
	2. Channelized			✓	
	3. Degradation			✓	

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Channel Evolution	4. Degradation and widening			✓	Simon 1989 (journal)
	5. Aggradation and widening		✓ *	✓	
	6. Quasi-equilibrium	✓			
	** Only late Stage 5 of the Simon model, where the stream has begun to construct a new floodplain at a lower elevation, is considered to be Functioning-at-Risk.*				
Bank Migration/ Lateral Stability	Meander Width Ratio for C and E stream types	≥ 3.5 (based on reference reach surveys)	3.0 to 3.5 as long as sinuosity is ≥ 1.2	< than 3.0	Rosgen, 2001 (proceedings) and 2006 (book)
	Lateral Erosion rate – Low BEHI Curve	Very low to Moderate NBS	Moderate to Very High NBS	Extreme NBS	
	Lateral Erosion rate – Moderate BEHI Curve	Very low to Low NBS	Low to High NBS	High to Extreme NBS	
	Lateral Erosion rate – High and Very High BEHI Curve	N/A	Low to Moderate NBS	Moderate to Extreme NBS	
	Lateral Erosion rate – Extreme BEHI Curve	N/A	Low NBS	Low to Extreme NBS	
	Lateral Erosion Rate (Bank Pins and Bank Profiles)	Erosion rate is similar to reference reach values, generally < 0.1 ft/yr	0.1 to 0.5 ft/yr	> 0.5 ft/yr	

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Bank Migration/ Lateral Stability	Lateral Erosion Rate for C4 streams (Cross Sections)	$\frac{w/Dproj}{w/Dref}$ = 1.0 to 1.2	$\frac{w/Dproj}{w/Dref}$ = 1.2 to 1.4	$\frac{w/Dproj}{w/Dref}$ = > 1.4	Simon and Langendoen 2006 (proceedings)
	Bank Stability and Toe Erosion Model	Fs > 1.3	1.0 < Fs > 1.3	Fs < 1.0	
Riparian Vegetation	Average Buffer Width (Ft) C and E Stream Types	> 150	30 to 150	< 30	Meyer et al., 2005 (journal)
	Buffer Width (Ft) from Meander Belt Width for C and E Stream Types	Meander belt width at least 3.5 times the bankfull width plus ≥ 15 feet from outside of meander bend	Meander belt width at least 3.5 times the bankfull width plus 10 to 15 feet from outside of meander bend	Meander belt width ≤ 3.5 times the bankfull width and/or ≤ 10 feet from outside of meander bend	Proposed as an option in this document
	Buffer Density (Stems/ac)	Parameter is similar to reference reach condition, with no additional maintenance required.	Parameter deviates from reference reach condition, limiting function, but the potential exists for full functionality over time or with moderate additional maintenance.	Significantly less functional than reference condition; little or no potential to improve without significant restoration effort.	
	Buffer Age				
	Buffer Composition				
	Buffer Growth				
	Canopy Density				
	Proper Functioning Condition (PFC)	Proper Functioning Condition	Functional At-Risk	Nonfunctional	Prichard et al., 1998 (USFS Technical Report)

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Riparian Vegetation	NRCS Rapid Visual Assessment Protocol	Natural vegetation extends at least one to two active channel widths on each side, or if less than one width, covers entire floodplain. (8-10)	Natural vegetation extends at least one-half to one-third active channel widths on each side, or filtering function moderately compromised. (3-5)	Natural vegetation less than one-third active channel widths on each side, or lack of regeneration, or filtering function severly compromised. (1)	NRCS Technical Report
	The EPA Rapid Bioassessment Protocol (RBP)	Width of riparian zone > 18 meters; humans have not impacted zone. (Optimal, 9-10)	Width of riparian zone 12-18 meters; human activities have minimally impacted zone. (Sub-Optimal, 6-8) Width of riparian zone 6-12 meters; human activities have impacted zone a great deal. (Marginal, 3-5)	Width of riparian zone < 6 meters; little or no riparian vegetation due to human activity. (Poor, 0-2)	Barbour et al., 1999 (EPA Technical Report)

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Riparian Vegetation	USFWS Stream Assessment Ranking (SAR)	All three zones of vegetation exist; runoff is primarly sheet flow; hillslopes < 10%; hillslopes > 200 ft from stream; ponding or wetland areas and litter or debris jams are well represented.	Only Zone 2 of vegetation is well represented; runoff is equally sheet and concentrated flow (moderate gully and rill erosion); hillslopes 20-40%; hillslopes 50-100 ft from stream; ponding or wetland areas and litter or debris jams are minimally represented.	No zones of vegetation well represented; runoff is primarily concentrated flow (extensive gully and rill erosion); hillslopes > 40%; hillslopes < 50 ft from stream; ponding or wetland areas and litter or debris jams are not well represented or completely absent.	Allen et al., 1999

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
	Perennial Streams in Alluvial Valleys (C, E)				
	Percent Riffle	60 to 70	70 to 80	> 80	Professional Judgement
			40 to 60	< 40	
	Pool-to-Pool Spacing Ratio (Watersheds < 10 mi^2)	4 to 5	3 to 4 and 5 to 7	< 3.0 and > 7	Leopold 1994, Gregory et al., 1994 journal), Whittake 1987 (book), Chin 1989 (journal), and Grant 1990 (journal)
Bed Form Diversity	Pool-to-Pool Spacing Ratio (Watersheds > 10 mi^2)	5 to 7	3.5 to 5 and 7 to 8	< 3.5 and > 8	Leopold 1994, Gregory et al., 1994 journal), Whittake 1987 (book), Chin 1989 (journal), and Grant 1990 (journal)
	Depth Variability – Gravel Bed Streams (Pool Max Depth Ratio)	> 1.5	1.2 to 1.5	< 1.2	Rosgen 2006 (book)
	Depth Variability – Sand Bed Streams (Pool Max Depth Ratio)	> 1.2	1.1 to 1.2	< 1.1	

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

GEOMORPHOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Bed Material Characterization	Bed material composition	Project Reach is not statistically different than reference reach.	N/A	Project Reach is statistically different (finer) than reference reach.	Bevenger and King, 2005 (USFS Technical Report)
Bed Form Diversity	**Moderate Gradient Perennial Streams in Colluvial Valleys**				
	Pool-to-Pool Spacing Ratio (Slope between 3 and 5%)	2 to 4	4 to 6	>6	Leopold 1994, Gregory et al., 1994 journal), Whittake 1987 (book), Chin 1989 (journal), and Grant 1990 (journal)
	Depth Variability (Pool Max Depth Ratio)	> 1.5	1.2 to 1.5	< 1.2	Leopold 1994, Gregory et al., 1994 journal), Whittake 1987 (book), Chin 1989 (journal), and Grant 1990 (journal)

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

PHYSICOCHEMICAL					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Water Quality	DO Temperature Turbidity	Meets water quality standards for designated use	Meets water quality standards for designated use	Does not meet water quality standards	Performance standards have not been developed for these parameters and are therefore based on reference reach comparisons and state water quality databases.
		Representative of reference reach and meets species requirements	Is not representative of reference reach and does not support species requirements	Is not representative of the reference reach	
				Does not support species requirements	
	pH Conductivity Turbidity	Representative of values measured in reference reach	Does not have representative reference reach values or	Statistically different than reference reach and does not support aquatic life	
			Does not support designated use or species requirements		

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

PHYSICOCHEMICAL					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Nutrients	Field test kits using reagents reactions	Meets water quality standards for designated use	Meets water quality standards for designated use, but is not representative of reference reach	Does not meet water quality standards	Performance standards have not been developed for these parameters and are therefore based on reference reach comparisons and state water quality databases.
	Laboratory analysis	Representative of reference reach	Does not cause eutrophication	Is not representative of the reference reach	
		Does not cause eutrophication		Causes eutrophication	
Organic Carbon	Laboratory analysis	Meet reference reach OC concentrations	Do not meet reference reach OC concentrations	Do not meet reference reach OC concentrations and are below a predetermined threshold determined for adequate organic processing	Performance standards have not been developed for these parameters and are therefore based on reference reach comparisons and state water quality databases.

