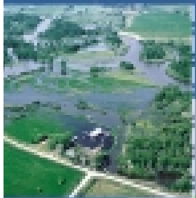

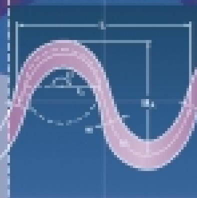


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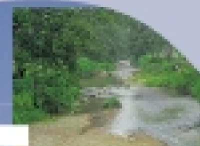
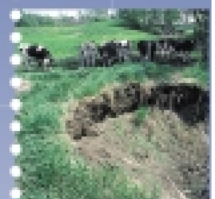
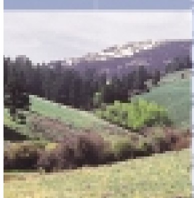
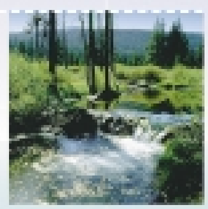


Principles, Processes, and Practices

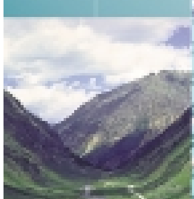
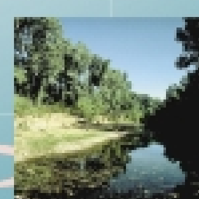
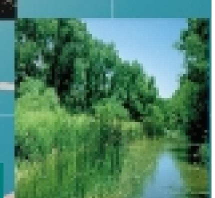

http://www.usda.gov/stream_restoration

See this site for downloads, addenda, and a catalog of the book's images.



By: The Federal Interagency Stream Restoration Working Group

FISRWG (10/1998). Stream Corridor Restoration: Principles, Processes, and Practices. By the Federal Interagency Stream Restoration Working Group (FISRWG)(15 Federal agencies of the US gov't). GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN3/PT.653. ISBN-0-934213-59-3.

Published October, 1998. Revised August, 2001.
adopted as Part 653 of the National Engineering Handbook, USDA-Natural Resources Conservation Service

Acknowledgments

Machines printed this document, but people translated their collective knowledge and experience into the printed word. The following agencies, people, and affiliates cooperated and worked together to produce the interagency document, "Stream Corridor Restoration: Principles, Processes, and Practices." Numerous other people also worked in support or consultative roles within and outside of the agencies, and their contribution is acknowledged and very much appreciated.

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The following federal agencies collaborated to produce this document:

U.S. Department of Agriculture

- Agricultural Research Service
- Cooperative State Research, Education, and Extension Service
- Forest Service
- Natural Resources Conservation Service

U.S. Environmental Protection Agency

Tennessee Valley Authority

Federal Emergency Management Agency

U.S. Department of Commerce

- National Oceanographic and Atmospheric Administration
  – National Marine Fisheries Service

U.S. Department of Defense

- Army Corps of Engineers

U.S. Department of Housing and Urban Development

U.S. Department of the Interior

- Bureau of Land Management
- Bureau of Reclamation
- Fish and Wildlife Service
- National Park Service
- U.S. Geological Survey

These federal agencies produced this document with their resources and human talent, forming and supporting a Production Team, a Communications Team, and a Steering Team.

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Stream Corridor Restoration: Principles, Processes, and Practices

Introduction

There is a phenomenal resiliency in the mechanisms of the earth. A river or lake is almost never dead. If you give it the slightest chance...then nature usually comes back.

— Rene Dubos 1981

Why Is Stream Corridor Restoration Important?

The United States has more than 3.5 million miles of rivers and streams that, along with closely associated floodplain and upland areas, comprise corridors of great economic, social, cultural, and environmental value. These corridors are complex ecosystems that include the land, plants, animals, and network of streams within them. They perform a number of ecological functions such as modulating streamflow, storing water, removing harmful materials from water, and providing habitat for aquatic and terrestrial plants and animals. Stream corridors also have vegetation and soil characteristics distinctly different from surrounding uplands and support higher levels of species diversity, species densities, and rates of biological productivity than most other landscape elements.

Streams and stream corridors evolve in concert with and in response to surrounding ecosystems. Changes within a surrounding ecosystem (e.g., watershed) will impact the physical, chemical, and biological processes occurring within a stream corridor. Stream systems normally function within natural ranges of flow, sediment movement, temperature, and other variables, in what is termed "dynamic equilibrium." When changes in these variables go beyond their natural ranges, dynamic equilibrium may be lost, often resulting in adjustments in the ecosystem that might conflict with societal needs. In some circumstances, a new dynamic equilibrium may

Fig. I.1: Stream corridor in the Midwest. *Stream corridors have great economic, social, cultural, and environmental values.*

eventually develop, but the time frames in which this happens can be lengthy, and the changes necessary to achieve this new balance significant.

Over the years, human activities have contributed to changes in the dynamic equilibrium of stream systems across the nation. These activities center on manipulating stream corridor systems for a wide variety of purposes, including domestic and industrial water supplies, irrigation, transportation, hydropower, waste disposal, mining, flood control, timber management, recreation, aesthetics, and more recently, fish and wildlife habitat. Increases in human population and industrial, commercial, and residential development place heavy demands on this country's stream corridors.

The cumulative effects of these activities result in significant changes, not only to stream corridors, but also to the ecosystems of which they are a part. These changes include degradation of water quality, decreased water storage and conveyance capacity, loss of habitat for fish and wildlife, and decreased recreational and aesthetic values (National Research Council 1992). According to the 1994 National Water Quality Inventory of 617,806 miles of rivers and streams, only 56 percent fully supported multiple uses, including drinking water supply, fish and wildlife habitat, recreation, and agriculture, as well as flood prevention and erosion control. Sedimentation and excess nutrients were the most significant causes of degradation (USEPA 1997) in the remaining 44 percent.

Human activity has profoundly affected rivers and streams in all parts of the world, to such an extent that it is now extremely difficult to find any stream which has not been in some way altered, and probably quite impossible to find any such river.

— H.B.N. Hynes 1970

Fig. I.2: Concrete-lined channel. *Stream systems across the nation have been altered for a wide variety of purposes.*

Given these statistics, the potential for restoring the conditions in our nation's rivers and streams and protecting them from further damage is almost boundless.

What Is Meant by Restoration?

Restoration is a complex endeavor that begins by recognizing natural or human-induced disturbances that are damaging the structure and functions of the ecosystem or preventing its recovery to a sustainable condition (Pacific Rivers Council 1996). It requires an understanding of the structure and functions of stream corridor ecosystems and

Restoration, Rehabilitation, and Reclamation

- Restoration *is reestablishment of the structure and function of ecosystems (National Research Council, 1992). Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. Implicit in this definition is that ecosystems are naturally dynamic. It is therefore not possible to recreate a system exactly. The restoration process reestablishes the general structure, function, and dynamic but self-sustaining behavior of the ecosystem.*
- Rehabilitation *is making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat (Dunster and Dunster 1996). Rehabilitation does not necessarily reestablish the predisturbance condition, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic.*
- Reclamation *is a series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery (Dunster and Dunster 1996). The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses.*

Restoration differs from rehabilitation and reclamation in that restoration is a holistic process not achieved through the isolated manipulation of individual elements. While restoration aims to return an ecosystem to a former natural condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose (National Research Council 1992).

the physical, chemical, and biological processes that shape them (Dunster and Dunster 1996).

Restoration, as defined in this document, includes a broad range of actions and measures designed to enable stream corridors to recover dynamic equilibrium and function at a self-sustaining level. The first and most critical step in implementing restoration is to, where possible, halt disturbance activities causing degradation or preventing recovery of the ecosystem (Kauffman et al. 1993). Restoration actions may range from passive approaches that involve removal or attenuation of chronic disturbance activities to active restoration that involves intervention and installation of measures to repair damages to the structure of stream corridors.

Restoration practitioners involved with stream corridors take one of three basic approaches to restoration:

- *Nonintervention and undisturbed recovery:* where the stream corridor is recovering rapidly, and active restoration is unnecessary and even detrimental.
- *Partial intervention for assisted recovery:* where a stream corridor is attempting to recover, but is doing so slowly or uncertainly. In such a case, action may facilitate natural processes already occurring.
- *Substantial intervention for managed recovery:* where recovery of desired functions is beyond the repair capacity of the ecosystem and active restoration measures are needed.

The specific goals of any particular restoration should be defined within the context of the current conditions and disturbances in the watershed,

Streams Have the Capability to Restore Themselves—We must be able to recognize these situations.

"Each stream," says Christopher Hunter, "is a whole greater than the sum of its geologic, climatic, hydrologic, and biologic parts." Those who would save rivers must first see each river whole, as a separate, vital, and unique group of elements and energies that constantly seeks its own dynamic equilibrium (from Nick Lyons, Foreword to Better Trout Habitat: A Guide to Stream Restoration and Management*; Hunter 1991). It is this almost living quality of streams, along with the capability to repair and sustain themselves with the removal of disturbances, that this document must convey to the reader. This document addresses the need within agencies for a comprehensive restoration context, an appreciation of the importance of removing key disturbances to allow streams to restore themselves, and to better determine those circumstances when active intervention in the restoration process is the preferred alternative.*

corridor, and stream. In all likelihood, restoration will not involve returning a system to its pristine or original condition. The goal should be to establish self-sustaining stream functions.

Because this document may be a primary reference on ecological restoration for many users, it is appropriate that more than one definition of restoration be included. The following definition of restoration has been adopted by the Society for Ecological Restoration (SER). "Ecological restoration is the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes, and structures, regional and historical context, and sustainable cultural practices."

Why Is a Stream Corridor Restoration Document Needed?

Interest in restoring stream corridor ecosystems is expanding nationally and internationally. Research is under way and guidelines are being developed for stream corridor restoration in both the public and private sectors. The number of case studies, published papers, technology exchanges, research projects, and symposia on both the technical and process aspects of stream corridor restoration is increasing.

Over the years, many federal agencies have contributed to this growing body of knowledge and have issued manuals and handbooks pertaining in some way to stream restoration. Much of this older literature, however, is significantly different from this document in terms of philosophy and technique. Narrow in scope and focusing on only specific aspects, regions, objectives, or treatments, it may be outdated and not reflective of new restoration techniques and philosophies. The result has been confusion and concern among both government agencies and the public on how to evaluate the need for development and implementation of restoration initiatives.

In response, this document represents an unprecedented cooperative effort by the participating federal agencies to produce a common technical reference on stream corridor restoration.

Recognizing that no two stream corridors and no two restoration initiatives are identical, this technical document broadly addresses the elements of restoration that apply in the majority of situations encountered. The document

It is axiomatic that no restoration can ever be perfect; it is impossible to replicate the biogeochemical and climatological sequence of events over geological time that led to the creation and placement of even one particle of soil, much less to exactly reproduce an entire ecosystem. Therefore, all restorations are exercises in approximation and in the reconstruction of naturalistic rather than natural assemblages of plants and animals with their physical environments.

— Berger 1990

is not a set of guidelines that cover every possible restoration situation, but it does provide a framework in which to plan restoration actions and alternatives.

What Does the Document Cover?

This document takes a more encompassing approach to restoration than most other texts and manuals. It provides broadly applicable guidance for common elements of the restoration process, but also provides alternatives, and references to alternatives, which may be appropriate for site-specific restoration activities. Moreover, the document incorporates and reflects the experiences of the collaborating agencies and provides a common technical reference that can be used to restore systems based on experiences and basic scientific knowledge.

As a general goal, this document promotes the use of ecological processes (physical, chemical, and biological) and minimally intrusive solutions to restore self-sustaining stream corridor func-

(a)

(b)

Fig. I.3: Stream corridor restoration can be applied in both (a) urban and (b) rural settings. *No matter the setting, vegetation and soil characteristics in the corridor differ distinctly from the surrounding uplands.*

The document is intended primarily for interdisciplinary technical and managerial teams and individuals responsible for planning, designing, and implementing stream corridor restoration initiatives.

tions. It provides information necessary to develop and select appropriate alternatives and solutions, and to make informed management decisions regarding valuable stream corridors and their watersheds. In addition, the document recognizes the complexity of most stream restoration work and promotes an integrated approach to restoration. It supports close cooperation among all participants in order to achieve a common set of objectives.

The guidance contained in this document is applicable nationwide in both urban and rural settings. The material presented applies to a range of stream types, including intermittent and perennial streams of all sizes, and rivers too small to be navigable by barges. It offers a scientific perspective on restoration work ranging from simple to complex, with the level of detail increasing as the scale moves from the landscape to the stream reach.

Fig. I.4: A stream corridor. *The document provides an overview of stream corridor structure and functions.*

Note that there are several things that this document is not intended to be.

- It is not a cookbook containing prescribed "recipes" or step-by-step instructions on how to restore a stream corridor.
- While this document refers to issues such as nonpoint source pollution and best management practices, wetlands restoration and delineation, lake and reservoir restoration, and water quality monitoring, it is not meant to focus on these subjects.
- It is not a policy-setting document. No contributing federal agency is strictly bound by its contents. Rather, it suggests and promotes a set of approaches, methods, and techniques applicable to most stream corridor restoration initiatives encountered by agencies and practitioners.
- It is not intended to be an exhaustive research document on the subject of stream corridor restoration. It does provide, however, many references for those desiring a deeper understanding of the principles and theories underlying techniques and issues discussed in general terms.

Who Is the Intended Audience?

The document is intended primarily for interdisciplinary technical and managerial teams and individuals responsible for planning, designing, and implementing stream corridor restoration initiatives. The document may also be useful to others who are working in stream corridors, including contractors, landowners, volunteers, agency staff, and other practitioners.

How Is the Document Organized?

The document is organized to provide an overview of stream corridors, steps in restoration plan development, and guidelines for implementing restoration.

The document has been divided into three principal parts. *Part I* provides background on the fundamental concepts of stream corridor structure, processes, functions, and the effects of disturbance. *Part II* focuses on a general restoration plan development process comprised of several fundamental steps. *Part III* examines the information presented in Parts I and II to consider how it can be applied in a restoration initiative.

Because of the size and complexity of the document, two features are used to assist the reader to maintain a clear orientation within the document. These features will allow the reader to more easily apply the information to specific aspects of a stream corridor restoration initiative. These features are:

- Chapter dividers that include major chapter sections and reader preview and review questions for each chapter. Table I.1 presents a summary of these questions by chapter.
- Short chapter summaries included at the beginning and end of each chapter that explain where the readers have been, where they are in the document, and where they are going.

A special emphasis has been placed on document orientation due to the special mission that the document has to fulfill. The document audience will include readers from many different technical backgrounds and with various levels of training. The orientation features have been included to reinforce the comprehensive and interdisciplinary perspective of stream corridor restoration.

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  - *United States Geological Survey*
  - *National Park Service*
- *United States Environmental Protection Agency*
- *Federal Emergency Management Agency*
- *Tennessee Valley Authority*

How Is the Document Intended to Be Used?

Use of the document mostly depends on the goals of the reader. To begin with, a quick overview of the material is suggested prior to more thorough reading. A reader seeking only a general understanding of the principles of stream restoration may skip over some of the technical details in the body of the document. Use of document sections, chapters, and headings allows each reader to readily identify whether further, more detailed reading on a subject will serve his or her purposes.

The reader is urged to recognize the interdisciplinary and technical nature of stream restoration. While some technical material may, on the surface, appear irrelevant, it may in fact be highly relevant to a specific part of the process of restoring a stream corridor.

Stream corridor restoration technologies and methodologies are evolving rapidly. Readers are encouraged to add their own notes on restoration and to make the document more relevant to local needs (e.g., a list of suitable native plant species for streambank revegetation).

This document is being published in a notebook form to allow insertion of:

- Updated material that will be made available at the Internet sites printed in the *Preface*.
- Addition of regional or locally relevant materials collected by the reader.

A Note About Units of Measurement

Metric units are commonly used throughout the world, but most data published in the United States are in English units. Although adoption of the metric system is on the increase in the United States—and for many federal agencies this conversion is mandated and being planned for—restorers of stream corridors will continue to use data that are in either metric or English units.

Appendix B contains a table of metric to English unit conversion factors, in case a unit conversion is needed.