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

BIOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Microbial Communities	Periphyton Index of Biological Integrity (PIBI)	≥ 72	61-71	≤ 60	Hill et al., 2000 (Journal)
Macrophytes	**Biological Indices**				
	Mean Trophic Rank (MTR)	> 65	25-65	< 25	Holmes et al., 1999 (Technical Report)
	Reference Index (RI)	-50 to 100	-70 to -50	< -70	Meilenger, 2005 (Journal)
Macroinvertebrate Communities	**Biological Indices**				
	Family-Level Biotic Index (FBI) Ranges	0.00-4.25	4.26-5.75	5.76-10.00	Hilsenhoff, 1988 (Journal)
		Excellent to Very Good	Good to Fair	Fairly Poor to Very Poor	
	WVSCI Ranges	68-100	45-61	0-45	Gerritsen et al., 2000; WVDEP
		Very Good to Good	Gray Area to Fair	Poor to Very Poor	
	Virginia Stream Condition Index	61-100	40-60	0-40	Burton J. and J. Gerritsen, 2003
		Exceptional to Similar to Ref.	Impaired Tier 1	Impaired Tier1 & 2	
	SOS Multimetric Index	7-12	N/A	0-6	Engel and Voshell, 2002
		Acceptable		Unacceptable	

APPENDIX A: STREAM FUNCTIONS PYRAMID (CONT.)

d. PERFORMANCE STANDARDS TABLE

BIOLOGY					
PARAMETER	MEASUREMENT METHOD	PERFORMANCE STANDARD			SOURCE
		FUNCTIONING	FUNCTIONING-AT-RISK	NOT FUNCTIONING	
Fish Communities	**Biological Indices**				
	Mid-Atlantic Highlands IBI	IBI > 72	IBI = 56 to 71	IBI < 56	McCormick et al., 2001
		Good to Excellent	Fair	Poor	
	Mid-Western Fish Community IBI	48-60	40-44	0-34	Karr et al., 1986
		Good to Excellent	Fair	Poor to No Fish	

APPENDIX B: APPLICATION SCENARIOS

APPLICATION: STREAM DEBIT AND CREDIT DETERMINATION SCENARIOS

The purpose of Appendix B is to illustrate how the Stream Functions Pyramid and its associated measurement methods and performance standards can be used as an aid in developing debit and credit determination methods for a variety of impact and restoration scenarios. A description of the debit and credit determination method is provided in Chapter 11, and the examples are shown below. These examples are not from actual permit applications or restoration projects. Rather, they are generic, yet realistic scenarios that are used to demonstrate how the debit and credit templates can be applied to a range of scenarios. They are broad based and lack the specificity needed for an actual debit/credit determination method. The purpose of these examples is to generate ideas about how function-based parameters, measurement methods and performance standards can be used in stream mitigation Standard Operating Procedures (SOPs).

The impact or debit scenarios include:
1. Culvert installations;
2. Channelization and bank hardening; and
3. Surface mining of high gradient streams.

The restoration or credit scenarios include:
1. Restoration of incised streams;
2. Restoration of stream flow for channels that have excessive water withdrawal;
3. Salmonid fish passage and habitat restoration; and
4. Restoration of high gradient, headwater streams.

Permitted Impact Scenarios (Debits)

Scenario 1: Culvert Installations

The following is a typical example of a new rural road and culvert installation with a stable, healthy upstream watershed. The post-impact condition is based on typical results of culvert installation and can be modified based on actual results or more quantitative assessments. Table B1A shows the typical impacts associated with culvert installations. Table B2a provides a narrative to support the data shown in table B1A, including the rationale for selecting the parameters. Table B3a shows how debits could be calculated for the permitted impact caused by the culvert installation.

Example Scenario

A permit application has been submitted to install a 60-inch diameter culvert for 500 feet of stream length. This is a standard culvert installation and the impact is predicted to extend 200 feet downstream and 100 feet upstream of the culvert for a total impact length of 800 feet. Upstream and downstream impacts are included based on hydraulic modeling analysis and impacts associated with past installations in the region. If other

culvert installation approaches, e.g., floodplain culverts, are used, the impact length could be reduced to the pipe length.

The upstream watershed has a drainage area of two square miles with a mix of agricultural and suburban land uses. The rainfall/runoff relationship is moderately stable and is not expected to significantly change in the near future. The channel is mildly incised with a Bank Height Ratio of 1.1; however, the channel was straightened in the past, creating a sinuosity of near 1.0. This has resulted in poor bed form diversity and a riffle-pool percentage of 90:10 and pool depth ratios less than 1.5. A vegetative buffer of 50 feet on each side of the channel is providing bank stability and cover, and is an effective filter from adjacent land uses. As a result, the basic water quality is representative of reference reach streams in the region; however, macroinvertebrate and fish communities do not reflect reference conditions due to poor habitat.

Degradation is expected to occur for 200 feet downstream of the culvert. The Bank Height Ratio will increase to 2.5 and the entrenchment ratio will decrease to 1.2. Bed form diversity will remain poor and riffle dominated with a few shallow pools. Some trees along the streambank are predicted to fall due to the high streambanks and large volume of water now carried by the channel. Lateral erosion is predicted to be moderate.

Aggradation is expected to occur for 100 feet upstream of the culvert. The Bank Height Ratio decreases to 1.0 and sand covers the riffles and fills the pools creating a plane bed. The vegetation remains intact.

Referring to Table B1A, the pre-disturbance condition is a mix of Functioning, Functioning-at-Risk, and Not Functioning scores for Levels 2-5. Therefore, the Functionality Before Impact Category (Table BD1c) is **Moderate**. The post-disturbance condition, shown on Table BD1a, indicates that most parameters will be Not Functioning through the culvert and downstream. Impacts are less upstream of the culvert with some parameters remaining as Functioning and a few becoming Not Functioning. Therefore, the culvert and downstream section will be evaluated together as a 700 foot impact with **High Functional loss**. The 100-foot upstream section has mostly Functioning scores with a few Not Functioning scores and is assessed with a **Moderate Functional Loss**.

Scenario 2: Channelization and Bank Hardening

A permit application has been submitted to straighten and "improve" 1,000 linear feet of stream channel. The "improvement" includes dredging (lowering) and widening the channel to carry the 100-year discharge. The bed material will remain with natural gravel, but the streambanks will be graded to a 2:1 slope and protected with rip rap. Backyard lawns will extend outward from the top of the streambank.

The existing channel is moderately incised with a bank height ratio of 1.4. The channel is located in an alluvial valley and has a sinuosity of 1.3 and alternating riffles (70%) and pools (30%). The pools are generally 2 to 2.5 times deeper than the riffles. A 10-foot riparian buffer of mature hardwood trees is present on both sides of the channel, providing bank stability and cover over the channel.

TABLE BD1a DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION

Table BD1a is completed by interpreting the information from the paragraph above and selecting parameters, measurement methods and performance standards from Appendix A.

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Not affected					
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	1.1	Functioning	1.0 – Upstream 2.5 – Downstream	Functioning upstream; Not Functioning through culvert and downstream
		Entrenchment Ratio	> 2.2	Functioning	> 2.2 – Upstream 1.2 – Downstream	Functioning upstream; Not Functioning through culvert and downstream
3 – Geomorphology	Channel Evolution	Rosgen	C or E	Functioning	C or E upstream G downstream	Functioning upstream; Not Functioning through culvert and downstream
	Lateral Stability	BEHI/NBS	Low	Functioning	Low – Upstream Moderate to high downstream	Functioning upstream; Not Functioning Downstream
	Riparian Vegetation	Rapid Bioassessment Protocol	8	Functioning-at-Risk	0 through culvert 8 – Upstream 6 – Downstream	Functioning upstream; Not Functioning through culvert and downstream
	Bed Form Diversity	Percent Riffle & Pool	90:10	Not Functioning	90:10 to 100% riffle	Not Functioning
		Pool Max Depth Ratio	< 1.5	Functioning-at-Risk	< 1.2	Not Functioning
	Bed Material Characterization	Size Class Pebble Count Analyzer	Same as upstream	Functioning	Finer – upstream of culvert Same – Downstream	Not Functioning upstream and culvert Functioning Downstream

TABLE BD1a DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
4 – Physicochemical	Water Quality	Dissolved Oxygen (mg/l)	Same as upstream	Functioning	Lower than upstream	Not Functioning
5 – Biology	Macroinvertebrate Communities	Hilsenhoff Biotic Index (HBI)	6	Not Functioning	8	Not Functioning
	Fish Communities	Index of Biotic Integrity (IBI)	Poor	Not Functioning	Poor	Not Functioning

TABLE BD1b DEBIT TEMPLATE 2: PRE- AND POST-DISTURBANCE CONDITIONS AND RATIONALE

Describe Pre- and Post-Disturbance Condition and Rationale for Selecting Parameters

Hydrology – The watershed hydrology is stable and is not expected to change. Therefore, Hydrology parameters were not selected.

Hydraulics – The existing channel is mildly incised and has access to a wide alluvial floodplain, i.e., there is floodplain connectivity. In this example, the culvert will likely cause channel incision downstream of the culvert, and bank height ratios are likely to increase, causing a Not Functioning score. The culvert will provide grade control for the upstream channel and the bank height ratio may decrease because of aggradation.

Geomorphology – The existing channel is a stable Rosgen C or E stream type that has been straightened, i.e., in this case, a low sinuosity will not change the stream type. The streambanks are stable with minimal bank erosion. There is a riparian buffer of bottomland hardwood trees. The upstream watershed and stream reach is stable. The bed form is riffle dominated due to past channelization. The channel is predicted to remain a C stream type upstream and change to a Gc downstream. Lateral stability will decrease from Functioning to Not Functioning due to channel incision downstream of the culvert. The riparian vegetation is totally removed along the length of the culvert and, therefore, would score Not Functioning. However, the riparian buffer remains intact upstream of the culvert (Functioning). Bed form diversity is altered upstream and downstream of the culvert. Upstream of the culvert, pools fill in with sediment during aggradation. This decreases depth variability and shifts the substrate distribution curve towards sand size material, which in this case is finer than the upstream riffle material. Channel incision downstream, along with a decrease in Width/Depth ratio, causes the riffles to erode and drain the pools. This creates a plane bed form.

Physicochemical – Since the upstream watershed is stable and there is an existing bottomland forest, the basic water quality parameters are Functioning. The only water quality parameter selected to measure is Dissolved Oxygen (DO). The other parameters will likely not be impacted to the point where their functioning score would be significantly different from the upstream reference reach or violate water quality standards. Due to the reduction in depth variability and bed form diversity, DO may shift from Functioning to Not Functioning.

Biology – Due to poor bed form diversity and riparian vegetation prior to culvert installation, macroinvertebrate and fish communities are Not Functioning before and after the disturbance.

TABLE BD1c DEBIT TEMPLATE 3: DEBIT REQUIREMENTS

PRE-DISTURBANCE CONDITION	POST-DISTURBANCE CONDITION			
	NO FUNCTIONAL LOSS	LOW TO MODERATE FUNCTIONAL LOSS	MODERATE TO HIGH FUNCTIONAL LOSS	DEBIT ADJUSTMENT (+/-)
Low (Mix of Functioning-at-Risk and Not Functioning)	(Post-disturbance condition matches pre-disturbance condition) No mitigation required	Greater number of Functioning-at-Risk and Not Functioning Scores 1.1 to 1.2	Mostly Not-Functioning Scores 1.2 to 1.3	0.1
Moderate (Mix of Functioning, Functioning-at-Risk, and Not Functioning)		Loss of Functioning scores and/or greater number of Functioning-at-Risk and Not Functioning Scores 1.3 to 1.5	Mix of Functioning-at-Risk and Not Functioning Scores 1.5 to 1.7	0.1
High (Functioning)		Mix of Functioning, Functioning-at-Risk, and Not Functioning Scores 1.7 to 1.9	Mix of Functioning-at-Risk and Not Functioning Scores 2.0	0.2

The overall calculations are shown below. The total debits calculated for this impact is 1260.

REACH	LENGTH (FT)	CATEGORY FROM TABLE B3	DEBIT RATIO (DEBITS/FT)	TOTAL
Upstream	100	Moderate / Moderate	1.4	100 X 1.4 = 140
Culvert and Downstream	700	Moderate / High	1.6	700 X 1.6 = 1120
Total	800			1120 + 140 = 1260

The upstream watershed is rural to suburban and moderately stable without major point sources of pollution. Nonpoint source pollution includes runoff from existing yards, homes, and secondary roads. These land uses have not caused significant increases to the rainfall/runoff relationship. A healthy community of benthic organisms and small native fish lives in the stream. Temperature and DO levels are representative of reference streams.

TABLE BD2a DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION

Table BD2a is completed by interpreting the information from the paragraph above and selecting parameters, measurement methods and performance standards from Appendix A.

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Not affected					
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	1.4	Functioning-at-Risk	> 2	Not Functioning
	Riparian Vegetation	Average buffer width	10	Not Functioning	0	Not Functioning
	Bed Form Diversity	Percent Riffle & Pool	70:30	Functioning	90:10 to 100% riffle	Not Functioning
		Pool Max Depth Ratio	2 – 2.5	Functioning	< 1.2	Not Functioning
4 – Physicochemical	Water Quality	Dissolved Oxygen	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
		Temperature	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
5 – Biology	Macroinvertebrate Communities	Family Level Biotic Index (FBI)	4	Functioning	8	Not Functioning
	Fish Communities	Index of Biotic Integrity (IBI)	Good	Functioning	Poor	Not Functioning

TABLE BD2b DEBIT TEMPLATE 2: PRE- AND POST-DISTURBANCE CONDITIONS AND RATIONALE

Describe Pre- and Post-Disturbance Condition and Rationale for Selecting Parameters

Hydrology – The watershed hydrology is stable and is not expected to change. Therefore, Hydrology parameters were not selected.

Hydraulics – The pre-disturbance Bank Height Ratio was provided in the summary report as 1.4, which is Functioning-at-Risk. The predicted post-disturbance ratio was not provided; however, it was stated that the channel would be designed to carry the 100-yr discharge. A Bank Height Ratio much greater than 2.0 is required to carry that amount of water and would be Not Functioning for floodplain connectivity.

Geomorphology – Information about the width of the riparian vegetation and bed form diversity (percent riffle/pool and depth variability) were provided in the summary report. Due to a narrow buffer width, the pre-disturbance condition is Not Functioning for riparian vegetation. Bed form diversity is Functioning. In order to transport water as quickly as possible, it is predicted that the buffer will be maintained as rip rap and maybe grass. Therefore, the riparian vegetation will remain Not Functioning. The channel will also be straightened and designed with a uniform cross section and profile, eliminating pool features. Therefore, a Not Functioning score is given to both bed form diversity measures.

Physicochemical – The summary report stated that the pre-disturbance DO and temperature levels matched the reference reach, which is a Functioning score. The post-disturbance condition is predicted to be Not Functioning due to the lack of buffer and pool features, and an overly wide channel, all of which contribute to higher stream temperatures and therefore lower DO levels.

Biology – The summary report states that a healthy community of benthic organisms and small native fish live in the stream pre-disturbance. Due to the removal of pool habitat and the decline in water quality, the post-disturbance score is Not Functioning.

Referring to Table BD2a, the majority of the pre-disturbance parameters are Functioning. The riparian vegetation is the only Not Functioning parameter and Floodplain Connectivity is Functioning-at-Risk. Using Table BD2c, this provides a Functionality Before Impact score of Moderate, but it would be the high end of Moderate. Table BD2a shows that the predicted post-disturbance condition is mostly Not Functioning with only one measurement method, conductivity, scoring a Functioning-at-Risk. This equals a High Functional Loss on Table BD2c. A Moderate/High yields a debit ratio range of 1.5 to 1.7. Since the pre-disturbance condition was on the higher end of Moderate, the 1.7 ratio is used. Therefore, the total debits for this site is 1,000 linear feet X 1.7 = 1,700 debits.