Feedback

Readers are encouraged to share their restoration experiences and provide feedback. They can do so by accessing the Stream Corridor Restoration home page on the Internet address printed in the Preface*. Other sources of information may also be found by exploring the cooperating agencies' home pages on the Internet.*

Table I.1

Chapter 1: Overview of Stream Corridors

1.A Physical Structure and Time at Multiple Scales

- *What are the structural components of a stream corridor?*
- *Why are stream corridors of special significance, and why should they be the focus of restoration efforts?*
- *What is the relationship between stream corridors and other landscape units at broader and more local scales?*
- *What scales should be considered for a stream corridor restoration?*

1.B A Lateral View Across the Stream Corridor

- *How is a stream corridor structured from side to side?*
- *How do these elements contribute to stream corridor functions?*
- *What role do these elements play in the life of the stream?*
- *What do we need to know about the lateral elements of a stream corridor to adequately characterize a stream corridor for restoration?*
- *How are the lateral elements of a stream corridor used to define flow patterns of a stream?*

1.C A Longitudinal View Along the Stream Corridor

- *What are the longitudinal structural elements of a stream corridor?*
- *How are these elements used to characterize a stream corridor?*
- *What are some of the basic ecological concepts that can be applied to streams to understand their function and characteristics on a longitudinal scale?*
- *What do we need to know about the longitudinal elements that are important to stream corridor restoration?*

Chapter 2: Stream Corridor Processes, Characteristics, and Functions

2.A Hydrologic and Hydraulic Processes

- *Where does stream flow come from?*
- *What processes affect or are involved with stream flow?*
- *How fast, how much, how deep, how often, and when does water flow?*
- *How is hydrology different in urban stream corridors?*

2.B Geomorphic Processes

- *What factors affect the channel cross section and channel profile?*
- *How are water and sediment related?*
- *Where does sediment come from and how is it transported downstream?*
- *What is an equilibrium channel?*
- *What should a channel look like in cross section and in profile?*
- *How do channel adjustments occur?*
- *What is a floodplain?*
- *Is there an important relationship between a stream and its floodplain?*

2.C Physical and Chemical Characteristics

- *What are the major chemical constituents of water?*
- *What are some important relationships between physical habitat and key chemical parameters?*
- *How are the chemical and physical parameters critical to the aquatic life in a stream corridor?*
- *What are the natural chemical processes in a stream corridor and water column?*
- *How do disturbances in the stream corridor affect the chemical characteristics of stream water?*

Table I.1 (continued)

2.D Biological Community Characteristics

- *What are the important biological components of a stream corridor?*
- *What biological activities and organisms can be found within a stream corridor?*
- *How does the structure of stream corridors support various populations of organisms?*
- *What are the structural features of aquatic systems that contribute to the biological diversity of stream corridors?*
- *What are some important biological processes that occur within a stream corridor?*
- *What role do fish have in stream corridor restoration?*

2.E Functions and Dynamic Equilibrium

- *What are the major ecological functions of stream corridors?*
- *How are these ecological functions maintained over time?*
- *Is a stream corridor stable?*
- *Are these functions related?*
- *How does a stream corridor respond to all the natural forces acting on it (i.e., dynamic equilibrium)?*

Chapter 3: Disturbance Affecting Stream Corridors

3.A Natural Disturbances

- *How does natural disturbance contribute to shaping a local ecology?*
- *Are natural disturbances bad?*
- *How do you describe or define the frequency and magnitude of natural disturbance?*
- *How does an ecosystem respond to natural disturbances?*
- *What are some types of natural disturbances you should anticipate in a stream corridor restoration?*

3.B Human-Induced Disturbances

- *What are some examples of human-induced disturbances at several landscape scales?*
- *What are the effects of some common human-induced disturbances such as dams, channelization, and the introduction of exotic species?*
- *What are some of the effects of land use activities such as agriculture, forestry, mining, grazing, recreation, and urbanization?*

Chapter 4: Getting Organized and Identifying Problems and Opportunities

4.A Getting Organized

- *Why is planning important?*
- *Is an Advisory Group needed?*
- *How is an Advisory Group formed?*
- *Who should be on an Advisory Group?*
- *How can funding be identified and acquired?*
- *How are technical teams established and what are their roles?*
- *What procedures should an Advisory Group follow?*
- *How is communication facilitated among affected stakeholders?*

Table I.1 (continued)

4.B Problem and Opportunity Identification

- *Why is it important to spend resources on the problem ("When everyone already knows what the problem is")?*
- *How can the anthropogenic changes that caused the need for the restoration initiative be altered or removed?*
- *How are data collection and analysis procedures organized?*
- *How are problems affecting the stream corridor identified?*
- *How are reference conditions for the stream corridor determined?*
- *Why are reference conditions needed?*
- *How are existing management activities influencing the stream corridor?*
- *How are problems affecting the stream corridor described?*

Chapter 5: Developing Goals, Objectives, and Restoration Alternatives

5.A Developing Restoration Goals and Objectives

- *How are restoration goals and objectives defined?*
- *How do you describe desired future conditions for the stream corridor and surrounding natural systems?*
- *What is the appropriate spatial scale for the stream corridor restoration?*
- *What institutional or legal issues are likely to be encountered during a restoration?*
- *What are the means to alter or remove the anthropogenic changes that caused the need for the restoration (i.e., passive restoration)?*

5.B Alternative Selection and Design

- *How does a restoration effort target solutions to treat causes of impairment and not just symptoms?*
- *What are important factors to consider when selecting among various restoration alternatives?*
- *What role does spatial scale, economics, and risk play in helping to select the best restoration alternative?*
- *Who makes the decisions?*
- *When is active restoration needed?*
- *When are passive restoration methods appropriate?*

Chapter 6: Implement, Monitor, Evaluate, and Adapt

6.A Restoration Implementation

- *What are the steps that should be followed for successful implementation?*
- *How are boundaries for the restoration defined?*
- *How is adequate funding secured for the duration of the project?*
- *What tools are useful for facilitating implementation?*
- *Why and how are changes made in the restoration plan once implementation has begun?*
- *How are implementation activities organized?*
- *How are roles and responsibilities distributed among restoration participants?*
- *How is a schedule developed for installation of the restoration measures?*
- *What permits and regulations will be necessary before moving forward with restoration measures?*

Table I.1 (continued)

6.B Restoration Monitoring, Evaluation, and Adaptive Management

- *What is the role of monitoring in stream corridor restoration?*
- *When should monitoring begin?*
- *How is a monitoring plan tailored to the specific objectives of a restoration initiative?*
- *Why and how is the success or failure of a restoration effort evaluated?*
- *What are some important considerations in developing a monitoring plan to evaluate the restoration effort?*

Chapter 7: Analysis of Corridor Condition

7.A Hydrologic Processes

- *How does the stream flow and why is this understanding important?*
- *Is streamflow perennial, ephemeral, or intermittent?*
- *What is the discharge, frequency, and duration of extreme high and low flows?*
- *How often does the stream flood?*
- *How does roughness affect flow levels?*
- *What is the discharge most effective in maintaining the stream channel under equilibrium conditions?*
- *How does one determine if equilibrium conditions exist?*
- *What field measurements are necessary?*

7.B Geomorphic Processes

- *How do I inventory geomorphic information on streams and use it to understand and develop physically appropriate restoration plans?*
- *How do I interpret the dominant channel adjustment processes active at the site?*
- *How deep and wide should a stream be?*
- *Is the stream stable?*
- *Are basin-wide adjustments occurring, or is this a local problem?*
- *Are channel banks stable, at-risk, or unstable?*
- *What measurements are necessary?*

7.C Chemical Characteristics

- *How do you measure the condition of the physical and chemical conditions within a stream corridor?*
- *Why is quality assurance an important component of stream corridor analysis activities?*
- *What are some of the water quality models that can be used to evaluate water chemistry data?*

7.D Biological Characteristics

- *What are some important considerations in using biological indicators for analyzing stream corridor conditions?*
- *Which indicators have been used successfully?*
- *What role do habitat surveys play in analyzing the biological condition of the stream corridor?*
- *How do you measure biological diversity in a stream corridor?*
- *What is the role of stream classification systems in analyzing stream corridor conditions?*
- *How can models be used to evaluate the biological condition of a stream corridor?*
- *What are the characteristics of models that have been used to evaluate stream corridor conditions?*

Table I.1 (continued)

Chapter 8: Restoration Design

8.A Valley Form, Connectivity, and Dimension

- *How do you incorporate all the spatial dimensions of the landscape into stream corridor restoration design?*
- *What criteria can be applied to facilitate good design decisions for stream corridor restoration?*

8.B Soil Properties

- *How do soil properties impact the design of restoration activities?*
- *What are the major functions of soils in the stream corridor?*
- *How are important soil characteristics, such as soil microfauna and soil salinity, accounted for in the design process?*

8.C Plant Communities

- *What is the role of vegetative communities in stream corridor restoration?*
- *What functions do vegetative communities fulfill in a stream corridor?*
- *What are some considerations in designing plant community restoration to ensure that all landscape functions are addressed?*
- *What is soil bioengineering and what is its role in stream corridor restoration?*

8.D Habitat Measures

- *What are some specific tools and techniques that can be used to ensure recovery of riparian and terrestrial habitat recovery?*

8.E Stream Channel Restoration

- *When is stream channel reconstruction an appropriate restoration option?*
- *How do you delineate the stream reach to be reconstructed?*
- *How is a stream channel designed and reconstructed?*
- *What are important factors to consider in the design of channel reconstruction (e.g., alignment and average slope, channel dimensions)?*
- *Are there computer models that can assist with the design of channel reconstruction?*

8.F Streambank Restoration

- *When should streambank stabilization be included in a restoration?*
- *How do you determine the performance criteria for streambank treatment, including the methods and materials to be used?*
- *What are some streambank stabilization techniques that can be considered for use?*

8.G Instream Habitat Recovery

- *What are the principal factors controlling the quality of instream habitat?*
- *How do you determine if an instream habitat structure is needed, and what type of structure is most appropriate?*
- *What procedures can be used to restore instream habitat?*
- *What are some examples of instream habitat structures?*
- *What are some important questions to address before designing, selecting, or installing an instream habitat structure?*

8.H Land Use Scenarios

- *What role does land use play in stream corridor degradation and restoration?*
- *What design approaches can be used to address the impacts of various land uses (e.g., dams, agriculture, forestry, grazing, mining, recreation, urbanization)?*
- *What are some disturbances that are often associated with specific land uses?*
- *What restoration measures can be used to mitigate the impacts of various land uses?*
- *What are the potential effects of the restoration measures?*

Chapter 9: Restoration Implementation, Monitoring, and Management

9.A Restoration Implementation

- *What are passive forms of restoration and how are they "implemented"?*
- *What happens after the decision is made to proceed with an active rather than a passive restoration approach?*
- *What type of activities are involved when installing restoration measures?*
- *How can impact on the stream channel and corridor be minimized when installing restoration measures (e.g., water quality, air quality, cultural resources, noise)?*
- *What types of equipment are needed for installing restoration measures?*
- *What are some important considerations regarding construction activities in the stream corridor?*
- *How do you inspect and evaluate the quality and impact of construction activities in the stream corridor?*
- *What types of maintenance measures are necessary to ensure the ongoing success of a restoration?*

9.B Monitoring Techniques Appropriate for Evaluating Restoration

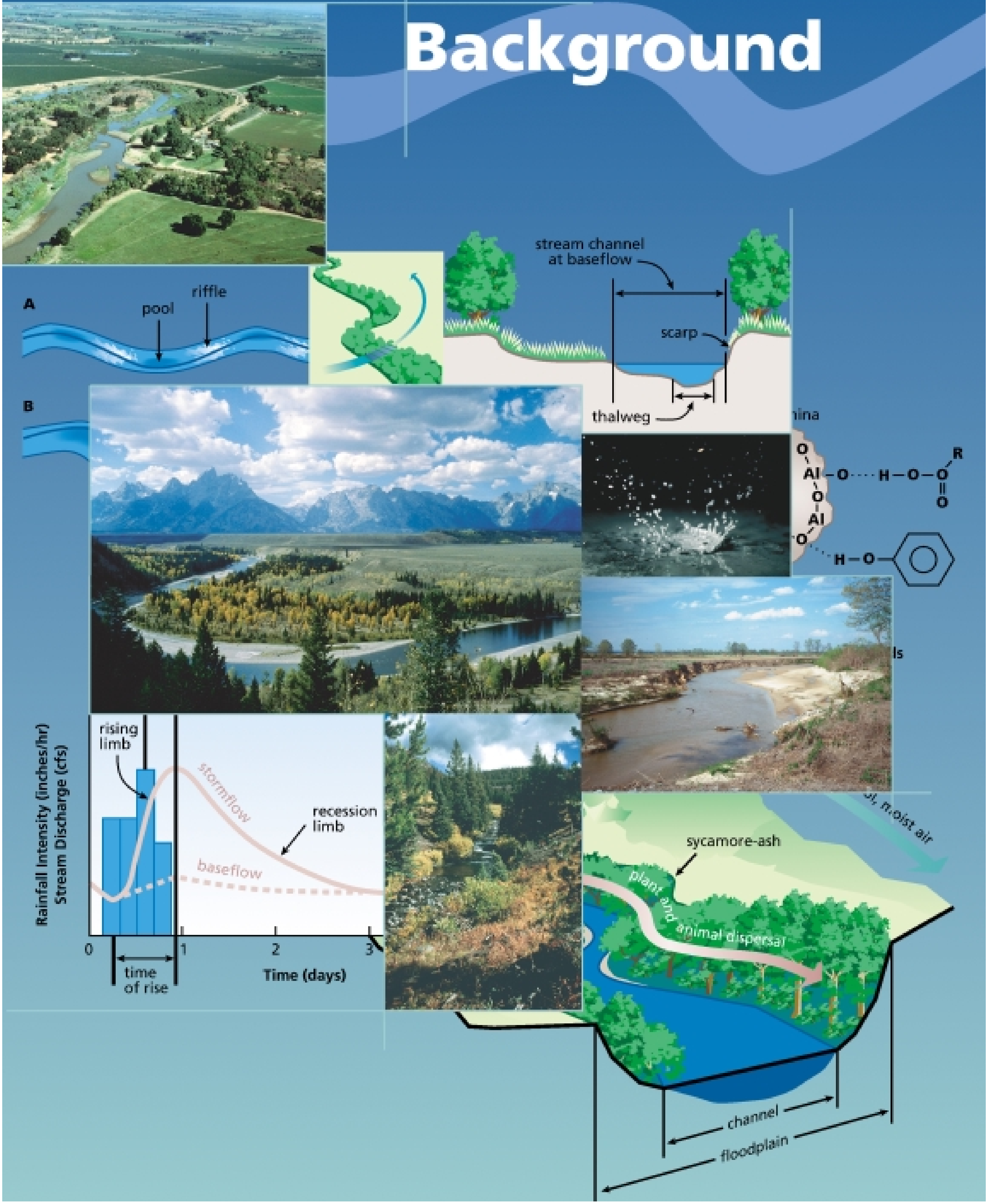
- *What methods are available for monitoring biological attributes of streams?*
- *What can assessment of biological attributes tell you about the status of the stream restoration?*
- *What physical parameters should be included in a monitoring management plan?*
- *How are the physical aspects of the stream corridor evaluated?*
- *How is a restoration monitoring plan developed, and what issues should be addressed in the plan?*
- *What are the sampling plan design issues that must be addressed to adequately detect trends in stream corridor conditions?*
- *How do you ensure that the monitoring information is properly collected, analyzed, and assessed (i.e., quality assurance plans)?*

9.C Restoration Management

- *What are important management priorities with ongoing activities and resource uses within the stream corridor?*
- *What are some management decisions that can be made to support stream restoration?*
- *What are some example impacts and management options with various types of resource use within the stream corridor (e.g., forest management, grazing, mining, fish and wildlife, urbanization)?*
- *When is restoration complete?*

Part I

Background

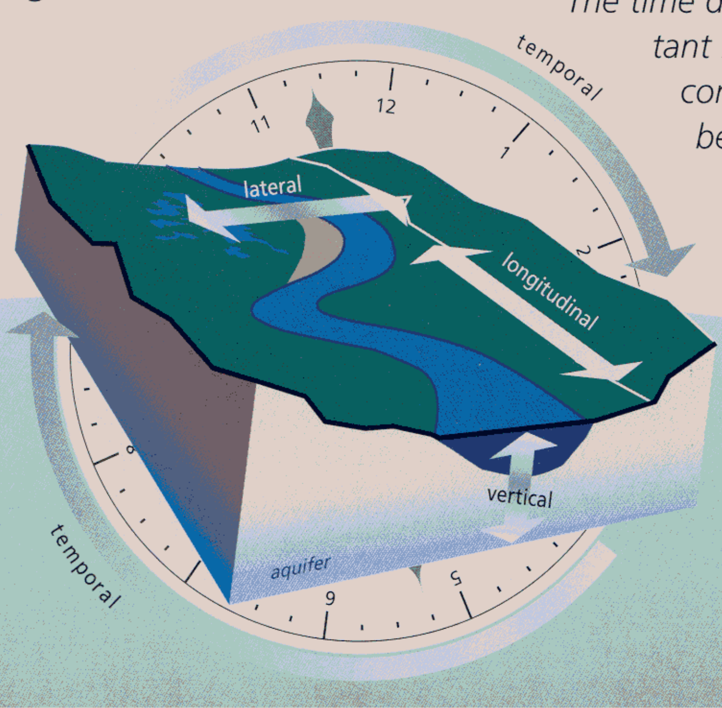


Background

The purpose of Part I is to provide background on fundamental concepts necessary for planning and designing stream corridor restoration. Ward (1989) described relationships that occur in the stream corridor using a four-dimensional framework (see figure below). This framework serves as a good starting point for examining stream corridors.

Untrained observers typically focus on only the longitudinal dimension of the framework—the stream as it flows from headwaters to mouth. This perspective is limited, however, because lateral and vertical movements of water, materials, energy, and organisms also influence the character of the stream corridor.

The time dimension is also critically important because stream corridors are constantly changing. Changes can be detected in any number of time frames—from minutes to millennia. A challenge for restoration practitioners,

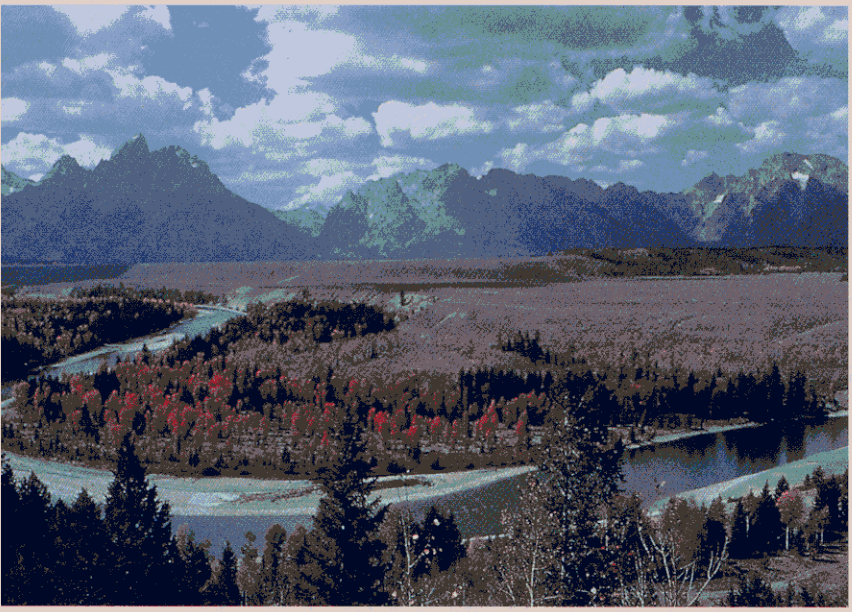


Dimensions of the stream corridor. A four-dimensional framework serves as a good starting point for examining stream corridors.

therefore, is to view time as well as space in the stream corridor.

The physical structure of the stream corridor is formed by the movement of water, materials, energy, and organisms within this multidimensional framework. As movement affects structure, so too does structure affect movement. This natural feedback loop helps to create a state of balance within the stream corridor known as dynamic equilibrium, which allows the corridor to accommodate limited change while maintaining its essential structure and functions.

Disturbances that affect stream corridors can be natural or human-induced. If they are severe enough, they can alter the structure and functions of a stream corridor to a point that dynamic equilibrium is disrupted. Restoration can then be employed to try to reestablish structure and functions so natural dynamic equilibrium can once again occur.



The care of the rivers is not a question of the rivers but of the human heart.

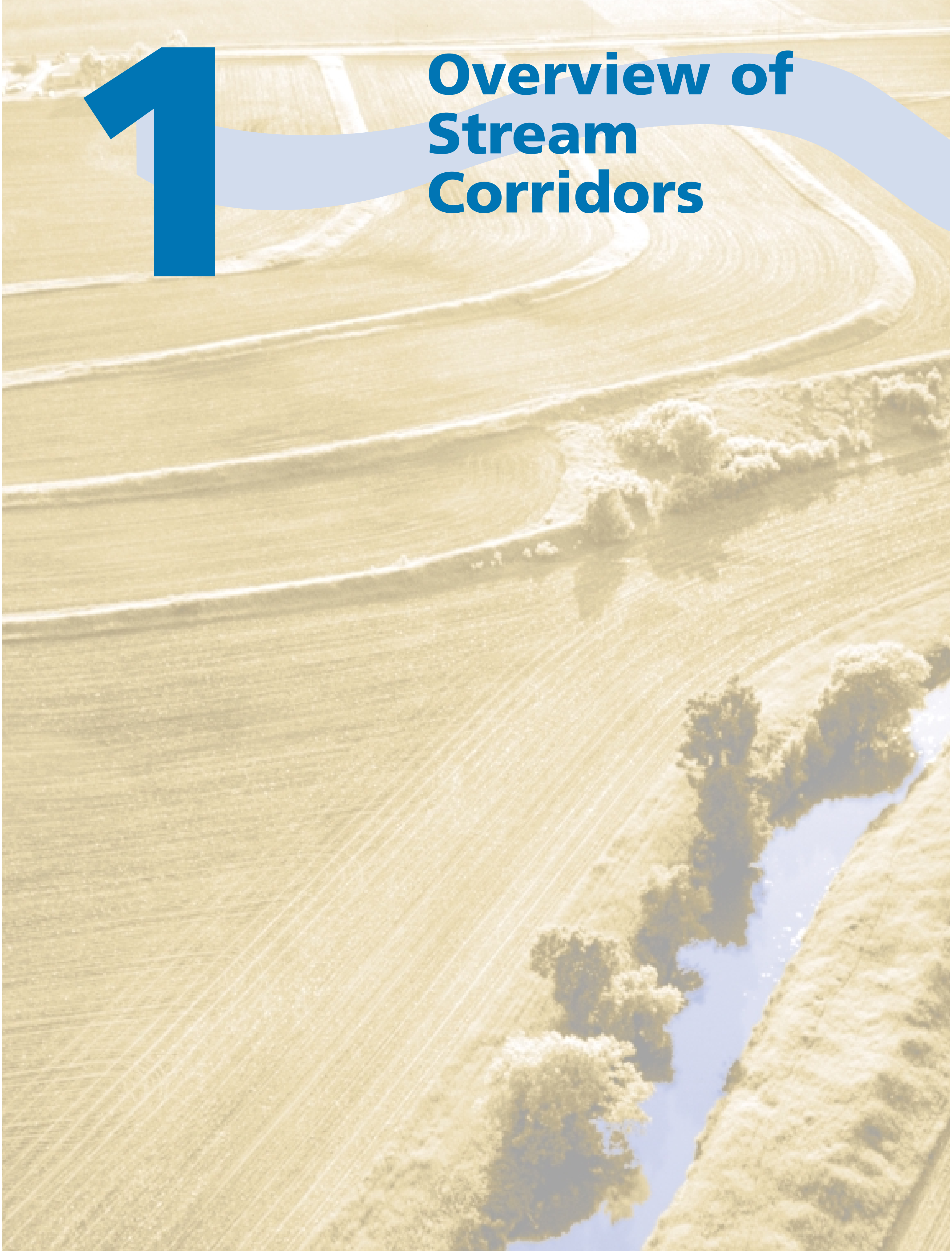
—Tanaka Shozo

Part I is composed of three chapters:

- ***Chapter 1*** *defines the components of the stream corridor and introduces the concepts of scale and structure. With these concepts in mind, structural elements within the stream corridor are examined first in the lateral and then in the longitudinal dimensions.*
- ***Chapter 2*** *presents information on the hydrologic and geomorphic processes that help build structure in the stream corridor. Also addressed are the chemical and biological characteristics that make a stream corridor unique in the landscape. The chapter concludes with a discussion of the six critical functions of the stream corridor ecosystem and introduces the concept of dynamic equilibrium.*
- ***Chapter 3*** *summarizes the range of disturbances that can stress the stream corridor ecosystem, impact dynamic equilibrium, and impair the corridor's ability to perform critical functions. Both natural and human-induced disturbances are discussed with a special emphasis on land use activities.*

The background information presented in Part I will be applied both in restoration planning (Part II) and plan implementation (Part III).

1 Overview of Stream Corridors



1.A Overview of Structure and Scale

- *What are the structural components of a stream corridor?*
- *Why are stream corridors of special significance, and why should they be the focus of restoration efforts?*
- *What is the relationship between stream corridors and other landscape units at broader and more local scales?*
- *What scales should be considered for a stream corridor restoration?*

1.B Stream Corridor Functions and Dynamic Equilibrium

- *How is a stream corridor structured from side to side?*
- *How do these elements contribute to stream corridor functions?*
- *What role do these elements play in the life of the stream?*
- *What do we need to know about the lateral elements of a stream corridor to adequately characterize a stream corridor for restoration?*
- *How are the lateral elements of a stream corridor used to define flow patterns of a stream?*

1.C A Longitudinal View Along the Stream Corridor

- *What are the longitudinal structural elements of a stream corridor?*
- *How are these elements used to characterize a stream corridor?*
- *What are some of the basic ecological concepts that can be applied to streams to understand their function and characteristics on a longitudinal scale?*
- *What do we need to know about the longitudinal elements that are important to stream corridor restoration?*

1 Overview of Stream Corridors

A stream corridor is an ecosystem that usually consists of three major elements:

- *Stream channel*
- *Floodplain*
- *Transitional upland fringe*

Together they function as dynamic and valued crossroads in the landscape. (**Figure 1.1**)*. Water and other materials, energy, and organisms meet and interact within the stream corridor over space and time. This movement provides critical functions essential for maintaining life such as cycling nutrients, filtering contaminants from runoff, absorbing and gradually releasing floodwaters, maintaining fish and wildlife habitats, recharging ground water, and maintaining stream flows.*

The purpose of this chapter is to define the components of the stream corridor and introduce the concepts of scale and structure. The chapter is divided into three subsections.

Figure 1.1: Stream corridors function as dynamic crossroads in the landscape. *Water and other materials, energy, and organisms meet and interact within the corridor.*

Section 1.A: Physical Structure and Time at Multiple Scales

An important initial task is to identify the spatial and time scales most appropriate for planning and designing restoration. This subsection introduces elements of structure used in landscape ecology and relates them to a hierarchy of spacial scales ranging from broad to local. The importance of integrating time scales into the restoration process is also discussed.

Section 1.B: A Lateral View Across the Stream Corridor

The purpose of this and the following subsection is to introduce the types of structure found within stream corridors. The focus here is on the lateral dimension of structure, which affects the movement of water, materials, energy, and organisms from upland areas into the stream channel.

Section 1.C: A Longitudinal View Along the Stream Corridor

This section takes a longitudinal view of structure, specifically as a stream travels down the valley from headwaters to mouth. It includes discussions of channel form, sediment transport and deposition, and how biological communities have adapted to different stages of the river continuum.

1.A Physical Structure and Time at Multiple Scales

A hierarchy of five *spatial scales*, which range from broad to local, is displayed in **Figure 1.2**. Each element within the scales can be viewed as an ecosystem with links to other ecosystems. These linkages are what make an ecosystem's external environment as important to proper functioning as its internal environment (Odum 1989).

Landscapes and stream corridors are ecosystems that occur at different spatial scales. Examining them as ecosystems is useful in explaining the basics of how landscapes, watersheds, stream corridors, and streams function. Many common ecosystem functions involve movement of materials (e.g., sediment and storm water runoff), energy (e.g., heating and cooling of stream waters), and organisms (e.g., movement of mammals, fish schooling, and insect swarming) between the internal and external environments (**Figure 1.3**).

The internal/external movement model becomes more complex when one considers that the external environment of a given ecosystem is a larger ecosystem. A stream ecosystem, for example, has an input/output relationship with the next higher scale, the stream corridor. This scale, in turn, interacts with the landscape scale, and so on up the hierarchy.

Similarly, because each larger-scale ecosystem contains the one beneath it, the structure and functions of the smaller ecosystem are at least part of the structure and functions of the larger. Furthermore, what is not part of the smaller ecosystem might be related to it through input or output relationships with neighboring ecosystems. Investigating relationships between structure and scale is a key first step for planning and designing stream corridor restoration.

Physical Structure

Landscape ecologists use four basic terms to define spatial structure at a particular scale (**Figure 1.4**):

- *Matrix*, the land cover that is dominant and interconnected over the majority of the land surface. Often the matrix is forest or agriculture, but theoretically it can be any land cover type.
- *Patch*, a nonlinear area (polygon) that is less abundant than, and different from, the matrix.
- *Corridor*, a special type of patch that links other patches in the matrix. Typically, a corridor is linear or elongated in shape, such as a stream corridor.
- *Mosaic*, a collection of patches, none of which are dominant enough to be interconnected throughout the landscape.

These simple structural element concepts are repeated at different spatial scales. The size of the area and the spatial resolution of one's observations determine what structural elements one is observing. For example, at the landscape scale one might see a matrix of mature forest with patches of cropland, pasture, clear-cuts, lakes, and wetlands. Looking more closely at a smaller area, one might consider an open woodland to be a series of tree crowns (the patches) against a matrix of grassy ground cover.

On a reach scale, a trout might perceive pools and well-sheltered, cool, pockets of water as preferred patches in a matrix of less desirable shallows and riffles, and the corridor along an undercut streambank might be its only way to travel safely among these habitat patches.

FAST FORWARD

Preview Chapter 2, Section E for a discussion of the six critical functions performed by stream corridor ecosystems.

Landscapes, watersheds, stream corridors, and streams are ecosystems that occur at different spatial scales.

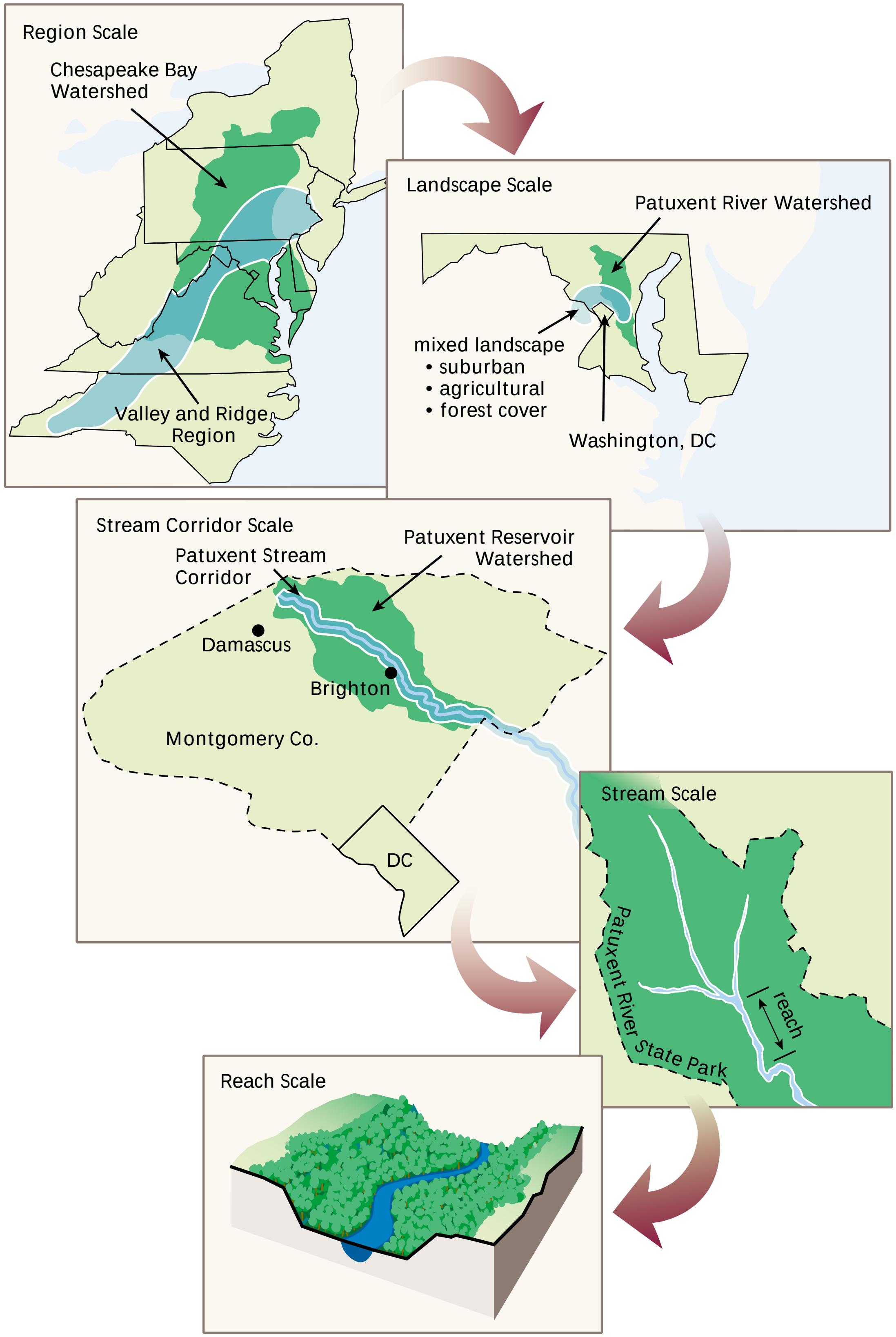


Figure 1.2: Ecosystems at multiple scales.
Stream corridor restoration can occur at any scale, from regional to reach.

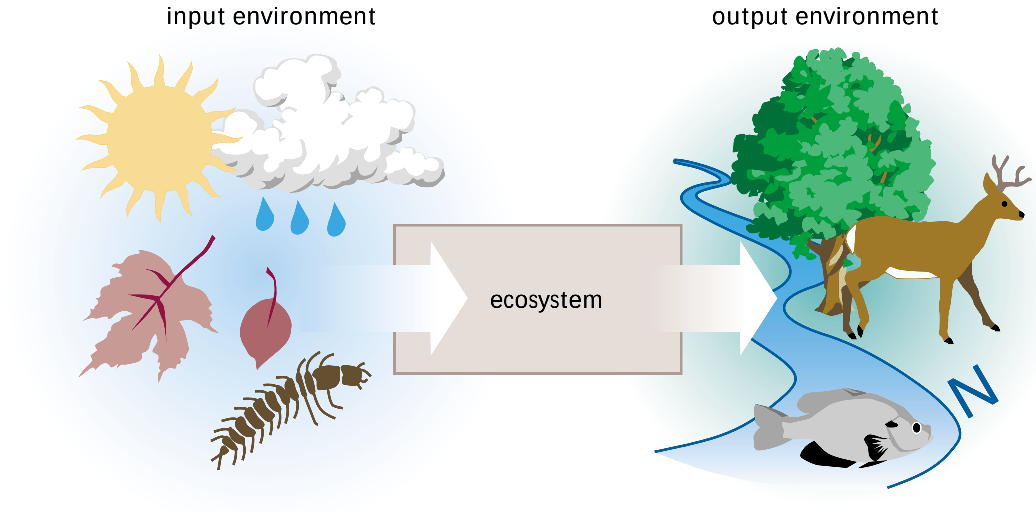


Figure 1.3: A simple ecosystem model. *Materials, energy, and organisms move from an external input environment, through the ecosystem, and into an external output environment.*

At the other extreme, the coarsest of the imaging satellites that monitor the earth's surface might detect only patches or corridors of tens of square miles in area, and matrices that seem to dominate a whole region. At all levels, the matrix-patch-corridor-mosaic model provides a useful common denominator for describing structure in the environment.

Figure 1.5 displays examples of the matrices, patches, and corridors at broad and local scales. Practitioners should always consider multiple scales when planning and designing restoration.

Structure at Scales Broader Than the Stream Corridor Scale

The landscape scale encompasses the stream corridor scale. In turn, the landscape scale is encompassed by the larger regional scale. Each scale within the hierarchy has its own characteristic structure.

The "watershed scale" is another form of spatial scale that can also encompass the stream corridor. Although watersheds occur at all scales, the term "watershed scale" is commonly used by many practitioners because many functions of the stream corridor are closely tied to drainage patterns. For this reason, the "watershed scale" is included in this discussion.

Landscape ecologists use four basic terms to define spatial structure at a particular scale—matrix, patch, corridor, and mosaic.

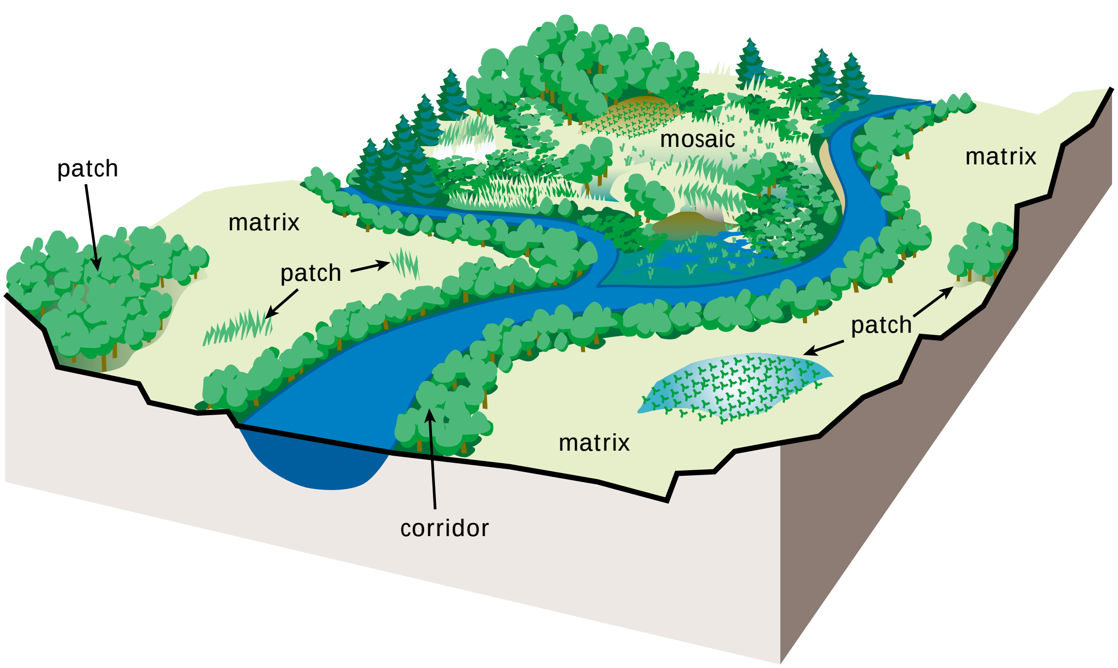
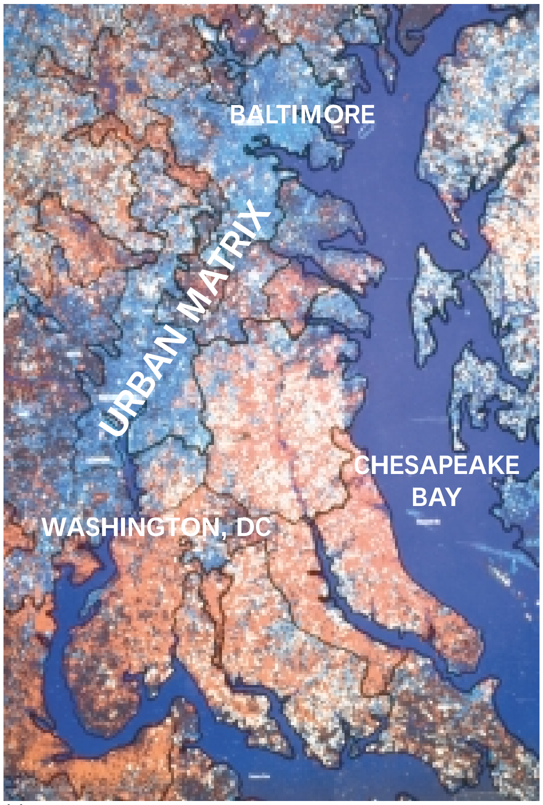


Figure 1.4: Spatial structure. *Landscapes can be described in terms of matrix, patch, corridor, and mosaic at various scales.*



(a)

(b)

Figure 1.5: Spatial structure at (a) broad and (b) local scales. *Patches, corridors, and matrices are visible at the broad regional scale and the local reach scale.*

Regional Scale

A *region* is a broad geographical area with a common macroclimate and sphere of human activities and interests (Forman 1995). The spatial elements found at the regional scale are called landscapes. **Figure 1.6** includes an example of the New England region with landscapes defined both by natural cover and by land use.