TABLE BD2c DEBIT TEMPLATE 3: DEBIT REQUIREMENTS

PRE-DISTURBANCE CONDITION	POST-DISTURBANCE CONDITION			
	NO FUNCTIONAL LOSS	LOW TO MODERATE FUNCTIONAL LOSS	MODERATE TO HIGH FUNCTIONAL LOSS	DEBIT ADJUSTMENT (+/-)
Low (Mix of Functioning-at-Risk and Not Functioning)	(Post-disturbance condition matches pre-disturbance condition) No mitigation required	Greater number of Functioning-at-Risk and Not Functioning Scores 1.1 to 1.2	Mostly Not-Functioning Scores 1.2 to 1.3	0.1
Moderate (Mix of Functioning, Functioning-at-Risk, and Not Functioning)		Loss of Functioning scores and/or greater number of Functioning-at-Risk and Not Functioning Scores 1.3 to 1.5	Mix of Functioning-at-Risk and Not Functioning Scores 1.5 to 1.7	0.1
High (Functioning)		Mix of Functioning, Functioning-at-Risk, and Not Functioning Scores 1.7 to 1.9	Mix of Functioning-at-Risk and Not Functioning Scores 2.0	0.2

Scenario 3: Surface Mining of High Gradient Streams

A permit has been submitted to impact 10,000 feet of headwater streams related to a large surface mine. The streams are all located in v-shaped and colluvial valleys and are classified as Rosgen A and B stream types. The streams are vertically and laterally stable with appropriate access to a floodprone area. The bank height ratio is 1.0 and the entrenchment ratio is 1.5. Bed form diversity is characterized by step-pools comprised of cobbles, boulders and large woody debris (LWD). Pool depths are typically greater than 1.5 times the mean riffle depth. Pool to pool spacing is less than 4 times the bankfull width. The riparian buffer spans the entire width of the valley and includes most of the hillslope as well. Buffer composition is characterized by a mature hardwood forest that totally covers the channel with an appropriate understory and minimal invasive species. Water quality is excellent with temperature, DO, pH, and conductivity levels representative of reference conditions. Large woody debris and smaller sticks and leaves can be found in the channel and on the floodprone area in quantities that are representative of reference conditions. Macroinvertebrate and small fish communities are also representative of reference conditions for small headwater channels.

The permitted surface mining operation requires the complete removal of the natural stream channel and associated riparian vegetation during mining. Stormwater BMPs, erosion control devices, and drainage channels will be constructed to comply with federal and state regulations; however, these practices do not prevent the loss of many stream functions. The new drainage channels will carry a 100-year discharge, which is much larger than the bankfull discharge. The channel bed and banks will be stabilized with rip rap. A uniform channel dimension and profile will be designed and constructed. Temporary vegetation will be established to provide erosion control. The post-disturbance water quality is predicted to increase conductivity and temperature and reduce pH and DO levels. The system will be devoid of LWD and smaller organic material. Macroinvertebrate and fish communities will not be representative of reference conditions.

From Table BD3a, the pre-disturbance condition is high with Functioning scores in all five Levels. This equals a **High** for Functionality Before Impact in Table BD3c. Again from Table BD3a, the post-disturbance condition shows mostly Not Functioning scores in all five Levels. This equals a **High** Functional Loss in Table BD3c. A **High/High** yields a debit ratio of 2.0 debits per foot. Therefore, the total debits are 10,000 ft X 2.0 debits/ft = 20,000 debits.

Stream Mitigation Scenarios (Credits)

The credit examples below represent restoration projects that are offsite from the permitted impact. A description of the credit determination method is provided in Chapter 11. For the scenarios below, a variety of credit determination methods are used to: 1) show different approaches to developing stream credits and 2) reflect the sometimes unique characteristics of a site, e.g., water withdrawal and dam removal. It may be helpful to review all of the credit determination methods in order to see the variety of approaches that are used.

The restoration or credit scenarios include:

1. Restoration of incised channels in alluvial valleys;
2. Restoration of stream flow for channels that have excessive water withdrawal;
3. Salmonid fish passage and habitat restoration; and
4. Restoration of high gradient, headwater streams.

Scenario 1: Restoration of Incised Channels in Alluvial Valleys

Channelization and subsequent incision is one of the biggest contributors to stream impairment. Incised channels can be found throughout the US and lead to excessive sedimentation from eroding bed and banks, which smothers aquatic habitats and reduces bed form diversity. These channels are often classified as unstable Rosgen Gc and F stream types. Restoration methods often follow Rosgen's Priority Levels of restoring incised channels (Rosgen, 1997), which is described in Chapter 3. The template below deviates from this approach by specifically focusing on the parameters from the Stream Functions Pyramid that relate to functions. This provides a more direct method for

describing functional lift. However, the same restoration methods that are used to implement Rosgen's Priority Levels can be used here.

Example Scenario

A mitigation provider has secured a restoration project reach of 5,000 feet. The site is located immediately downstream from a state forest and the entire upstream watershed is forested and stable. The existing reach is located on a beef farm and the cattle have full access to the channel. The stream is highly incised with a bank height ratio of 3.0; however, there is a bedrock knickpoint at the upstream end of the project. The stream is not incised upstream of the knickpoint. The channel is very straight and devoid of bed form diversity. Over 90% of the bed is riffle. There is no buffer and bank erosion is prevalent throughout the reach. Because of these impacts, there are few aquatic organisms living in the channel. Stream temperatures are high and DO levels are low, based on a comparison to the upstream reference reach.

Because the upstream watershed is very healthy, the mitigation provider proposes to complete a Restoration 1 approach. As a review, the restoration options are shown below. A description of each is provided in Chapter 11.

Restoration 1 – Reach scale restoration, connected to a healthy watershed
Restoration 2 – Reach scale restoration, variable upstream watershed conditions

For this project, a Rosgen Priority Level 1 restoration approach is proposed. A new meandering channel will be constructed and reconnected to the original floodplain at the bedrock knickpoint. The floodplain is 50 times wider than the channel and a sinuosity of 1.4 is used. The new stream type is a C4. The design includes alternating riffles and pools, with the pools containing root wads with cover logs and other structures to provide stability, LWD and cover. The depth variability includes a percent riffle:pool ratio of 70:30 and maximum pool depth ratios greater than 2.0. A meander width ratio of 7 is used with a buffer that extends for 25 feet beyond the belt width. The old channel (prior to restoration) is filled with material excavated for the new channel with large portions converted into riparian wetlands. Additional wood is used to create wetland complexity and provide habitat for salamanders, frogs and other amphibians. Due to the excellent health of the upstream watershed and the structural improvements to the project reach, DO and temperature levels return to reference condition by the fourth year after restoration construction. The aquatic macroinvertebrate and fish communities return to reference condition by year 5.

Table BC1a shows that the pre-restoration condition for all parameters was Not Functioning and that the predicted post-restoration condition improved all of those parameters to Functioning score. Using Table BC1c, this would yield a **Maximum Lift**, and 0.8 to 1.0 credits per foot could be assigned to the restored channel length. Based on the high quality of this example, a ratio of 1.0 is selected. The restored channel length is 5,000 feet X 1.4 sinuosity = 7,000 feet. Total credits = 7,000 ft X 1.0 = 7,000 credits.

TABLE BD3a DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION

Table BD3a is completed by interpreting the information from the paragraph above and selecting parameters, measurement methods and performance standards from Appendix A.

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Runoff	N/A	N/A	Functioning	N/A	Not Functioning
	Flow Duration	N/A	N/A	Functioning	N/A	Not Functioning
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	1.0	Functioning	> 2	Not Functioning
		Entrenchment Ratio	1.4	Functioning	1.2	Functioning-at-Risk
	Groundwater/ Surface-Water Interaction	N/A		Functioning	N/A	Not Functioning
3 – Geomorphology	Riparian Vegetation	RBP	9	Functioning	0	Not Functioning
	Bed Form Diversity	Pool to Pool Spacing	< 4	Functioning	> 4	Not Functioning
		Pool Max Depth Ratio	> 1.5	Functioning	< 1.2	Not Functioning
	Large Woody Debris	LWDI	Same as reference condition	Functioning	Does not equal reference condition and is not trending in that direction	Not Functioning
	Bed material characterization	RSI	< 70	Functioning	> 85	Not Functioning

TABLE BD3a DEBIT TEMPLATE 1: FUNCTIONAL LOSS DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
4 – Physicochemical	Water Quality	Dissolved Oxygen	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
		Temperature	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
		Conductivity	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
		pH	Same as reference	Functioning	Is not representative of reference reach and does not meet species requirements	Not Functioning
5 – Biology	Macroinvertebrate Communities	Family-Level Biotic Index (FBI)	4	Functioning	8	Not Functioning
	Fish Communities	Index of Biotic Integrity (IBI)	Good	Functioning	Poor	Not Functioning

TABLE BD3b DEBIT TEMPLATE 2: PRE- AND POST-DISTURBANCE CONDITIONS AND RATIONALE

Describe Pre- and Post-Disturbance Condition and Rationale for Selecting Parameters

Hydrology – Performance standards have not been provided for Runoff and Flow Duration parameters. However, they are included in this example because surface mining negatively impacts these function-based parameters. Runoff often increases and flow duration decreases to Not Functioning levels, based on a comparison to reference or pre-mining conditions.

Hydraulics – These high-gradient streams do not have floodplains, but they do have floodprone areas that should be accessed at flows greater than bankfull. The post-disturbance bank height ratio is not provided in the report summary; however, the value will be well over 2 to carry the 100-yr discharge. The entrenchment ratio is predicted to decrease slightly as the bankfull channel is replaced with a large trapezoidal channel. Groundwater/surface-water interaction was also selected, even though it doesn't have a performance standard. The pre-disturbance condition would likely include Functioning groundwater/surface-water interaction. If the surface mining operation raises the channel and/or places the channel on fill, these processes will become Not Functioning.

Geomorphology – A mature forest provides a Functioning score for riparian vegetation prior to the disturbance. The riparian vegetation becomes Not Functioning after mining because the vegetation is totally removed. The temporary vegetation does not provide the same stability, cover and water quality as the mature forest. Bed form diversity measures all changes from Functioning to Not Functioning because the drainage channels are not designed with reference condition values of pool-pool-spacing and depth variability. Large woody debris is expected to become Not Functioning because the forest will be cleared (removing the wood source) and the design channels do not incorporate wood. Bed material will move from Functioning to Not Functioning because native mixtures of colluvium will be replaced by rip rap.

Physicochemical – All water quality measurement methods shift from Functioning to Not Functioning because they no longer resemble reference conditions. Dissolved oxygen and pH will likely decrease and conductivity and possibly temperature will increase.

Biology – The macroinvertebrate and fish communities also shift from Functioning to Not Functioning because of all the impacts to the supporting functions. The Hydrology, Hydraulic and Geomorphology functions cannot support the water quality functions that in turn support the Biology functions.

TABLE BD3c DEBIT TEMPLATE 3: DEBIT REQUIREMENTS

PRE-DISTURBANCE CONDITION	POST-DISTURBANCE CONDITION			
	NO FUNCTIONAL LOSS	LOW TO MODERATE FUNCTIONAL LOSS	MODERATE TO HIGH FUNCTIONAL LOSS	DEBIT ADJUSTMENT (+/-)
Low (Mix of Functioning-at-Risk and Not Functioning)	(Post-disturbance condition matches pre-disturbance condition) No mitigation required	Greater number of Functioning-at-Risk and Not Functioning Scores 1.1 to 1.2	Mostly Not Functioning Scores 1.2 to 1.3	0.1
Moderate (Mix of Functioning, Functioning-at-Risk, and Not Functioning)		Loss of Functioning scores and/or greater number of Functioning-at-Risk and Not Functioning Scores 1.3 to 1.5	Mix of Functioning-at-Risk and Not Functioning Scores 1.5 to 1.7	0.1
High (Functioning)		Mix of Functioning, Functioning-at-Risk, and Not Functioning Scores 1.7 to 1.9	Mix of Functioning-at-Risk and Not Functioning Scores 2.0	0.2

Scenario 2: Restoration of Stream Flow for Channels That Have Excessive Water Withdrawal

The following example is a common stream impairment in the western U.S. where water supply is scarce. In these systems, baseflow often diminishes in a downstream direction due to excessive water withdrawals for drinking water, irrigation, etc. This can have a negative effect on baseflow duration and stream biota. In many cases, water withdrawal can convert a perennial stream to intermittent, with the streambed being totally dry in the summer months.

The *literal* restoration of stream flows, where water is returned to the channel and not used for irrigation or other uses, requires policy decisions that do not apply to the Stream Functions Pyramid. However, there are cases where stream restoration activities may be able to improve base flow conditions. The example below focuses on a scenario that can benefit from alterations to the stream channel (morphology) rather than an example where water is returned to the channel by manipulating the hydrologic cycle.

TABLE BC1a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION

Table BC1a is completed by interpreting the information from the paragraphs above and selecting parameters, measurement methods and performance standards from Appendix A.

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	N/A					
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	3.0	Not Functioning	1.0	Functioning
		Entrenchment Ratio	1.1	Not Functioning	> 2.2	Functioning
3 – Geomorphology	Large Woody Debris Storage and Transport	LWDI	LWDI does not equal LWDI of reference reach	Not Functioning	LWDI equals LWDI of reference reach	Functioning
	Channel Evolution	Rosgen Stream Type Succession Scenarios	G or F4	Not Functioning	C 4	Functioning
	Bank Migration/ Lateral Stability	BEHI/NBS	High and Very High BEHI Curve Moderate to Extreme NBS	Not Functioning	Low BEHI Curve Very low to Moderate NBS	Functioning

TABLE BC1a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-DISTURBANCE CONDITION		PREDICTED POST-DISTURBANCE CONDITION	
			VALUE	RATING	VALUE	RATING
3 – Geomorphology	Riparian Vegetation	Buffer Width (ft) from Meander Belt Width	0	Not Functioning	MWR of 7 and additional width of 25 ft	Functioning
		Buffer Density, Composition, Age, Growth and Canopy Density	Significantly less functional than reference reach condition; little or no potential to improve without significant restoration effort.	No Functioning	By year 5, riparian vegetation is on a trajectory to become similar to the upstream reference condition.	Functioning
	Bed Form Diversity	Percent Riffle and Pool	90:10	Not Functioning	70:30	Functioning
		Depth Variability (Pool Max Depth Ratio)	< 1.2	Not Functioning	> 2	Functioning
4 – Physicochemical	Basic Water Chemistry	Temperature	Project Reach is statistically different (higher) than reference reach.	Not Functioning	Project Reach is not statistically different than reference reach by year 4.	Functioning
		Dissolved Oxygen	Project Reach is statistically different (lower) than reference reach.	Not Functioning	Project Reach is not statistically different than reference reach by year 4.	Functioning
5 – Biology	Benthic	Family-level Biological Index (FBI)	8	Not Functioning	2	Functioning
	Fish Communities	McCormick Index of Biological Integrity	50	Not Functioning	75	Functioning

TABLE BC1b CREDIT TEMPLATE 2: PRE- AND POST-RESTORATION CONDITIONS AND RATIONALE

Describe Pre- and Post-Restoration Condition and Rationale for Selecting Parameters

Hydrology – The watershed hydrology is stable and is not expected to change. Therefore, Hydrology parameters were not selected.

Hydraulic – The existing channel is severely incised (Bank Height Ratio of 3) and does not have access to a wide alluvial floodplain. The channel will be reconnected to the floodplain through a Rosgen Priority Level 1 Restoration. The Bank Height Ratio will be reduced to 1.0 and all flows greater than bankfull will spread onto a floodplain that is 50 times wider than the channel, making the entrenchment ratio well over 2.2.

Geomorphology – The existing channel is an incised Gc or F4 channel. The stream is straight and incised with poor bed form diversity and severe bank erosion. The valley is wide without constraints, but the riparian buffer is very thin. The new channel will include a sinuosity of 1.4, which will reduce stream velocity and help support bed form diversity. The additional wood structures will also help create deeper pools and better depth variability. A wide riparian buffer will be planted to help maintain bank stability, provide cover, and regulate water and air temperatures. Large woody debris will be incorporated into the channel to provide further bed form complexity and habitat. The predicted result is that all of the Geomorphology parameters and associated measurement methods shown in Table B4a will shift from Not Functioning to Functioning.

Physicochemical – Since the upstream watershed is nearly pristine, water quality entering the project reach is very good. Temperature does increase through the project reach due to lack of vegetative cover and the high channel width associated with G/F channels, creating Not Functioning scores pre-restoration. The lack of bed form diversity and high temperatures cause low DO levels. These two parameters are selected because they are impaired but can likely be improved with restoration efforts. The restoration activities under the Geomorphology category, along with healthy watershed, will provide the channel form necessary to reduce water temperature and increase DO levels. This is primarily through the increase in bed form diversity (improved riffles) and the establishment of a wide riparian buffer. Since these parameters and measurement methods require an established buffer in addition to proper channel form, they are predicted to take 4 years to reach a Functioning score.

Biology – Similar to the Physicochemical parameters, the Biology conditions entering the project reach are Functioning, but become degraded due to the reach conditions. Macroinvertebrate and Fish Community parameters are selected because the reach scale activities in combination with the high quality watershed indicate a high potential for restoring these parameters to a Functioning level. The improvement to Pyramid Levels 2-4, along with the health of the upstream watershed, will provide the channel form and processes necessary to support Functioning macroinvertebrate and fish communities. However, since the water quality parameter will not reach a Functioning level until year 4, it is predicted to take 5 years to reach a Functioning score for macroinvertebrate and fish communities.