Practitioners should always consider multiple scales when planning and designing restoration.

Matrices in the United States include:

- Deserts and arid grasslands of the arid Southwest.
- Forests of the Appalachian Mountains.
- Agricultural zones of the Midwest.

At the regional scale, patches generally include:

- Major lakes (e.g., the Great Lakes).
- Major wetlands (e.g., the Everglades).
- Major forested areas (e.g., redwood forests in the Pacific Northwest).
- Major metropolitan zones (e.g., the Baltimore-Washington, DC, metropolitan area).
- Major land use areas such as agriculture (e.g., the Corn Belt).

Corridors might include:

- Mountain ranges.
- Major river valleys.
- Interregional development along a major transportation corridor.

Most practitioners of stream corridor restoration do not usually plan and design restoration at the regional scale. The perspective is simply too broad for most projects. Regional scale is introduced here because it encompasses the scale very pertinent to stream corridor restoration—the landscape scale.

Landscape Scale

A *landscape* is a geographic area distinguished by a repeated pattern of components, which include both natural communities like forest patches and wetlands and human-altered areas like croplands and villages. Landscapes can vary in size from a few to several thousand square miles.

At the landscape scale, patches (e.g., wetlands and lakes) and corridors (e.g., stream corridors) are usually described as ecosystems. The matrix is usually identified in terms of the predominant natural vegetation community (e.g., prairie-type, forest-type, and wetland-type) or land-use-dominated ecosystem (e.g., agriculture and urban) (**Figure 1.7**).

Landscapes differ from one another based on the consistent pattern formed by their structural elements, and the predominant land cover that comprises their patches, corridors, and matrices.

Examples of landscapes in the United States include:

- A highly fragmented east coast mosaic of suburban, forest, and agricultural patches.
- A north-central agricultural matrix with pothole wetlands and forest patches.
- A Sonoran desert matrix with willow-cottonwood corridors.
- A densely forested Pacific Northwest matrix with a pattern of clear-cut patches.

A landscape is a geographic area distinguished by a repeated pattern of components, which include both natural communities like forest patches and wetlands and human-altered areas like croplands and villages.

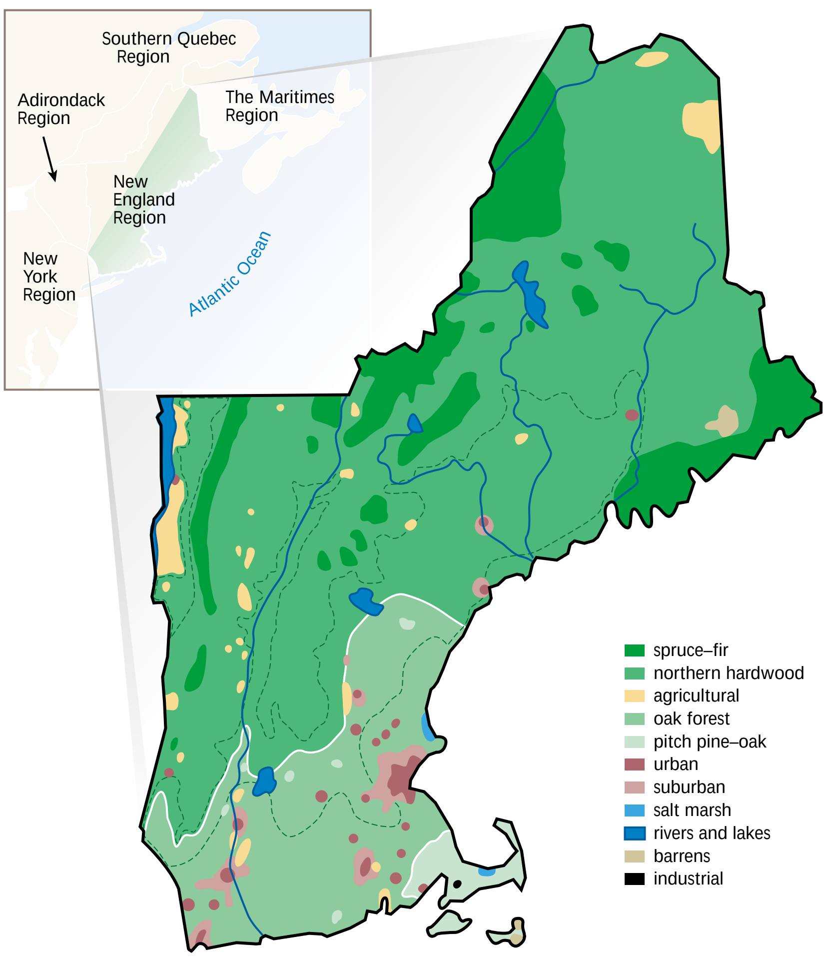


***Figure 1.6**: The New England region. Structure in a region is typically a function of natural cover and land use.*
Source: Forman (1995). Reprinted with the permission of Cambridge University Press.

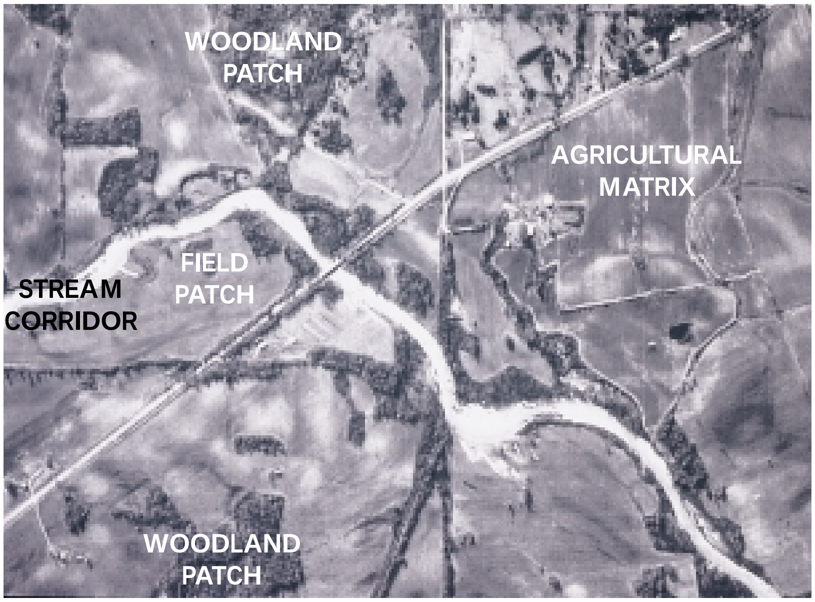


Figure 1.7: Structure at the landscape scale. *Patches and corridors are visible within an agricultural matrix.*

A woodlot within an agricultural matrix and a wetland in an urban matrix are examples of patches at the landscape scale. Corridors at this scale include ridgelines, highways, and the topic of this document—stream corridors.

At the landscape scale it is easy to perceive the stream corridor as an ecosystem with an internal environment and external environment (its surrounding landscape). Corridors play an important role at the landscape scale and at other scales. Recall that a key attribute of ecosystems is the movement of energy, materials, and organisms in, through, and out of the system. Corridors typically serve as a primary pathway for this movement. They connect patches and function as conduits between ecosystems and their external environment. Stream corridors in particular provide a heightened level of functions because of the materials and organisms found in this type of landscape linkage.

A more complete broad scale perspective of the stream corridor is achieved when watershed science is combined with landscape ecology.

Spatial structure, especially in corridors, helps dictate movement in, through, and out of the ecosystem; conversely, this movement also serves to change the structure over time. Spatial structure, as it appears at any one point in time, is therefore the end result of movement that has occurred in the past. Understanding this feedback loop between movement and structure is a key to working with ecosystems in any scale.

"Watershed Scale"

Much of the movement of material, energy, and organisms between the stream corridor and its external environments is dependent on the movement of water. Consequently, the watershed concept is a key factor for planning and designing stream corridor restoration. The term "scale," however, is incorrectly applied to watersheds.

A *watershed* is defined as an area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel (Dunne and Leopold 1978). Watersheds, therefore, occur at multiple scales. They range from the largest river basins, such as the watersheds of the Mississippi, Missouri, and Columbia, to the watersheds of very small streams that measure only a few acres in size.

The term "watershed scale" (singular) is a misnomer because watersheds occur at a very wide range of scales. This document focuses primarily on the watersheds of small to medium-scale streams and rivers. Watersheds in this size range can contain all or part of a few different landscapes or can be entirely encompassed by a larger landscape.

Ecological structure within watersheds can still be described in matrix, patch, corridor, and mosaic terms, but a discussion of watershed structure is more meaningful if it also focuses on elements such as upper, middle, and lower watershed zones; drainage divides; upper and lower hillslopes; terraces, floodplains, and deltas; and features within the channel. These elements and their related functions are discussed in sections B and C of this chapter.

In short, watersheds and landscapes overlap in size range and are defined by different environmental processes. Whereas the landscape is defined primarily by terrestrial patterns of land cover that may continue across drainage divides to where the consistent pattern ends, the watershed's boundaries are based on the drainage divides themselves. Moreover, the ecological processes occurring in watersheds are more closely linked to the presence and movement of water; therefore as functioning ecosystems, watersheds also differ from landscapes.

The difference between landscape scale and "watershed scale" is precisely why practitioners should consider both when planning and designing stream corridor restoration. For decades the watershed has served as the geographic unit of choice because it requires consideration of hydrologic and geomorphic processes associated with the movement of materials, energy, and organisms into, out of, and through the stream corridor.

The exclusive use of watersheds for the broad-scale perspective of stream corridors, however, ignores the materials, energy, and organisms that move across and through landscapes independent of water drainage. Therefore, a more complete broad-scale perspective of the stream corridor is achieved when watershed science is combined with landscape ecology.

Hydrologic Unit Cataloging and Reach File/National Hydrography Dataset

The USGS developed a national framework for cataloging watersheds of different geographical scales. Each level, or scale, in the hierarchy is designated using the hydrologic unit cataloging (HUC) system. At the national level this system involves an eight-digit code that uniquely identifies four levels of classification.

The largest unit in the USGS HUC system is the water resource region. Regions are designated by the first two digits of the code. The remaining numbers are used to further define subwatersheds within the region down to the smallest scale called the cataloging unit. For example, 10240006 is the hydrologic unit code for the Little Nemaha River in Nebraska. The code is broken down as follows:

10	*Region*
1024	*Subregion*
102400	*Accounting code*
10240006	*Cataloging unit*

There are 21 regions, 222 subregions, 352 accounting units, and 2,150 cataloging units in the United States. The USGS's Hydrologic Unit Map Series documents these hierarchical watershed boundaries for each state. Some state and federal agencies have taken the restoration initiative to subdivide the cataloging unit into even smaller watersheds, extending the HUC code to 11 or 14 digits.

The Reach File/National Hydrography Dataset (RF/NHD) is a computerized database of streams, rivers, and other water bodies in the United States. It is cross-referenced with the HUC system in a geographic information system (GIS) format so users can easily identify both watersheds and the streams contained within their boundaries.

Structure at the Stream Corridor Scale

The stream corridor is a spatial element (a corridor) at the watershed and landscape scales. But as a part of the hierarchy, it has its own set of structural elements (**Figure 1.8**). Riparian (streamside) forest or shrub cover is a common matrix in stream corridors. In other areas, herbaceous vegetation might dominate a stream corridor.

Examples of patches at the stream corridor scale include both natural and human features such as:

- Wetlands.
- Forest, shrubland, or grassland patches.
- Oxbow lakes.
- Residential or commercial development.
- Islands in the channel.
- Passive recreation areas such as picnic grounds.

Figure 1.8: Structural elements at a stream corridor scale. *Patches, corridors, and matrix are visible within the stream corridor.*

Corridors at the stream corridor scale include two important elements—the stream channel and the plant community on either side of the stream. Other examples of corridors at this scale might include:

- Streambanks
- Floodplains
- Feeder (tributary) streams
- Trails and roads

Structure Within the Stream Corridor Scale

At the stream scale, patches, corridors, and the background matrix are defined within and near the channel and include elements of the stream itself and its low floodplains (**Figure 1.9**). At the next lower scale, the stream itself is segmented into reaches.

Reaches can be distinguished in a number of ways. Sometimes they are defined by characteristics associated with flow. High-velocity flow with rapids is obviously separable from areas with slower flow and deep, quiet pools. In other instances practitioners find it useful to define reaches based on chemical or biological factors, tributary confluences, or by some human influence that makes one part of a stream different from the next.

Examples of patches at the stream and reach scales might include:

- Riffles and pools
- Woody debris
- Aquatic plant beds
- Islands and point bars

Examples of corridors might include:

- Protected areas beneath overhanging banks.

- The thalweg, the "channel within the channel" that carries water during low-flow conditions.
- Lengths of stream defined by physical, chemical, and biological similarities or differences.
- Lengths of stream defined by human-imposed boundaries such as political borders or breaks in land use or ownership.

Temporal Scale

The final scale concept critical for the planning and design of stream corridor restoration is time.

In a sense, temporal hierarchy parallels spatial hierarchy. Just as global or regional spatial scales are usually too large to be relevant for most restoration initiatives, planning and designing restoration for broad scales of time is not usually practical. Geomorphic or climatic changes, for example, usually occur over centuries to millions of years. The goals of restoration efforts, by comparison, are usually described in time frames of years to decades.

Land use change in the watershed, for example, is one of many factors that can cause disturbances in the stream corridor. It occurs on many time scales, however, from a single year (e.g., crop rotation), to decades (e.g., urbanization), to centuries (e.g., long-term forest management). Thus, it is critical for the practitioner to consider a relevant range of time scales when involving land use issues in restoration planning and design.

Flooding is another natural process that varies both in space and through time. Spring runoff is cyclical and therefore fairly predictable. Large, hurricane-induced floods that inundate lands far beyond the channel are neither cyclical nor predictable, but still should be

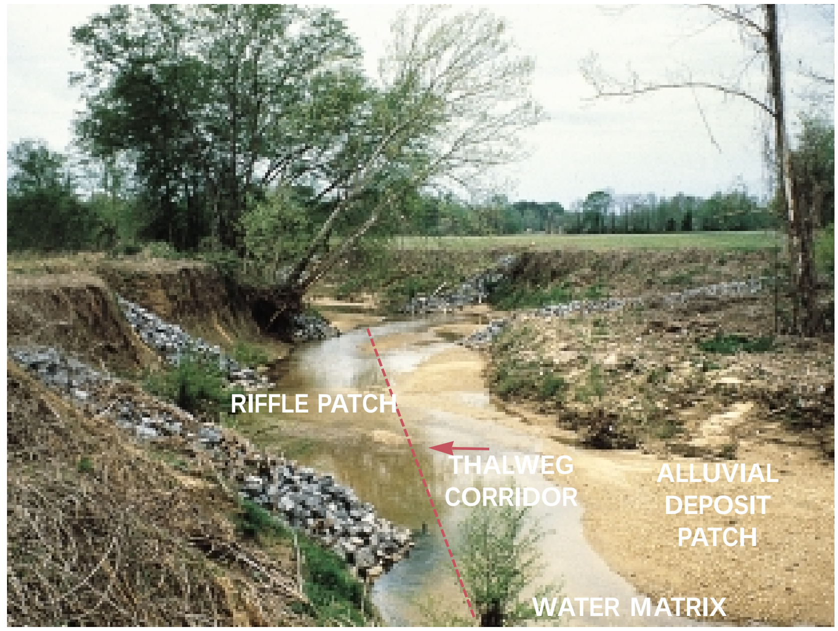


Figure 1.9: Structural elements at a stream scale. *Patches, corridors, and matrix are visible within the stream.*

planned for in restoration designs. Flood specialists rank the extent of floods in temporal terms such as 10-year, 100-year, and 500-year events (10%, 1%, 0.2% chance of recurrence. See Chapter 7 *Flow Frequency Analysis* for more details.). These can serve as guidance for planning and designing restoration when flooding is an issue.

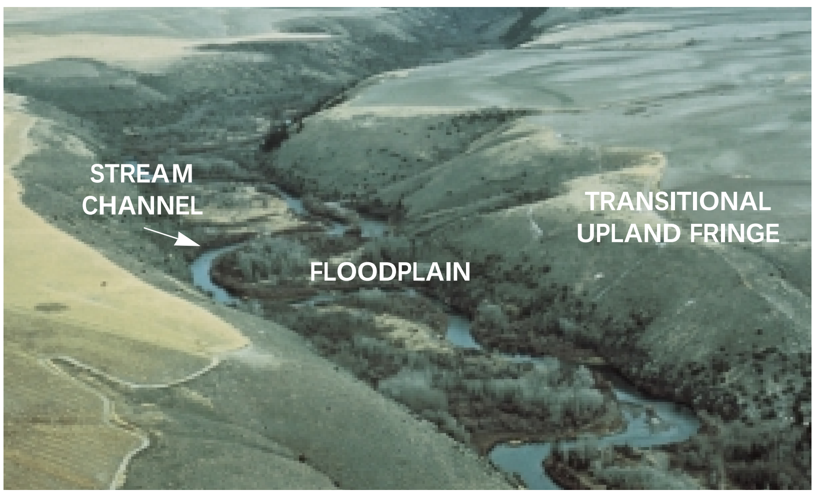
Practitioners of stream corridor restoration may need to simultaneously plan in multiple time scales. If an instream structure is planned, for example, care might be taken that (1) installation does not occur during a critical spawning period (a short-term consideration) and (2) the structure can withstand a 100-year flood (a long-term consideration). The practitioner should never try to freeze conditions as they are, at the completion of the restoration. Stream corridor restoration that works with the dynamic behavior of the stream ecosystem will more likely survive the test of time.