TABLE BC1c CREDIT TEMPLATE 3: CREDIT CALCULATIONS

RESTORATION 1 CREDIT CATEGORIES	PRE-RESTORATION CONDITION	POST-RESTORATION CONDITION	CREDITS PER FOOT
Maximum Lift	All parameters in Pyramid Levels 2 and 3 have Not Functioning scores. Parameters in Levels 4 and 5 are Not Functioning or Functioning-at-Risk.	Functioning scores for Levels 1-5	0.8 to 1.0
Moderate Lift	Mix of Not-Functioning and Functioning-at-Risk scores for parameter Levels 2 through 5	Functioning scores for Levels 1-5	0.6 to 0.8
Low Lift	Mix of Not-Functioning, Functioning-at-Risk and Functioning scores for parameter Levels 2 through 5	Functioning scores for Levels 1-5	0.4 to 0.6

Example Scenario

A 5,000 foot restoration project has been secured to improve base flow conditions that have been impacted by excessive water withdrawals. The project reach is in an agricultural setting and the withdrawals are used for irrigation. The stream is in a wide alluvial valley and is approximately 75 feet wide. The sinuosity is 1.3, which is appropriate given the stream and valley condition. The channel is moderately incised with a Bank Height Ratio of 1.2. There is a 10-foot buffer with a mixture of cottonwoods and some herbaceous vegetation; however, beyond that is cropland. The moderate incision and lack of buffer has created localized bank erosion in the outside of several meander bends. The streambed and banks are comprised of well-graded (poorly sorted) gravel, sand, and cobble with the median particle size in the gravel range. Bed form diversity is moderate with pools existing in the outside of the meander bends; however, the overall depth variability and complexity is low. This is primarily caused by the lack of baseflow and LWD. When baseflow is present, basic water quality parameters of DO, temperature and pH are representative of reference conditions. However, due to the adjacent cropland, lack of buffer and incision, nitrate-nitrogen levels are higher than reference conditions, but not high enough to cause eutrophication. Macroinvertebrate and fish communities reflect reference reach conditions in the winter, but not the summer when baseflow is low or absent.

The goal of the restoration project is to improve baseflow duration in the summer months, reduce streambank erosion, and to reduce nitrate-nitrogen levels. A restoration approach is proposed to work with the existing channel alignment since the overall planform geometry is stable and to save the existing cottonwoods that help provide bank

stability, cover and denitrification. The dimension of the channel will be modified to create a smaller baseflow channel within the existing bankfull channel. In addition, in-stream structures will be used to raise the stream bed and thereby reduce the Bank Height Ratio to 1.0. The objective with this approach is to improve groundwater/surface-water interaction by raising the water table and increasing bank storage in the winter months. Gravel material will be excavated from the pools and used to construct the riffles. Cross vanes will be used to raise the bed, provide grade control and increase the number of pools. Large woody debris will also be introduced into the channel to further aid in raising the bed and creating pools. The increased number of pools in conjunction with the improved groundwater/surface-water interaction is predicted to improve base-flow. Bioengineering and LWD will be used to stabilize the eroding streambanks. In addition, the buffer will be expanded to 100 feet on both sides of the stream. This will provide a buffer to treat nutrient (nitrogen) runoff and create favorable conditions for denitrification. These changes are predicted to return water quality, nutrient, macroinvertebrate and fish communities to reference conditions.

Table BC2c shows the credit ratios in credits per foot for restoration projects associated with excessive water withdrawals. The rows represent the function scores from the pre-restoration condition provided in Table BC2a. The columns are from the post-restoration scores in Table BC2a. Credits are only provided for functional lift, so if the post-restoration condition is equal to or less than the pre-restoration condition, credits are not provided. In addition, categories are assigned to the different levels of functional lift. Projects with low pre-restoration functionality scores are eligible for restoration credits, moderate pre-restoration scores for enhancement, and high pre-restoration scores for preservation. This is shown in Table BC2a.

For this example, the Before Functionality score is **Low** — Flow duration is Not Functioning, there is a mix of Functioning-at-Risk and Not Functioning scores for Levels 2-4 and the Level 5 scores are Not Functioning. All post-restoration scores are Functioning, so this equals a **High** After Functionality score. A **Low/High** result yields a credit ratio of 1.0. Therefore, the total amount of credits for this site is 5,000 ft X 1.0 credits/ft = 5,000 credits.

Scenario 3: Salmonid Fish Passage and Habitat Restoration

The restoration of salmonid fish passage and habitat is a major focus in the Pacific Northwest and to a lesser degree in the Atlantic Northeast. In the Northwest, the construction and maintenance of dams have had a negative impact on the migration of salmonids from the ocean to headwater spawning areas. In addition, fish habitat has been reduced from logging and other impacts that have created channel incision and changes to bed material size and composition.

TABLE BC2a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	Flow Duration	N/A		Not Functioning	N/A	Functioning
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	1.2	Functioning	1.0	Functioning
	Groundwater/ Surface-Water Interaction	N/A		Functioning-at-Risk	N/A	Functioning
	Large Woody Debris Storage and Transport	LWDI	LWDI does not equal LWDI of reference reach.	Not Functioning	LWDI equals LWDI of reference reach.	Functioning
	Bank Migration/ Lateral Stability	BEHI/NBS in meander bends	High and Very High BEHI Curve Moderate to Extreme NBS	Functioning-at-Risk	Low BEHI Curve Very low to Moderate NBS	Functioning
	Riparian Vegetation	Average Buffer Width (ft)	10	Not Functioning	100 ft	Functioning
		Buffer Density, Composition, Age, Growth and Canopy Density	Significantly less functional than reference reach condition; little or no potential to improve without significant restoration effort.	Not Functioning	By year 5, riparian vegetation is on a trajectory to become similar to the upstream reference condition.	Functioning

TABLE BC2a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
2 – Hydraulics	Bed Form Diversity	Percent Riffle and Pool	80:20	Functioning-at-Risk	65:35	Functioning
		Depth Variability (Pool Max Depth Ratio)	1.2	Functioning-at-Risk	> 2	Functioning
4 – Physicochemical	Water Quality	Temperature	Project Reach is not statistically different than reference.	Functioning	Project Reach is not statistically different than reference reach.	Functioning
		Dissolved Oxygen	Project Reach is not statistically different than reference.	Functioning	Project Reach is not statistically different than reference reach.	Functioning
	Nutrients	Nitrate-Nitrogen	Not representative of reference reach, but does not cause eutrophication.	Functioning-At-Risk	Project reach is representative of reference reach.	Functioning
5 – Biology	Benthic	Family-Level Biological Index (FBI)	5 / 8	Not Functioning in summer/ Functioning in winter	8	Functioning
	Fish Communities	McCormick Index of Biological Integrity	50 / 75	Not Functioning in summer/ Functioning in winter	75	Functioning

TABLE BC2b CREDIT TEMPLATE 2: PRE- AND POST-RESTORATION CONDITIONS AND RATIONALE

Describe Pre- and Post-Restoration Condition and Rationale for Selecting Parameters

Hydrology – Performance standards are not provided from flow duration; however, the summary report states that flow duration does not support species requirements in the summer months. For these scenarios, the upstream reach or paired watershed can be used to set a performance standard based on the reference condition.

Hydraulic – Floodplain connectivity is Functioning with a Bank Height Ratio of 1.2; however, this is on the border between Functioning and Functioning-at-Risk. The post-restoration condition is predicted to improve floodplain connectivity by decreasing the ratio to 1.0. This may help improve groundwater/surface-water interactions and support denitrification. Groundwater/surface-water interaction was selected even though there is not a performance standard to acknowledge that these processes are key to improving flow duration. Groundwater/surface-water interaction can be assessed directly with shallow wells or tracers or indirectly assessed by measuring the results like the Physicochemical and Biology parameters and measurement methods.

Geomorphology – Large woody debris has been removed from the channel and is Not Functioning. Large woody debris will be added to the channel to create pools and encourage bed aggradation. The prediction is that post-restoration condition will be Functioning. There is a 10-foot buffer with cottonwood trees that will remain. The buffer will be expanded to 100 feet to provide bank stability, cover, and treatment of agricultural runoff. The existing bank erosion is on the outside of the meander bends, and since the overall pattern is stable, bioengineering and wood structures will be used to improve lateral stability to a Functioning level. Existing bed form diversity is Functioning-at-Risk because pools are shallow and only located in the apex of bends. Large woody debris and in-stream structures will be used to create a more complex bed form.