Stream corridor restoration that works with the dynamic behavior of the stream ecosystem will more likely survive the test of time.

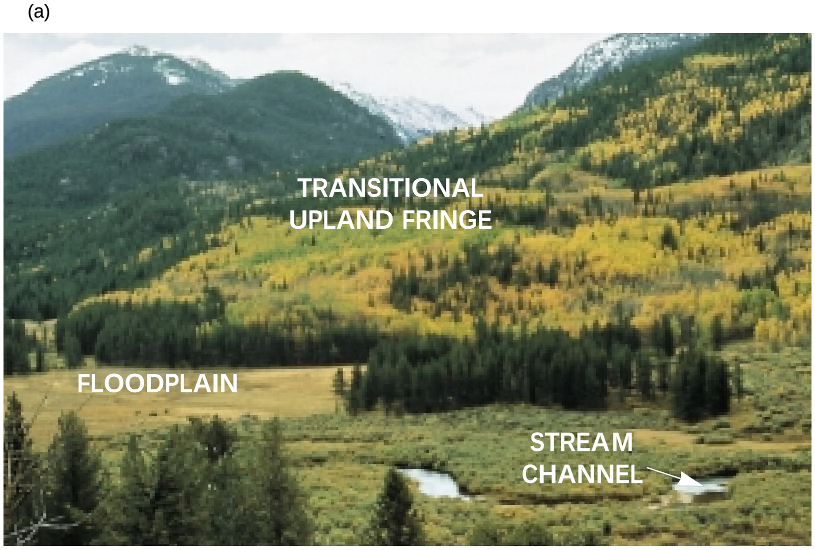
1.B A Lateral View Across the Stream Corridor

The previous section described how the matrix-patch-corridor-mosaic model can be applied at multiple scales to examine the relationships between the stream corridor and its external environments. This section takes a closer look at physical structure in the stream corridor itself. In particular, this section focuses on the lateral dimension. In cross section, most stream corridors have three major components (**Figure 1.10**):

- *Stream channel*, a channel with flowing water at least part of the year.
- *Floodplain*, a highly variable area on one or both sides of the stream channel that is inundated by floodwaters at some interval, from frequent to rare.
- *Transitional upland fringe*, a portion of the upland on one or both sides of the floodplain that serves as a transitional zone or edge between the floodplain and the surrounding landscape.



(a)



(b)

Figure 1.10: The three major components of a stream corridor in different settings (a) and (b). *Even though specific features might differ by region, most stream corridors have a channel, floodplain, and transitional upland fringe.*

Some common features found in the river corridor are displayed in **Figure 1.11**. In this example the floodplain is seasonally inundated and includes features such as floodplain forest, emergent marshes and wet meadows. The transitional upland fringe includes an upland forest and a hill prairie. Landforms such as natural levees, are created by processes of erosion and sedimentation, primarily during floods. The various plant communities possess unique moisture tolerances and requirements and consequently occupy distinct landforms.

Each of the three main lateral components is described in the following subsections.

Stream Channel

Nearly all channels are formed, maintained, and altered by the water and sediment they carry. Usually they are gently rounded in shape and roughly parabolic, but form can vary greatly.

Figure 1.12 presents a cross section of a typical stream channel. The sloped bank is called a *scarp*. The deepest part of the channel is called the *thalweg*. The dimensions of a channel cross section define the amount of water that can

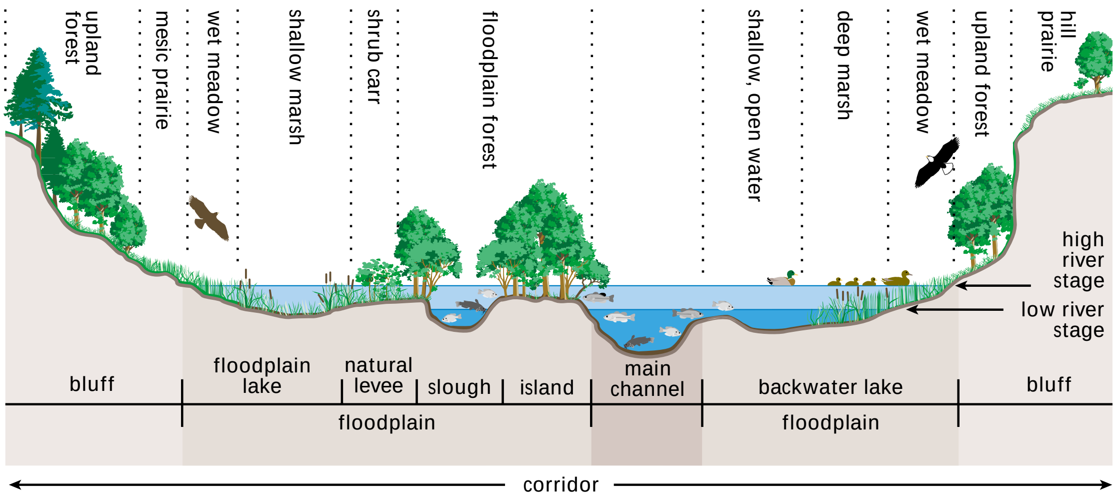


Figure 1.11: A cross section of a river corridor. *The three main components of the river corridor can be subdivided by structural features and plant communities. (Vertical scale and channel width are greatly exaggerated.)*

Source: Sparks, Bioscience, vol. 45, p. 170, March 1995. ©1995 American Institute of Biological Science.

pass through without spilling over the banks. Two attributes of the channel are of particular interest to practitioners, channel equilibrium and streamflow.

Lane's Alluvial Channel Equilibrium

Channel equilibirum involves the interplay of four basic factors:

- Sediment discharge (Q_s)
- Sediment particle size (D_{50})
- Streamflow (Q_w)
- Stream slope (S)

Lane (1955) showed this relationship qualitatively as:

$$Q_s \cdot D_{50} \propto Q_w \cdot S$$

This equation is shown here as a balance with sediment load on one weighing pan and streamflow on the other (**Figure 1.13**). The hook holding the sediment pan can slide along the horizontal arm according to sediment size. The hook holding the streamflow side slides according to stream slope.

Channel equilibrium occurs when all four variables are in balance. If a change occurs, the balance will temporarily be tipped and equilibrium lost. If one variable changes, one or more of the other variables must increase or decrease proportionally if equilibrium is to be maintained. For example, if slope is increased and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased (e.g., by an interbasin transfer) and the slope stays the same, sediment load or sediment particle size has to increase to maintain channel equilibrium. A stream seeking a new equilibrium tends to erode more sediment and of larger particle size.

Alluvial streams that are free to adjust to changes in these four variables generally do so and reestablish new equilibrium conditions. Non-alluvial streams such as bedrock or artificial, concrete channels are unable to follow Lane's relationship because of their inability to

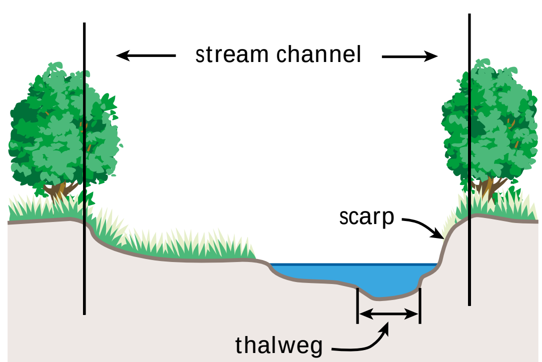


Figure 1.12: Cross section of a stream channel. *The scarp is the sloped bank and the thalweg is the lowest part of the channel.*

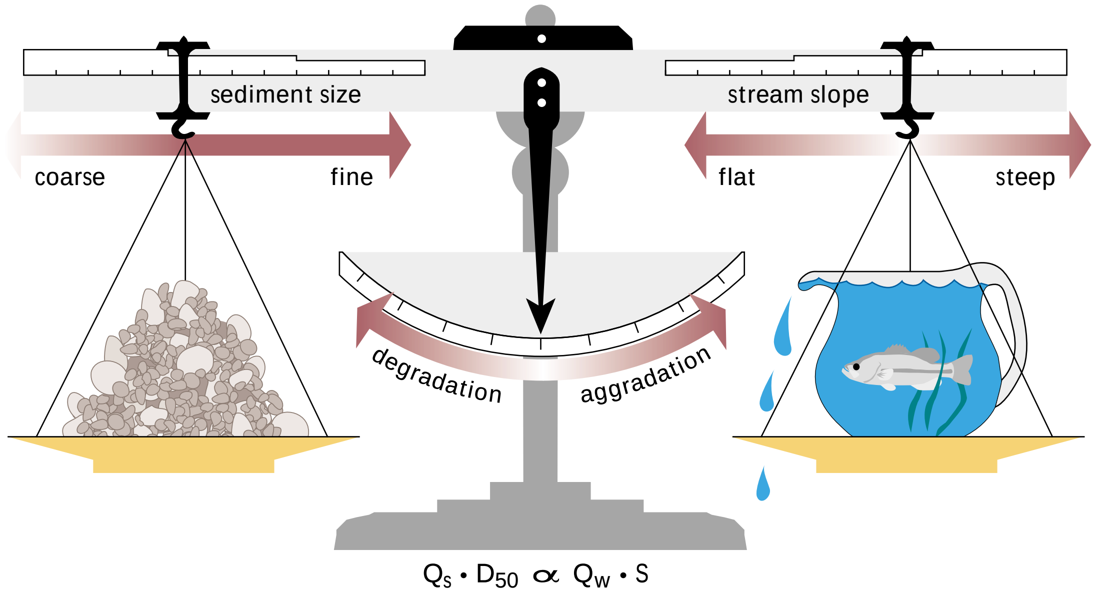


Figure 1.13: Factors affecting channel equilibrium. *At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.*

Source: Rosgen (1996), from Lane, ***Proceedings***, 1955. Published with the permission of American Society of Civil Engineers.

FAST FORWARD

Preview Chapter 2, Section B for more discussion on the stream balance equation. Preview Chapter 7, Section B for nformation on measuring and analyzing these variables and the use of sediment transport equations.

adjust the sediment size and quantity variables.

The stream balance equation is useful for making qualitative predictions concerning channel impacts due to changes in runoff or sediment loads from the watershed. Quantitative predictions, however, require the use of more complex equations.

Sediment transport equations, for example, are used to compare sediment load and energy in the stream. If excess energy is left over after the load is moved, channel adjustment occurs as the stream picks up more load by eroding its banks or scouring its bed. No matter how much complexity is built into these and other equations of this type, however, they all relate back to the basic balance relationships described by Lane.

Streamflow

A distinguishing feature of the channel is streamflow. As part of the water cycle, the ultimate source of all flow is precipitation. The pathways precipitation takes after it falls to earth, however, affect many aspects of streamflow including its quantity, quality, and timing. Practitioners usually find it useful to divide flow into components based on these pathways.

The two basic components are:

- *Stormflow*, precipitation that reaches the channel over a short time frame through overland or underground routes.
- *Baseflow*, precipitation that percolates to the ground water and moves slowly through substrate before reaching the channel. It sustains streamflow during periods of little or no precipitation.

Streamflow at any one time might consist of water from one or both sources. If neither source provides water to the channel, the stream goes dry.

A *storm hydrograph* is a tool used to show how the discharge changes with time (**Figure 1.14**). The portion of the hydrograph that lies to the left of the peak is called the *rising limb*, which shows how long it takes the stream to peak following a precipitation event. The portion of the curve to the right of the peak is called the *recession limb*.

Channel and Ground Water Relationships

Interactions between ground water and the channel vary throughout the watershed. In general, the connection is strongest in streams with gravel riverbeds in well-developed alluvial floodplains.

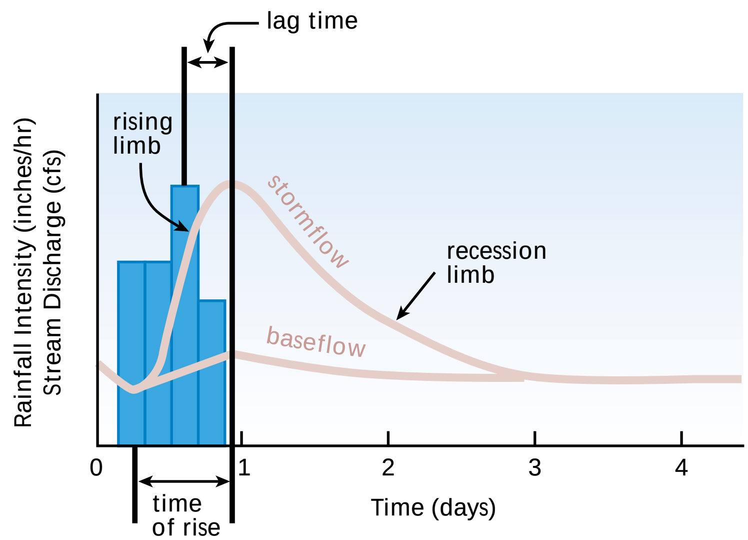


Figure 1.14: A storm hydrograph. *A hydrograph shows how long a stream takes to rise from baseflow to maximum discharge and then return to baseflow conditions.*

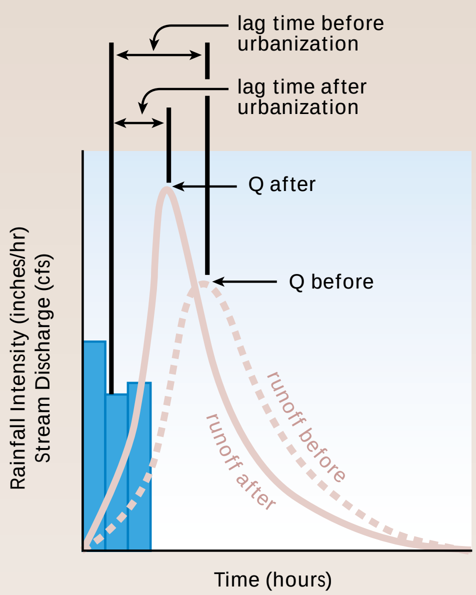


Figure 1.15: A comparison of hydrographs before and after urbanization. *The discharge curve is higher and steeper for urban streams than for natural streams.*

Change in Hydrology After Urbanization

The hydrology of urban streams changes as sites are cleared and natural vegetation is replaced by impervious cover such as rooftops, roadways, parking lots, sidewalks, and driveways. One of the consequences is that more of a stream's annual flow is delivered as storm water runoff rather than baseflow. Depending on the degree of watershed impervious cover, the annual volume of storm water runoff can increase by up to 16 times that for natural areas (Schueler 1995). In addition, since impervious cover prevents rainfall from infiltrating into the soil, less flow is available to recharge ground water. Therefore, during extended periods without rainfall, baseflow levels are often reduced in urban streams (Simmons and Reynolds 1982).

*Storm runoff moves more rapidly over smooth, hard pavement than over natural vegetation. As a result, the rising limbs of storm hydrographs become steeper and higher in urbanizing areas (**Figure 1.15**). Recession limbs also decline more steeply in urban streams.*

Figure 1.16 presents two types of water movement:

- *Influent or "losing" reaches* lose stream water to the aquifer.
- *Effluent or "gaining" reaches* receive discharges from the aquifer.

Practitioners categorize streams based on the balance and timing of the stormflow and baseflow components. There are three main categories:

- *Ephemeral streams* flow only during or immediately after periods of precipitation. They generally flow less than 30 days per year (**Figure 1.17**).
- *Intermittent streams* flow only during certain times of the year. Seasonal flow in an intermittent stream usually lasts longer than 30 days per year.
- *Perennial streams* flow continuously during both wet and dry times. Baseflow is dependably generated from the movement of ground water into the channel.

Discharge Regime

Discharge is the term used to describe the volume of water moving down the channel per unit time (**Figure 1.18**). The basic unit of measurement used in the United States to describe discharge is cubic foot per second (cfs).

Figure 1.17: An ephemeral stream. *Ephemeral streams flow only during or immediately after periods of precipitation.*

Discharge is calculated as:

$$Q = A\ V$$

where:

Q = Discharge (cfs)

A = Area through which the water is flowing in square feet

V = Average velocity in the downstream direction in feet per second

As discussed earlier in this section, streamflow is one of the variables that determine the size and shape of the channel. There are three types of characteristic discharges:

- *Channel-forming (or dominant) discharge*. If the streamflow were held constant at the channel-forming

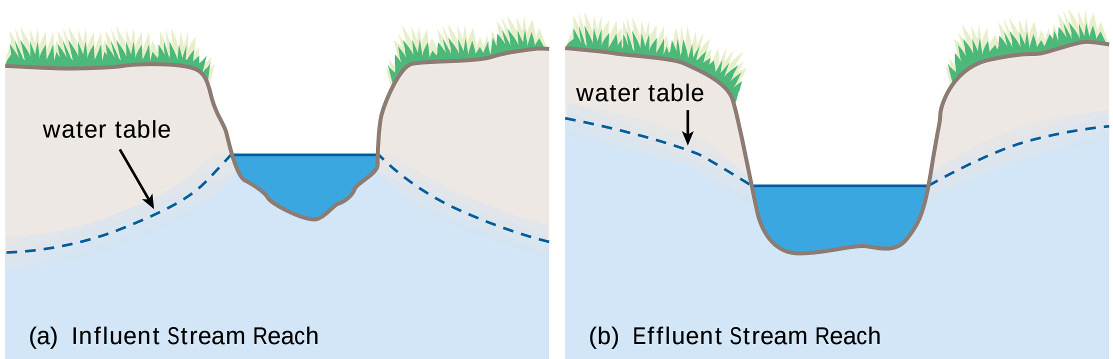
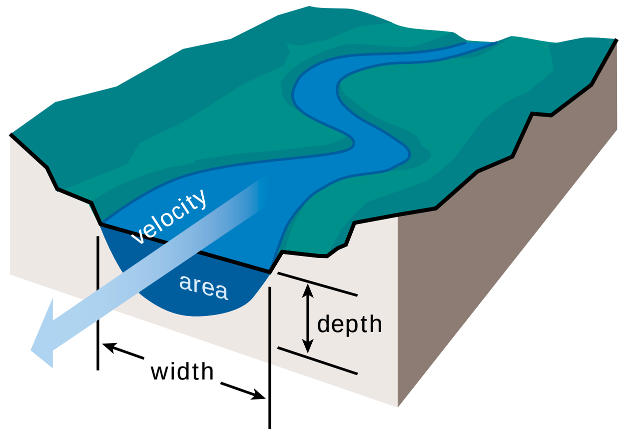


Figure 1.16: Cross sections of (a) influent and (b) effluent stream reaches. *Influent or "losing" reaches lose stream water to the aquifer. Effluent or "gaining" reaches receive discharges from the aquifer.*

discharge, it would result in channel morphology close to the existing channel. However, there is no method for directly calculating channel-forming discharge.

An estimate of channel-forming discharge for a particular stream reach can, with some qualifications, be related to depth, width, and shape of channel. Although channel-forming discharges are strictly applicable only to channels in equilibrium, the concept can be used to select appropriate channel geometry for restoring a disturbed reach.



- *Effective discharge*. The effective discharge is the calculated measure of channel-forming discharge. Computation of effective discharge requires long-term water and sediment measurements, either for the stream in question or for one very similar.

  Since this type of data is not often available for stream restoration sites, modeled or computed data are sometimes substituted. Effective discharge can be computed for either stable or evolving channels.

Bankfull discharge. This discharge occurs when water just begins to leave the channel and spread onto the floodplain (Figure 1.19). Bankfull discharge is equivalent to channel-forming (conceptual) and effective (calculated) discharge.

Figure 1.19: Bankfull discharge. This is the flow at which water begins to leave the channel and move onto the floodplain.

Channel-Forming Discharge

To envision the concept of channel-forming discharge, imagine placing a water hose discharging at constant rate in a freshly tilled garden. Eventually, a small channel will form and reach an equilibrium geometry.

At a larger scale, consider a newly constructed floodwater- retarding reservoir that slowly releases stored floodwater at a constant flow rate. This flow becomes the new channel-forming discharge and will alter channel morphology until the channel reaches equilibrium.

FAST FORWARD

Preview Chapter 7, Section B for a discussion of calculating effective discharge. This computation should be performed by a professional with a good background in hydrology, hydraulics, and sediment transport.

Floodplain

The floor of most stream valleys is relatively flat. This is because over time the stream moves back and forth across the valley floor in a process called lateral migration. In addition, periodic flooding causes sediments to move longitudinally and to be deposited on the valley floor near the channel. These two processes continually modify the floodplain.

Through time the channel reworks the entire valley floor. As the channel migrates, it maintains the same average size and shape if conditions upstream remain constant and the channel stays in equilibrium.

Two types of floodplains may be defined (**Figure 1.20**):

- *Hydrologic floodplain*, the land adjacent to the baseflow channel residing below bankfull elevation. It is inundated about two years out of three. Not every stream corridor has a hydrologic floodplain.
- *Topographic floodplain*, the land adjacent to the channel including the hydrologic floodplain and other lands up to an elevation based on the elevation reached by a flood peak of a given frequency (for example, the 100-year floodplain).

Professionals involved with flooding issues define the boundaries of a floodplain in terms of flood frequencies. Thus, 100-year and 500-year floodplains are commonly used in the development of planning and regulation standards.

Flood Storage

The floodplain provides temporary storage space for floodwaters and sediment produced by the watershed. This attribute serves to add to the *lag time* of a flood—the time between the middle of the rainfall event and the runoff peak.

If a stream's capacity for moving water and sediment is diminished, or if the sediment loads produced from the watershed become too great for the stream to transport, flooding will occur more frequently and the valley floor will begin to fill. Valley filling results in the temporary storage of sediment produced by the watershed.

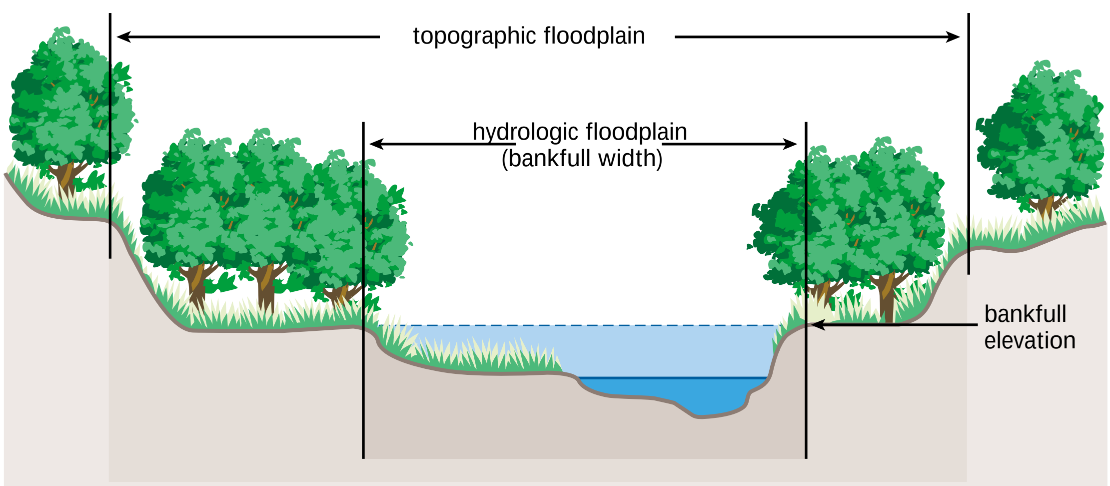


***Figure 1.20*: Hydrologic and topographic floodplains.** *The hydrologic floodplain is defined by bankfull elevation. The topographic floodplain includes the hydrologic floodplain and other lands up to a defined elevation.*

Landforms and Deposits

Topographic features are formed on the floodplain by the lateral migration of the channel (**Figure 1.21**). These features result in varying soil and moisture conditions and provide a variety of habitat niches that support plant and animal diversity.

Floodplain landforms and deposits include:

- *Meander scroll*, a sediment formation marking former channel locations.
- *Chute*, a new channel formed across the base of a meander. As it grows in size, it carries more of the flow.
- *Oxbow*, a term used to describe the severed meander after a chute is formed.
- *Clay plug*, a soil deposit developed at the intersection of the oxbow and the new main channel.
- *Oxbow lake*, a body of water created after clay plugs the oxbow from the main channel.
- *Natural levees*, formations built up along the bank of some streams that flood. As sediment-laden water spills over the bank, the sudden loss of depth and velocity causes coarser-sized sediment to drop out of suspension and collect along the edge of the stream.
- *Splays*, delta-shaped deposits of coarser sediments that occur when a natural levee is breached. Natural levees and splays can prevent floodwaters from returning to the channel when floodwaters recede.
- *Backswamps*, a term used to describe floodplain wetlands formed by natural levees.

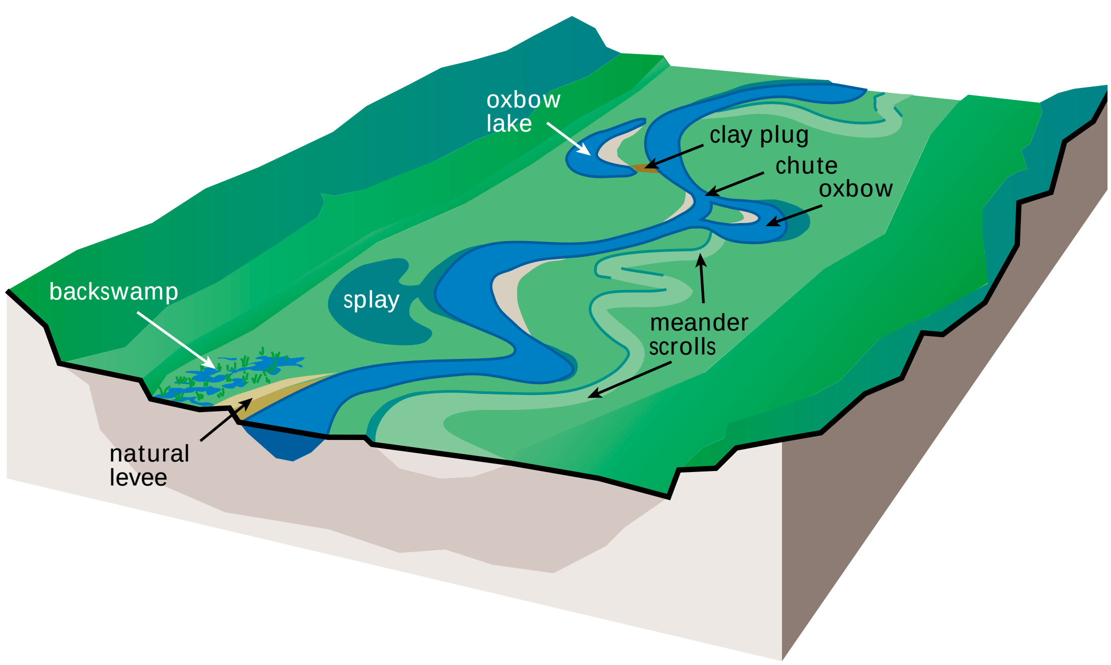


Figure 1.21: Landforms and deposits of a floodplain. *Topographic features on the floodplain caused by meandering streams.*

Transitional Upland Fringe

The transitional upland fringe serves as a transitional zone between the floodplain and surrounding landscape. Thus, its outside boundary is also the outside boundary of the stream corridor itself.

While stream-related hydrologic and geomorphic processes might have formed a portion of the transitional upland fringe in geologic times, they are not responsible for maintaining or altering its present form. Consequently, land use activities have the greatest potential to impact this component of the stream corridor.

There is no typical cross section for this component. Transitional upland fringes can be flat, sloping, or in some cases, nearly vertical (**Figure 1.22**). They can incorporate features such as hillslopes, bluffs, forests, and prairies, often modified by land use. All transitional upland fringes have one common attribute, however: they are distinguishable from the surrounding landscape by their greater connection to the floodplain and stream.

An examination of the floodplain side of the transitional upland fringe often reveals one or more benches. These landforms are called *terraces* (**Figure 1.23**). They are formed in response to new patterns of streamflow, changes in sediment size or load, or changes in watershed base level—the elevation at the watershed outlet.

Terrace formation can be explained using the aforementioned stream balance equation (Figure 1.13). When one or more variables change, equilibrium is lost, and either degradation or aggradation occurs.

Figure 1.24 presents an example of terrace formation by channel incision. Cross section A represents a nonincised channel. Due to changes in streamflow or sediment delivery, equilibrium is lost

Figure 1.22: Transitional upland fringe. *This component of the stream corridor is a transition zone between the floodplain and the surrounding landscape.*

Figure 1.23: Terraces formed by an incising stream. *Terraces are formed in response to new patterns of streamflow or sediment load in the watershed.*

and the channel degrades and widens. The original floodplain is abandoned and becomes a terrace (cross section B). The widening phase is completed when a floodplain evolves within the widened channel (cross section C).

Geomorphologists often classify landscapes by numbering surfaces from the lowest surface up to the highest surface. Surface 1 in most landscapes is the bottom of the main channel. The next highest surface, Surface 2, is the floodplain. In the case of an incising stream, Surface 3 usually is the most recently formed terrace, Surface 4 the next older terrace, and so on. The numbering system thus reflects the ages of the surfaces. The higher the number, the older the surface.

Boundaries between the numbered surfaces are usually marked by a scarp, or relatively steep surface. The scarp between a terrace and a floodplain is especially important because it helps confine floods to the valley floor. Flooding occurs much less frequently, if at all, on terraces.

Vegetation Across the Stream Corridor

Vegetation is an important and highly variable element in the stream corridor. In some minimally disturbed stream corridors, a series of plant communities might extend uninterrupted across the entire corridor. The distribution of these communities would be based on different hydrologic and soil conditions. In smaller streams the riparian vegetation might even form a canopy and enclose the channel. This and other configuration possibilities are displayed in **Figure 1.25**.

Plant communities play a significant role in determining stream corridor condition, vulnerability, and potential for (or lack of) restoration. Thus, the type, extent and distribution, soil moisture preferences, elevation, species composition, age, vigor, and rooting depth are all important characteristics that a practitioner must consider when planning and designing stream corridor restoration.

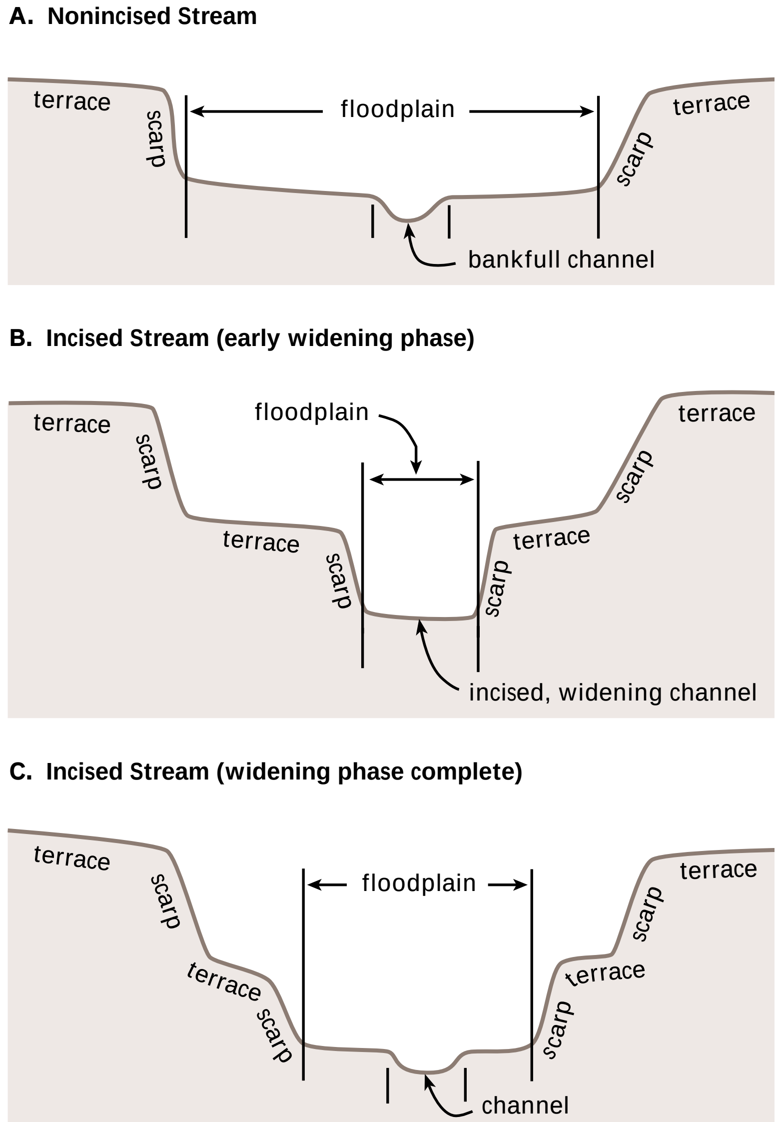


Figure 1.24: Terraces in (A) nonincised and (B and C) incised streams. *Terraces are abandoned floodplains, formed through the interplay of incising and floodplain widening.*

Flood-Pulse Concept

Floodplains serve as essential focal points for the growth of many riparian

FAST FORWARD

Preview Chapter 2, Section D for more information on plant community characteristics.

plant communities and the wildlife they support. Some riparian plant species such as willows and cottonwoods depend on flooding for regeneration. Flooding also nourishes floodplains with sediments and nutrients and provides habitat for invertebrate communities, amphibians, reptiles, and fish spawning.

The flood-pulse concept was developed to summarize how the dynamic interaction between water and land is exploited by the riverine and floodplain biota (**Figure 1.26**). Applicable primarily on larger rivers, the concept demonstrates that the predictable advance and retraction of water on the floodplain in a natural setting enhances biological productivity and maintains diversity (Bayley 1995).

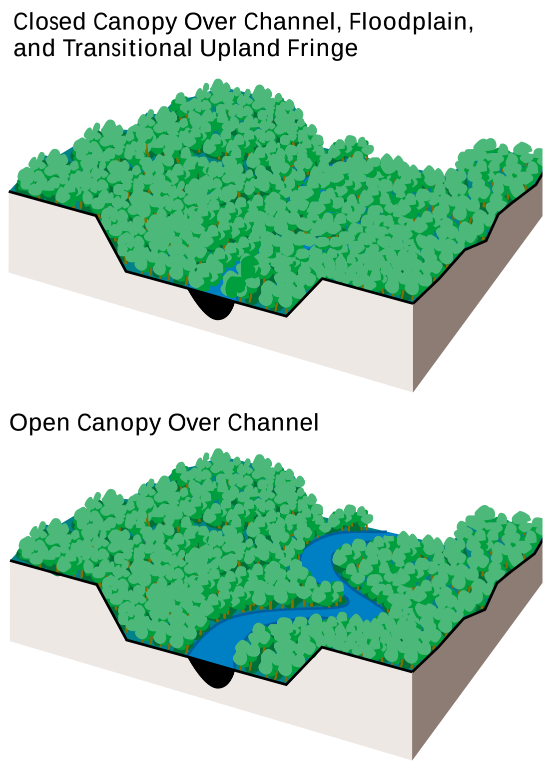


Figure 1.25: Examples of vegetation structure in the stream corridor. *Plant communities play a significant role in determining the condition and vulnerability of the stream corridor.*

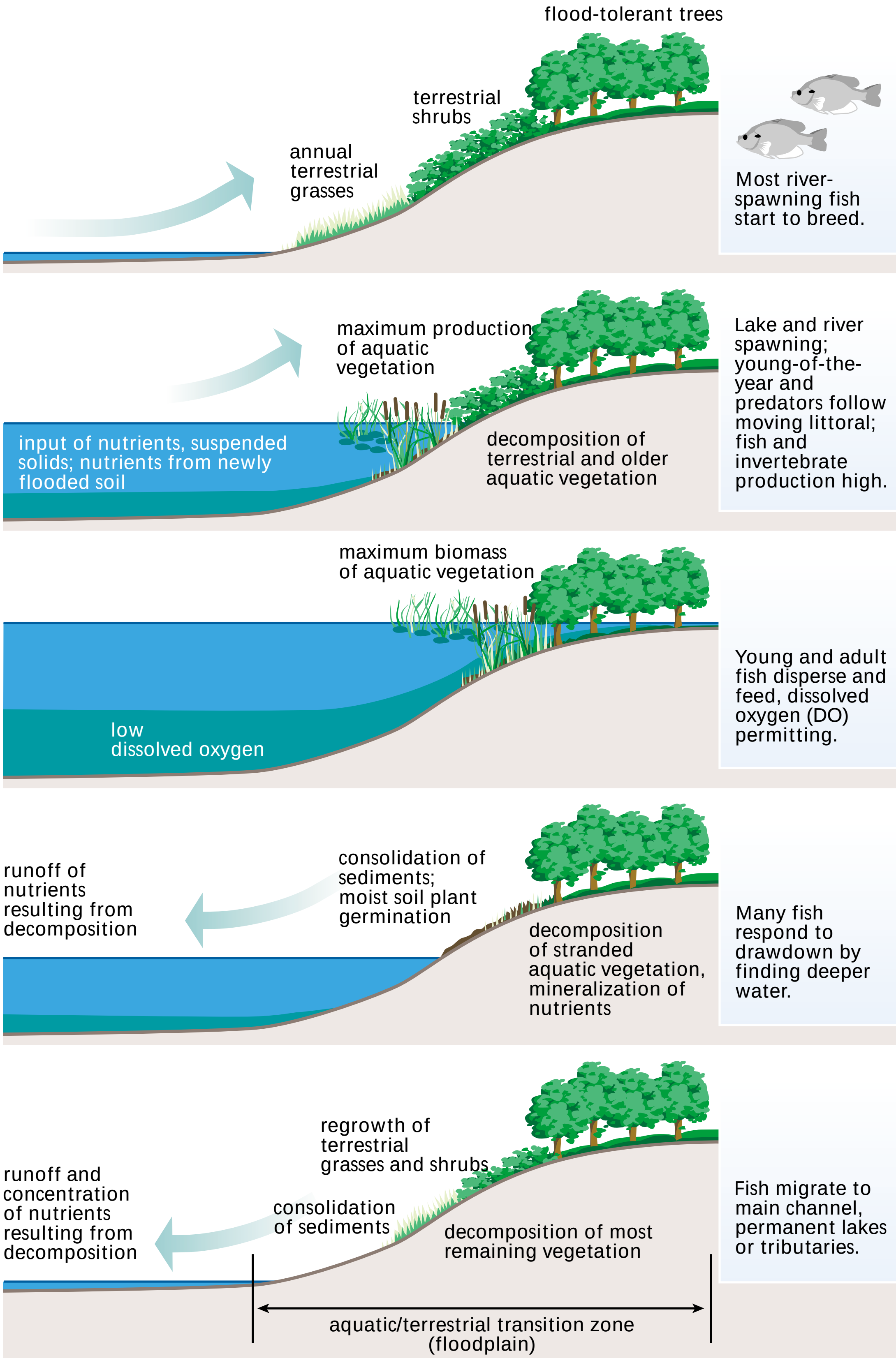


Figure 1.26: Schematic of the flood-pulse concept. *A vertically exaggerated section of a floodplain in five snapshots of an annual hydrological cycle. The left column describes the movement of nutrients. The right column describes typical life history traits of fish.*

Source: Bayley, ***Bioscience***, vol. 45, p.154, March 1995. ©1995 American Institute of Biological Science.