Physicochemical – Temperate and DO levels are used to measure water quality and are both Functioning when water is present. These levels are supported by the existing cottonwood trees, moderate bed form diversity, and health of the upstream watershed. No change in the function score is predicted post-restoration, however these parameters will be measurable for longer periods of time due to longer flow duration. Elevated levels of nitrate-nitrogen enter the stream before restoration from adjacent cropland. Post-restoration buffer and higher water table will support denitrification processes.

Biology – Macroinvertebrate and fish communities are Not Functioning in the summer months when flow duration is below the level needed to support aquatic life. Post-restoration, macroinvertebrate and fish communities will be Functioning year round.

TABLE BC2c CREDIT TEMPLATE 3: CREDIT CALCULATIONS

BEFORE FUNCTIONALITY	AFTER FUNCTIONALITY			
	Low (Flow duration is Functioning-at-Risk. Other key parameters in Level 2-4 are Functioning-at-Risk or Not Functioning). Key parameters in Level 5 are Not Functioning)	**Moderate** (Flow duration is Functioning. Other key parameters in Level 2-4 are Functioning-at-Risk or Not Functioning). Key parameters in Level 5 are Not Functioning)	**High** (Flow duration is Functioning. Other key parameters in Level 2-5 are Functioning)	**Category**
Low (Flow duration is Not Functioning. Other key parameters in Level 2-4 are Functioning-at-Risk or Not Functioning). Key parameters in Level 5 are Not Functioning)	_____	0.8	1.0	Restoration
Moderate (Flow duration is Not Functioning. Other key parameters in Level 2-4 are a mix of Functioning, Functioning-at-Risk and Not Functioning). Key parameters in Level 5 are Functioning-at-Risk and Not Functioning)	_____	_____	0.6	Enhancement
High (Flow duration is Not Functioning. Other key parameters in Level 2-4 are a mix of Functioning, Functioning-at-Risk and Not Functioning). Key parameters in Level 5 are Functioning-at-Risk and Not Functioning)	_____	_____	0.2	Preservation

Restoration efforts have focused on dam removal and restoring salmonid habitat, typically by adding large woody debris to the channels. These engineered log jams are often used to raise the stream bed, stabilize streambanks, and to create sediment storage areas upstream of the log jam while coarsening the bed downstream. The example below includes the removal of a dam to create fish passage and the installation of LWD and other natural structures to stabilize the bed and create salmonid habitat.

Example Scenario

A restoration site has been secured that includes a 10-foot high dam removal and 10,000 feet of degraded channel, 2,000 feet downstream of the dam and 8,000 feet upstream. The stream is approximately 50 feet wide with a gravel/cobble bed. The watershed is forested, but is managed for silviculture. The existing Bank Height Ratio is 1.5 downstream of the dam with moderate bank erosion and a coarse bed. The bed has aggraded upstream of the dam, reducing the Bank Height Ratio to 1.2 and creating a finer grain size distribution for the bed material. Streambank erosion is low. A forested buffer extends the width of the valley throughout the full length of the project reach. Basic water quality (pH, DO, conductivity and turbidity) meets the species requirements for salmonids, which are plentiful downstream of the dam. These fish, however, are unable to migrate past the dam due to its height. In addition, the bed material upstream is unsuitable for salmonid habitat due to the aggradation of fine sediments.

The restoration approach includes the removal of the 10-foot high dam and the installation of engineered log jams and other structures to stabilize the stream bed. The structures will be installed throughout the project length to reduce Bank Height Ratios downstream of the dam and to spread out the elevation drop throughout the reach. The structures will create a step-pool bed form, creating more resting areas for salmonids. Fine grain sediments will still accumulate upstream of the structures leaving coarser material downstream. However, the individual facet length of finer grained sediment will be much less than above the dam. In addition, the wood will provide refuge for the fish and habitat for aquatic insects.

The pre-restoration condition is a mix of Functioning, Functioning-at-Risk and Not Functioning scores, with the downstream condition scoring lower for Hydraulic, Geomorphology and Biology functions. This equals a Before Functionality score of **Moderate**. The post-restoration condition is predicted to be Functioning for all key parameters, yielding an **After** Restoration score of High. A **Moderate/High** score provides a credit ratio of 0.7. The total number of credits is 10,000 feet X 0.7 credit/ft = 7,000 credits.

TABLE BC3a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	N/A	N/A		N/A	N/A	N/A
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	1.5 (Downstream of dam) 1.2 (Upstream of dam)	Functioning-at-Risk Functioning	1.2	Functioning
	Flow Dynamics	Velocity	Does not meet species requirements	Not Functioning	Meets species requirements	Functioning
3 – Geomorphology	Large Woody Debris Storage and Transport	LWDI	LWDI does not equal LWDI of reference reach	Not Functioning	LWDI equals LWDI of reference reach	Functioning
	Bank Migration/ Lateral Stability	BEHI/NBS	Moderate downstream of dam Low upstream of dam	Functioning-at-Risk Functioning	Low	Functioning
	Riparian Vegetation	Average Buffer Width (ft)	> 150	Functioning	> 150	Functioning
		Buffer Density, Composition, Age, Growth and Canopy Density	Similar to reference reach condition	Functioning	Similar to reference reach condition	Functioning
	Bed Form Diversity	Depth Variability (Pool Max Depth Ratio)	1.2 (Downstream of dam) < 1.2 (Upstream of dam)	Functioning-at-Risk Not Functioning	> 2	Functioning

TABLE BC3a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER	MEASUREMENT METHOD	PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
4 – Physicochemical	Basic Water Quality	Temperature	Project Reach is not statistically different than reference.	Functioning	Project Reach is not statistically different than reference reach.	Functioning
		Dissolved Oxygen	Project Reach is not statistically different than reference.	Functioning	Project Reach is not statistically different than reference reach.	Functioning
		Conductivity, pH	Project Reach is not statistically different than reference.	Functioning	Project Reach is not statistically different than reference reach.	Functioning
5 – Biology	Benthic Macroinvertebrate Communities	Family-Level Biological Index (FBI)	5 (Downstream) 8 (Upstream)	Functioning-at-Risk Not Functioning	2	Functioning
	Fish Communities	McCormick Index of Biological Integrity	70 (Downstream) 55 (Upstream)	Functioning-at-Risk Not Functioning	75	Functioning

TABLE BC3b CREDIT TEMPLATE 2: PRE- AND POST-RESTORATION CONDITIONS AND RATIONALE

Describe Pre- and Post-Restoration Condition and Rationale for Selecting Parameters

Hydrology – While silviculture can change the rainfall/runoff relationship, the watershed hydrology in this example is stable. Hydrology parameters are used for the design, but not as performance standards.

Hydraulic – A Bank Height Ratio of 1.5 indicates that the channel is moderately incised downstream of the dam. This may be due to reduced sediment supply caused by the dam, past changes to hydrology, past channelization, or a combination of impacts. The lower Bank Height Ratio of 1.2 upstream of the dam is caused by sedimentation. Flow dynamics was not described in the example scenario; however, the dam and channel incision will increase channel velocities downstream of the dam. For this reason, velocity was added as a measurement method. For this example, a performance standard was added based on species requirements.

Geomorphology – Large woody debris has been removed from the channel and is therefore Not Functioning before restoration. Engineered log jams will be the primary structure used in the restoration and will create a Functioning score post-restoration. There is moderate bank erosion downstream of the dam, which is primarily a result of channel incision. This has created a Functioning-at-Risk pre-restoration score. The structures will be used to reduce the bank heights and improve bank stability, improving the score to Functioning. A mature forest exists throughout the project reach and is Functioning pre- and post-restoration. Bed form diversity is measured by depth variability and shows a Functioning-at-Risk pre-restoration score downstream of the dam. This is caused by a reduction in sediment supply and channel incision. There are fewer riffles and pools upstream of the dam due to sedimentation, resulting in a Not Functioning score.

Physicochemical – All water quality measurement methods are Functioning pre- and post-restoration for this example due to the health of the upstream watershed and low water retention from the dam.