1.C A Longitudinal View Along the Stream Corridor

The processes that develop the characteristic structure seen in the lateral view of a stream corridor also influence structure in the longitudinal view. Channel width and depth increase downstream due to increasing drainage area and discharge. Related structural changes also occur in the channel, floodplain, and transitional upland fringe, and in processes such as erosion and deposition. Even among different types of streams, a common sequence of structural changes is observable from headwaters to mouth.

Longitudinal Zones

The overall longitudinal profile of most streams can be roughly divided into three zones (Schumm 1977). Some of the changes in the zones are characterized in **Figures 1.27** and **1.28**.

Zone 1, or headwaters, often has the steepest gradient. Sediment erodes from slopes of the watershed and moves downstream. Zone 2, the transfer zone, receives some of the eroded material. It is usually characterized by wide floodplains and meandering channel patterns. The gradient flattens in Zone 3, the primary depositional zone. Though the figure displays headwaters as mountain streams, these general patterns and changes are also often applicable to watersheds with relatively small topographic relief from the headwaters to mouth. It is important to note that erosion, transfer, and deposition occur in all zones, but the zone concept focuses on the most dominant process.

Watershed Forms

All watersheds share a common definition: a *watershed* is an "area of land that

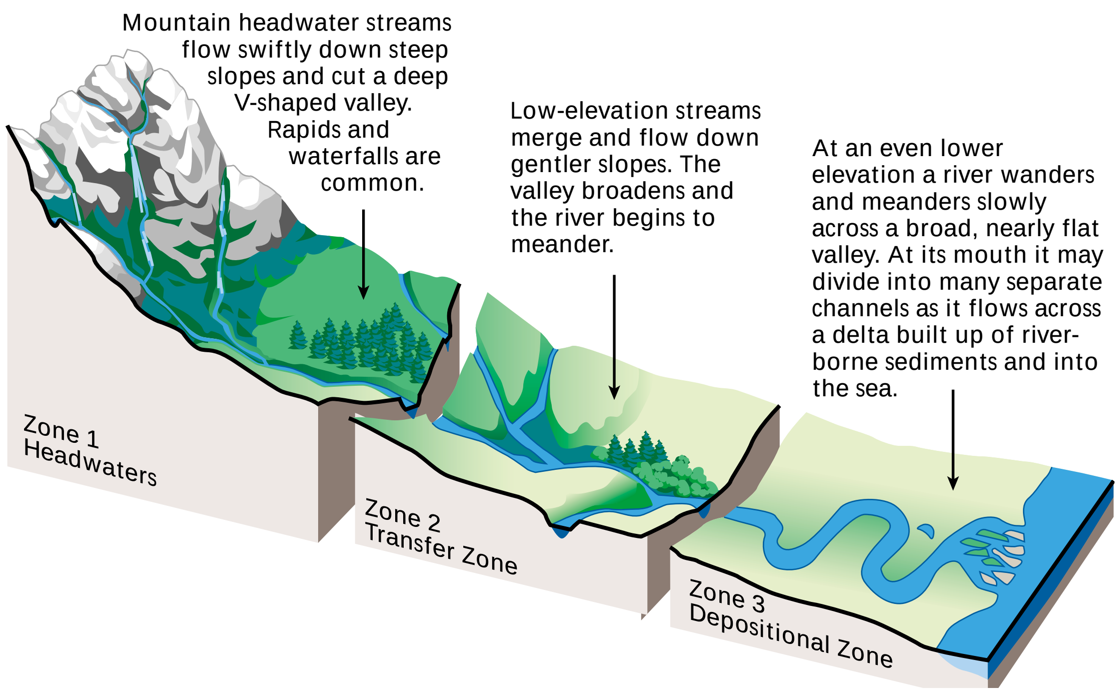


Figure 1.27: Three longitudinal profile zones. *Channel and floodplain characteristics change as rivers travel from headwaters to mouth.*

Source: Miller (1990). ©1990 Wadsworth Publishing Co.

drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel" (Dunne and Leopold 1978). Form varies greatly, however, and is tied to many factors including climatic regime, underlying geology, morphology, soils, and vegetation.

Drainage Patterns

One distinctive aspect of a watershed when observed in planform (map view) is its drainage pattern (**Figure 1.29**). Drainage patterns are primarily controlled by the overall topography and underlying geologic structure of the watershed.

Stream Ordering

A method of classifying, or ordering, the hierarchy of natural channels within a watershed was developed by Horton (1945). Several modifications of the original stream ordering scheme have

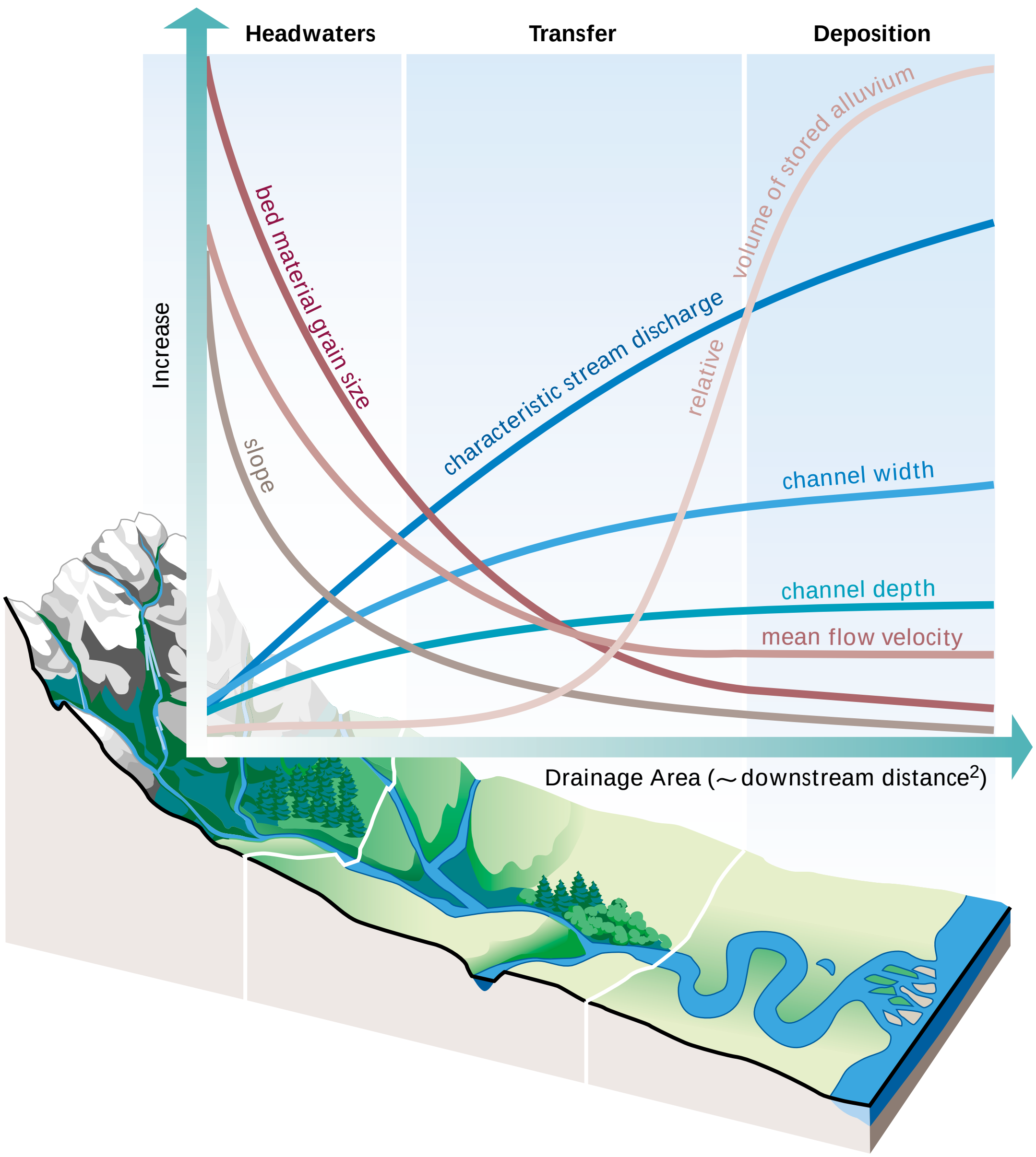


Figure 1.28: Changes in the channel in the three zones. *Flow, channel size, and sediment characteristics change throughout the longitudinal profile.*

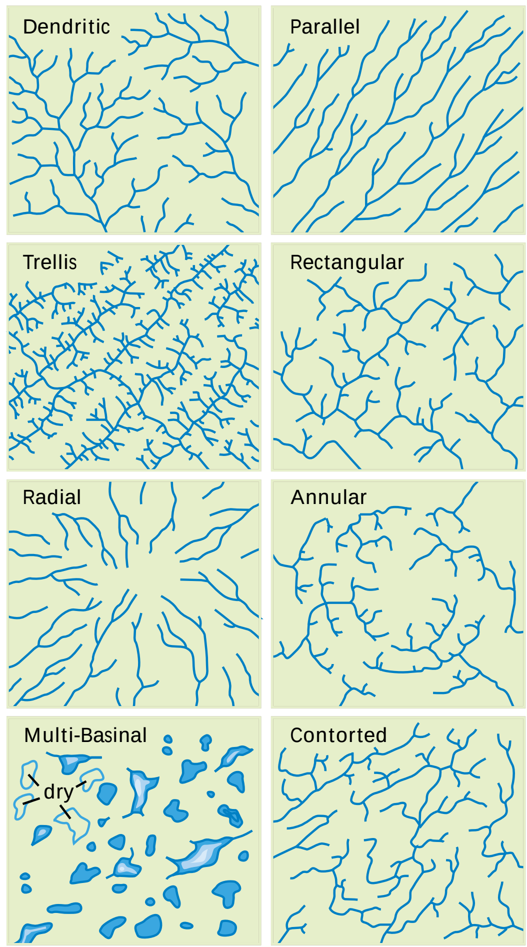


Figure 1.29: Watershed drainage patterns. *Patterns are determined by topography and geologic structure.*
Source: A.D. Howard, AAPG © 1967, reprinted by permission of the American Association of Petroleum Geologists.

been proposed, but the modified system of Strahler (1957) is probably the most popular today.

Strahler's stream ordering system is portrayed in **Figure 1.30**. The uppermost channels in a drainage network (i.e., headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on. Note in the figure that the intersection of a channel with another

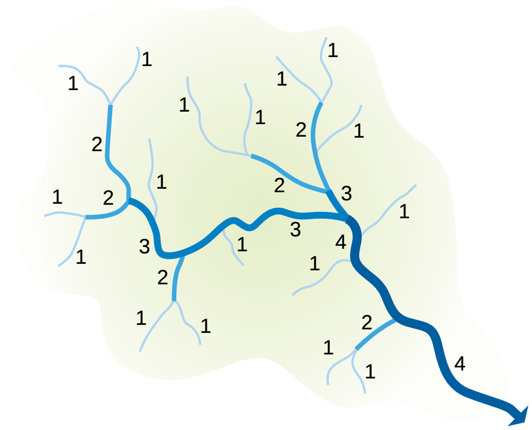


Figure 1.30: Stream ordering in a drainage network. *Stream ordering is a method of classifying the hierarchy of natural channels in a watershed.*

channel of lower order does not raise the order of the stream below the intersection (e.g., a fourth-order stream intersecting with a second-order stream is still a fourth-order stream below the intersection).

Within a given drainage basin, stream order correlates well with other basin parameters, such as drainage area or channel length. Consequently, knowing what order a stream is can provide clues concerning other characteristics such as which longitudinal zone it resides in and relative channel size and depth.

Channel Form

The form of the channel can change as it moves through the three longitudinal zones. Channel form is typically described by two characteristics—thread (single or multiple) and sinuosity.

Single- and Multiple-Thread Streams

Single-thread (one-channel) streams are most common, but multiple-thread streams occur in some landscapes (**Figure 1.31**). Multiple-thread streams are further categorized as either braided or anastomosed streams.

Three conditions tend to promote the formation of braided streams:

- Erodible banks.
- An abundance of coarse sediment.
- Rapid and frequent variations in discharge.

Braided streams typically get their start when a central sediment bar begins to form in a channel due to reduced streamflow or an increase in sediment load. The central bar causes water to flow into the two smaller cross sections on either side. The smaller cross section results in a higher velocity flow. Given erodible banks, this causes the channels to widen. As they do this, flow velocity decreases, which allows another central bar to form. The process is then repeated and more channels are created.

In landscapes where braided streams occur naturally, the plant and animal communities have adapted to frequent and rapid changes in the channel and riparian area. In cases where disturbances trigger the braiding process, however, physical conditions might be too dynamic for many species.

The second, less common category of multiple-thread channels is called *anastomosed streams*. They occur on much flatter gradients than braided streams and have channels that are narrow and deep (as opposed to the wide, shallow channels found in braided streams). Their banks are typically made up of fine, cohesive sediments, making them relatively erosion-resistant.

Anastomosed streams form when the downstream base level rises, causing a rapid buildup of sediment. Since bank materials are not easily erodible, the original single-thread stream breaks up into multiple channels. Streams entering deltas in a lake or bay are often anastomosed. Streams on alluvial fans, in contrast, can be braided or anastomosed.

Sinuosity

Natural channels are rarely straight. Sinuosity is a term indicating the amount of curvature in the channel (**Figure 1.32**). The *sinuosity* of a reach is computed by dividing the channel

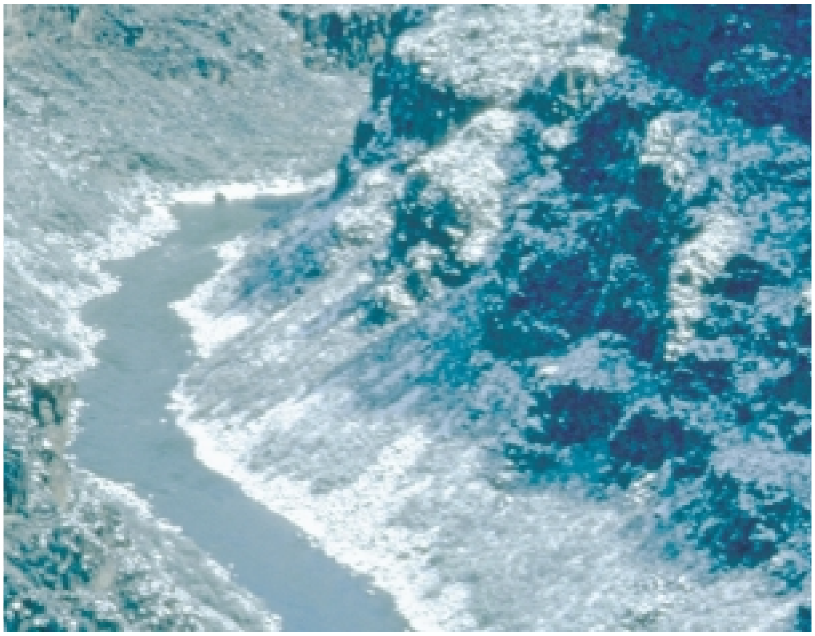
(a)

(b)

Figure 1.31: (a) Single-thread and (b) braided streams. *Single-thread streams are most common. Braided streams are uncommon and usually formed in response to erodible banks, an abundance of coarse sediment, and rapid and frequent variations in discharge.*

centerline length by the length of the valley centerline. If the channel length/valley length ratio is more than about 1.3, the stream can be considered meandering in form.

Sinuosity is generally related to the product of discharge and gradient.



(a)

(b)

Figure 1.32: Sinuosity: (a) low and (b) extreme. *Low to moderately sinuous streams are usually found in Zones 1 and 2 of the longitudinal profile. Extremely sinuous streams are more typical of Zone 3.*

Low to moderate levels of sinuosity are typically found in Zones 1 and 2 of the longitudinal profile. Extremely sinuous streams often occur in the broad, flat valleys of Zone 3.

Pools and Riffles

No matter the channel form, most streams share a similar attribute of alternating, regularly spaced, deep and shallow areas called *pools* and *riffles* (**Figure 1.33**). The pools and riffles are associated with the thalweg, which meanders within the channel. Pools typically form in the thalweg near the outside bank of bends. Riffle areas usually form between two bends at the point where the thalweg crosses over from one side of the channel to the other.