Biology – The two methods of measurement shown are examples from Chapter 10 and were developed for different regions. As methods are developed for the Northwest, they should be added as a measurement method. If indexes are not available, a reference reach approach could be used to compare the pre- and post-restoration condition to a reference condition specifically for salmonids.

TABLE BC3c CREDIT TEMPLATE 3: CREDIT CALCULATIONS

BEFORE FUNCTIONALITY	AFTER FUNCTIONALITY			
	Low (Dam is removed. Key parameters in Level 2-4 are Functioning-at-Risk or Not Functioning). Key parameters in Level 5 are Not Functioning)	**Moderate** (Dam is removed. Key parameters in Level 2-4 are Functioning or Functioning-at-Risk. Key parameters in Level 5 are Functioning-at-Risk)	**High** (Dam is removed. Key parameters in Level 2-5 are Functioning)	**Category**
Low (Dam is in place. Key parameters in Level 2-4 are Functioning-at-Risk or Not Functioning). Key parameters in Level 5 are Not Functioning)	_____	0.8	1.0	Restoration
Moderate (Dam is in place. Key parameters in Level 2-4 are a mix of Functioning, Functioning-at-Risk and Not Functioning). Key parameters in Level 5 are Functioning-at-Risk and Not Functioning)	_____	0.6	0.7	Enhancement

Scenario 4: Restoration of High Gradient, Headwater Streams

The restoration of high gradient, headwater streams is common in mountain regions of the US, especially the Appalachian Mountains where restoration is often associated with coal mining impacts. In addition, mountain headwater streams are often restored in the East and the West to improve trout fishing. These streams are often found in v-shaped or colluvial valleys and are often A or B stream types, and sometimes Cb stream types. Energy is dissipated through vertical meandering rather than lateral meandering, which is measured by sinuosity. In these higher-gradient streams, step-pool bed forms create vertical meandering, which dissipates energy and creates the habitat needed for many fish species, including trout. Therefore, restoration efforts focus more on bed form diversity and more specifically measurement methods like pool-to-pool spacing and pool depths than measures like sinuosity.

Example Scenario

A stream restoration project has been secured to restore 12,000 feet of mountain headwater streams. The representative valley slope is 5% and the stream types are a B4. The streams are located on an abandoned mine site. A uniform channel was sized to carry the 25-year discharge and material from the mine site was used to line the channels. There are no trees along the riparian corridor other than a few small shrubs. Over the years, the channels have further incised and bank erosion is prevalent throughout the reaches. The streams are ephemeral to perennial; however, due to poor bed form diversity and high flow energy, the stream does not support aquatic life in the perennial reaches. The pH of the stream is a little lower than reference conditions.

The restoration approach is a watershed scale effort. The ephemeral, intermittent and perennial streams are reconstructed based on natural channel design principles. The focus of the restoration is to create a channel that only carries the bankfull discharge. All other flows are transported onto a floodprone area, including the 25-year discharge. This is also called a nested-channel approach. The pool-to-pool spacing and pool depths are designed based on the slope of the channel, with steeper reaches having shorter pool spacing than flatter reaches. A combination of boulders and wood are used to create the step-pool structures. The channels are connected through a dendritic drainage pattern. Topsoil and mulch are used to amend the soils in the riparian area and a 200-foot buffer of hardwood trees and native shrubs is established.

This scenario fits the same credit determination method as the restoration of incised channels. For this example, the pre-restoration condition included all Not Functioning scores. Since this is a watershed scale approach, all of the post-restoration scores are Functioning through Level 5. This results in a **Maximum Lift** with a credit range of 0.8 to 1.0. For this example, 0.9 credits are used. The total credits are 12,000 feet X 0.9 credits/ft = 10,800 credits.

TABLE BC4a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION

LEVEL AND CATEGORY	PARAMETER		PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
1 – Hydrology	N/A	N/A		N/A	N/A	N/A
2 – Hydraulics	Floodplain Connectivity	Bank Height Ratio	> 2.0	Not Functioning	1.0	Functioning
3 – Geomorphology	Large Woody Debris Storage and Transport	LWDI	LWDI does not equal LWDI of reference reach	Not Functioning	LWDI equals LWDI of reference reach	Functioning
	Bank Migration/ Lateral Stability	BEHI/NBS	High	Not Functioning	Low	Functioning
	Riparian Vegetation	Average Buffer Width (ft)	0	Not Functioning	> 150	Functioning
		Buffer Density, Composition, Age, Growth and Canopy Density	None	Not Functioning	Similar to reference reach condition	Functioning
	Bed Form Diversity	Depth Variability (Pool Max Depth Ratio)	< 1.2	Not Functioning	> 2	Functioning

TABLE BC4a CREDIT TEMPLATE 1: FUNCTIONAL LIFT DETERMINATION (CONT.)

LEVEL AND CATEGORY	PARAMETER		PRE-RESTORATION CONDITION		POST-RESTORATION CONDITION	
			VALUE	RATING	VALUE	RATING
4 – Physicochemical	Water Quality	pH	Slightly lower than reference condition	Functioning-at-Risk	Project Reach is not statistically different than reference reach and support species requirements by year 10.	Functioning
5 – Biology	Benthic Macroinvertebrate Communities	WVSCI	40	Not Functioning	70 by year 10	Functioning
	Fish Communities	Mid-Atlantic Highlands IBI	35	Not Functioning	75 by year 10	Functioning

TABLE BC4b CREDIT TEMPLATE 2: PRE- AND POST-RESTORATION CONDITIONS AND RATIONALE

Describe Pre- and Post-Restoration Condition and Rationale for Selecting Parameters

Hydrology – For this example, the Hydrology is stable enough to proceed with the project, especially since the restoration is a watershed-scale effort. Restoration efforts will likely reduce runoff and may increase flow duration. Therefore, there parameters could be added as performance standards and evaluated against a reference condition.

Hydraulic – The Bank Height Ratio was not provided for the pre-restoration scenario; however, the channel was designed to carry a 25-year discharge and would therefore be severely incised. The new channel will be sized within the larger channel to carry the bankfull discharge and the larger channel will be used as a floodprone area. This will convert the Hydraulic functions from Not Functioning to Functioning. Groundwater/surface-water exchange was not selected for this example, because the restoration approach is a watershed-scale approach and there isn't a concern about the stream classification, e.g., ephemeral or intermittent. If this was a concern, additional restoration approaches could be used to change the groundwater/surface-water interaction. And in reality, the addition of step-pools will likely improve flow through the hyporheic zone.

Geomorphology – The existing channel is devoid of LWD. Wood will be incorporated into the step-pool channels so that the restored stream has an amount of wood that is representative of reference streams. Pre-restoration bank erosion is high due to the oversized channel and absence of vegetation. The change in channel dimension and the establishment of a riparian buffer will reduce bank erosion to Functioning levels. The crux of the restoration approach is the establishment of step-pool bed forms. These features will provide vertical control and dissipate energy. They will also provide key habitat, along with LWD, for native fish species.

Physicochemical – pH is Functioning-at-Risk due to past mining activities, the over-sized channel, and lack of riparian vegetation. The combination of changes to channel dimension (nested-channel), bed form diversity (LWD and step-pools), re-establishment of the drainage network, and establishment of a riparian buffer will slowly improve water quality. It is predicted to take 10 years before fully Functioning scores will be obtained.

Biology – Macroinvertebrate and fish communities are Not Functioning pre-restoration due to all of the impacts to Level 2-4 functions. The restoration of these functions will support the recruitment of aquatic insects and native fish. It is predicted that Functioning levels will be achieved by year 10.

TABLE BC4c CREDIT TEMPLATE 3: CREDIT CALCULATIONS

CREDIT CATEGORIES	PRE-RESTORATION CONDITION	POST-RESTORATION CONDITION	CREDITS PER FOOT
Maximum Lift	All parameters in Pyramid Levels 2 and 3 have Not Functioning scores. Parameters in Levels 4 and 5 are Not Functioning or Functioning-at-Risk.	Functioning scores for Levels 1-5.	0.8 to 1.0
Moderate Lift	Mix of Not-Functioning and Functioning-at-Risk scores for parameter Levels 2 through 5.	Functioning scores for Levels 1-5.	0.6 to 0.8
Low Lift	Mix of Not-Functioning, Functioning-at-Risk and Functioning scores for parameter Levels 2 through 5.	Functioning scores for Levels 1-5.	0.4 to 0.6