The makeup of the streambed plays a role in determining pool and riffle characteristics. Gravel and cobble-bed streams typically have regularly spaced pools and riffles that help maintain channel stability in a high-energy environment. Coarser sediment particles are found in riffle areas while smaller particles occur in pools. The pool-to-pool or riffle-to-riffle spacing is normally about 5 to 7 times the channel width at bankfull discharge (Leopold et al. 1964).

Sand-bed streams, on the other hand, do not form true riffles since the grain size distribution in the riffle area is similar to that in the pools. However, sand-bed streams do have evenly spaced pools. High-gradient streams also usually have pools but not riffles, but for a different reason. In this case, water moves from pool to pool in a stairstep fashion.

Vegetation Along the Stream Corridor

Vegetation is an important and highly variable element in the longitudinal as well as the lateral view. Floodplains are narrow or nonexistent in Zone 1 of the longitudinal profile; thus flood-dependent or tolerant plant communities tend to be limited in distribution. Upland plant communities, such as forests on moderate to steep slopes in the eastern or northwestern United States, might come close to bordering the stream and create a canopy that leaves little open sky visible from the channel. In other parts of the country, headwaters in flatter terrain may support plant communities dominated by grasses and broad-leaved herbs, shrubs, or planted vegetation.

Despite the variation in plant community type, many headwaters areas provide organic matter from vegetation along with the sediment they export to Zones 2 and 3 downstream. For example, logs and woody debris from headwaters forests are among the most ecologically important features supporting food chains and instream habitat structure in Pacific Northwest rivers from the mountains to the sea (Maser and Sedell 1994).

Zone 2 has a wider and more complex floodplain and larger channel than Zone 1. Plant communities associated with floodplains at different elevations might vary due to differences in soil type, flooding frequency, and soil moisture. Localized differences in erosion and deposition of sediment add complexity and diversity to the types of plant communities that become established.

The lower gradient, larger stream size, and less steep terrain in Zone 2 often attract more agricultural or residential development than in the headwaters

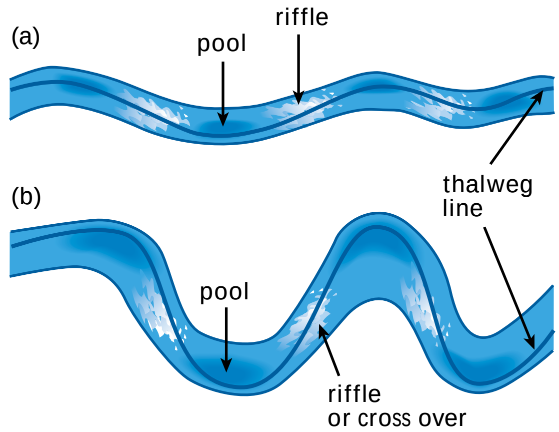


Figure 1.33: Sequence of pools and riffles in (a) straight and (b) sinuous streams. *Pools typically form on the outside bank of bends and riffles in the straight portion of the channel where the thalweg crosses over from one side to the other.*

zone. This phenomenon frequently counteracts the natural tendency to develop broad and diverse stream corridor plant communities in the middle and lower reaches. This is especially true when land uses involve clearing the native vegetation and narrowing the corridor.

Often, a native plant community is replaced by a planted vegetation community such as agricultural crops or residential lawns. In such cases, stream processes involving flooding, erosion/deposition, import or export of organic matter and sediment, stream corridor habitat diversity, and water quality characteristics are usually significantly altered.

The lower gradient, increased sediment deposition, broader floodplains, and greater water volume in Zone 3 all set the stage for plant communities different from those found in either upstream zone. Large floodplain wetlands become prevalent because of the generally flatter terrain. Highly productive and diverse biological communities, such as bottomland hardwoods, establish themselves in the deep, rich alluvial soils of the floodplain. The slower flow in the channel also allows emergent marsh vegetation, rooted floating or free-floating plants, and submerged aquatic beds to thrive.

The changing sequence of plant communities along streams from source to mouth is an important source of biodiversity and resiliency to change. Although many, or perhaps most, of a stream corridor's plant communities might be fragmented, a continuous corridor of native plant communities is desirable. Restoring vegetative connectivity in even a portion of a stream will usually improve conditions and increase its beneficial functions.

The River Continuum Concept

The River Continuum Concept is an attempt to generalize and explain longitudinal changes in stream ecosystems (**Figure 1.34**) (Vannote et al. 1980). This conceptual model not only helps to identify connections between the watershed, floodplain, and stream systems, but it also describes how biological communities develop and change from the headwaters to the mouth. The River Continuum Concept can place a site or reach in context within a larger watershed or landscape and thus help practitioners define and focus restoration goals.

The River Continuum Concept hypothesizes that many first- to third-order headwater streams are shaded by the riparian forest canopy. This shading, in turn, limits the growth of algae, periphyton, and other aquatic plants. Since energy cannot be created through photosynthesis (autotrophic production), the aquatic biota in these small streams is dependent on *allochthonous* materials (i.e., materials coming from outside the channel such as leaves and twigs). Biological communities are uniquely adapted to use externally derived organic inputs. Consequently, these headwater streams are considered *heterotrophic* (i.e., dependent on the energy produced in the surrounding watershed). Temperature regimes are also relatively stable due to the influence of ground water recharge, which tends to reduce biological diversity to those species with relatively narrow thermal niches.

Predictable changes occur as one proceeds downstream to fourth-, fifth-, and sixth-order streams. The channel widens, which increases the amount of incident sunlight and average temperatures. Levels of primary production increase in response to increases in light, which shifts many streams to a dependence on *autochthonous* materials (i.e., materials coming from inside the channel), or internal autotrophic production (Minshall 1978).

In addition, smaller, preprocessed organic particles are received from upstream sections, which serves to balance autotrophy and heterotrophy within the stream. Species richness of the invertebrate community increases as a variety of new habitat and food resources appear. Invertebrate functional groups, such as the grazers and collectors, increase in abundance as they adapt to using both autochthonous and allochthonous food resources. Midsized streams also decrease in thermal stability as temperature fluctuations increase, which further tends to increase biotic diversity by increasing the number of thermal niches.

Larger streams and rivers of seventh to twelfth order tend to increase in physical stability, but undergo significant changes in structure and biological function. Larger streams develop increased reliance on primary productivity by

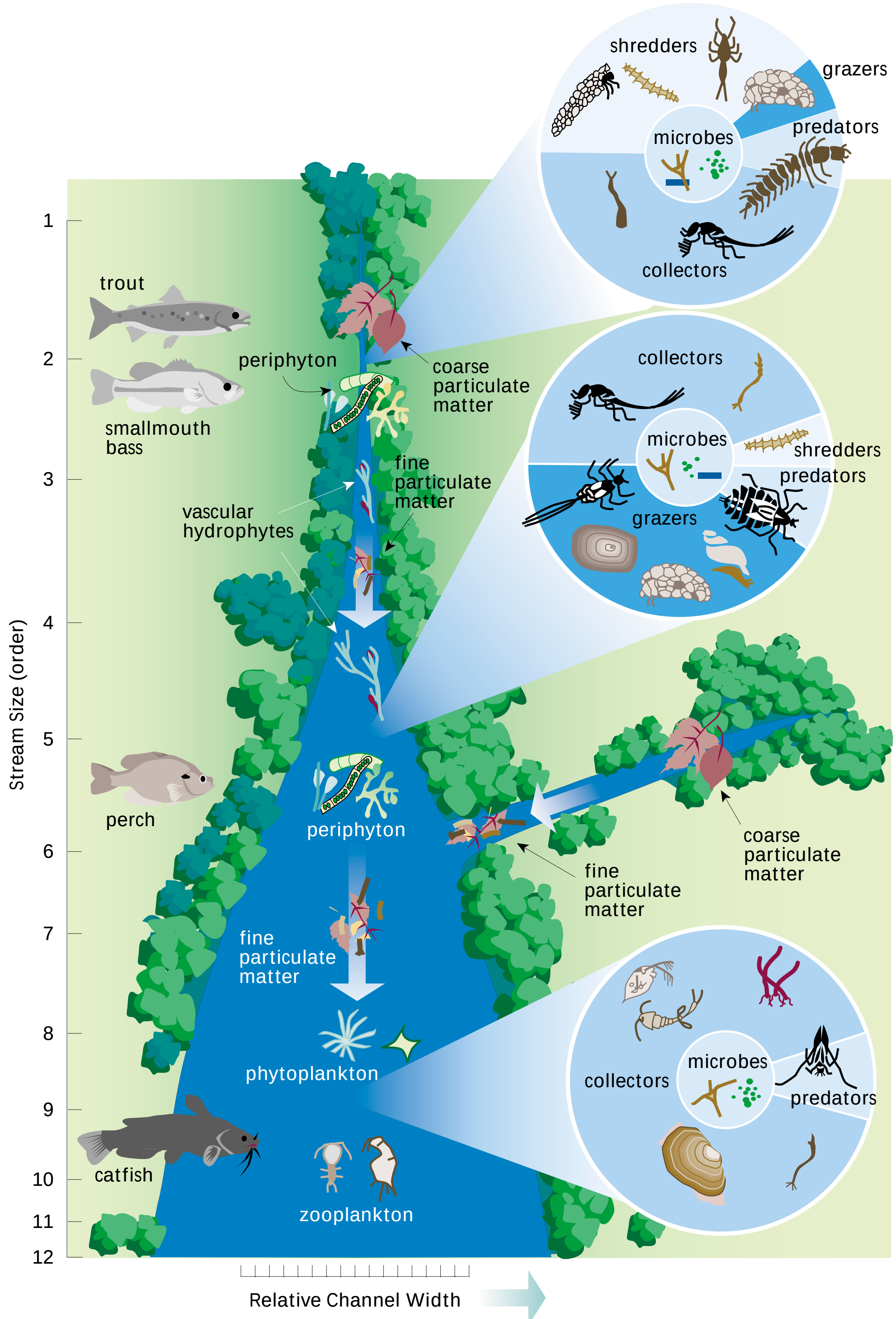


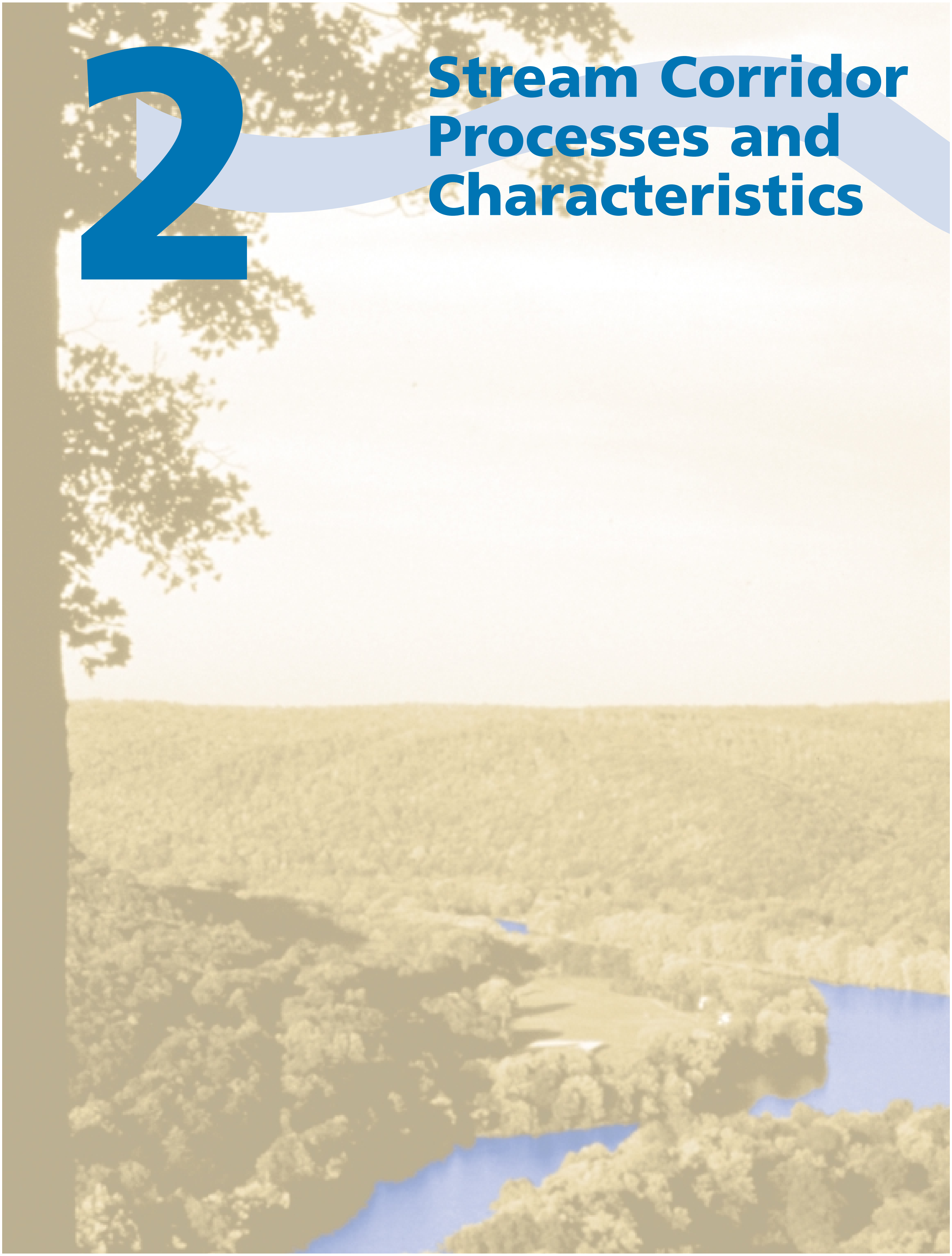
Figure 1.34: The River Continuum Concept. *The concept proposes a relationship between stream size and the progressive shift in structural and functional attributes.*
Source: Vannote et al. (1980). Published with the permission of NRC Research Press.

phytoplankton, but continue to receive heavy inputs of dissolved and ultra-fine organic particles from upstream. Invertebrate populations are dominated by fine-particle collectors, including zooplankton. Large streams frequently carry increased loads of clays and fine silts, which increase turbidity, decrease light penetration, and thus increase the significance of heterotrophic processes.

The influence of storm events and thermal fluctuations decrease in frequency and magnitude, which increases the overall physical stability of the stream. This stability increases the strength of biological interactions, such as competition and predation, which tends to eliminate less competitive taxa and thereby reduce species richness.

The fact that the River Continuum Concept applies only to perennial streams is a limitation. Another limitation is that disturbances and their impacts on the river continuum are not addressed by the model. Disturbances can disrupt the connections between the watershed and its streams and the river continuum as well.

The River Continuum Concept has not received universal acceptance due to these and other reasons (Statzner and Higler 1985, Junk et al. 1989). Nevertheless, it has served as a useful conceptual model and stimulated much research since it was first introduced in 1980.



2 Stream Corridor Processes and Characteristics

2.A Hydrologic and Hydraulic Processes

- *Where does stream flow come from?*
- *What processes affect or are involved with stream flow?*
- *How fast, how much, how deep, how often and when does water flow?*
- *How is hydrology different in urban stream corridors?*

2.B Geomorphic Processes

- *What factors affect the channel cross section and channel profile?*
- *How are water and sediment related?*
- *Where does sediment come from and how is it transported downstream?*
- *What is an equilibrium channel?*
- *What should a channel look like in cross section and in profile?*
- *How do channel adjustments occur?*
- *What is a floodplain?*
- *Is there an important relationship between a stream and its floodplain?*

2.C Chemical Processes

- *What are the major chemical constituents of water?*
- *What are some important relationships between physical habitat and key chemical parameters?*
- *How are the chemical and physical parameters critical to the aquatic life in a stream corridor?*
- *What are the natural chemical processes in a stream corridor and water column?*
- *How do disturbances in the stream corridor affect the chemical characteristics of stream water?*

2.D Biological Processes

- *What are the important biological components of a stream corridor?*
- *What biological activities and organisms can be found within a stream corridor?*
- *How does the structure of stream corridors support various populations of organisms?*
- *What are the structural features of aquatic systems that contribute to the biological diversity of stream corridors?*
- *What are some important biological processes that occur within a stream corridor?*
- *What role do fish have in stream corridor restoration?*

2.E Stream Corridor Functions and Dynamic Equilibrium

- *What are the major ecological functions of stream corridors?*
- *How are these ecological functions maintained over time?*
- *Is a stream corridor stable?*
- *Are these functions related?*
- *How does a stream corridor respond to all the natural forces acting on it (i.e., dynamic equilibrium)?*

2 Stream Corridor Processes, Characteristics, and Functions

Chapter 1 provided an overview of stream corridors and the many perspectives from which they should be viewed in terms of scale, equilibrium, and space. Each of these views can be seen as a "snapshot" of different aspects of a stream corridor.

Chapter 2 presents the stream corridor in motion, providing a basic understanding of the different processes that make the stream corridor look and function the way it does. While Chapter 1 presented still images, this chapter provides "film footage" to describe the processes, characteristics, and functions of stream corridors through time.

Section 2.A: Hydrologic and Hydraulic Processes

Understanding how water flows into and through stream corridors is critical to restorations. How fast, how much, how deep, how often, and when water flows are important basic questions that must be answered to

Figure 2.1: A stream corridor in motion. *Processes, characteristics, and functions shape stream corridors and make them look the way they do.*

make appropriate decisions about stream corridor restoration.

Section 2.B: Geomorphic Processes

This section combines basic hydrologic processes with physical or geomorphic functions and characteristics. Water flows through streams but is affected by the kinds of soils and alluvial features within the channel, in the floodplain, and in the uplands. The amount and kind of sediments carried by a stream largely determines its equilibrium characteristics, including size, shape, and profile. Successful stream corridor restoration, whether active (requiring direct changes) or passive (management and removal of disturbance factors), depends on an understanding of how water and sediment are related to channel form and function and on what processes are involved with channel evolution.

Section 2.C: Physical and Chemical Characteristics

The quality of water in the stream corridor is normally a primary objective of restoration, either to improve it to a desired condition, or to sustain it. Restoration should consider the physical and chemical characteristics that may not be readily apparent but that are nonetheless critical to the functions and processes of stream corridors. Changes in soil or water chemistry to achieve restoration goals usually involve managing or altering elements in the landscape or corridor.

Section 2.D: Biological Community Characteristics

The fish, wildlife, plants, and humans that use, live in, or just visit the stream corridor are key elements to consider in restoration. Typical goals are to restore, create, enhance, or protect habitat to benefit life. It is important to understand how water flows, how sediment is transported, and how geomorphic features and processes evolve; however, a prerequisite to successful restoration is an understanding of the living parts of the system and how the physical and chemical processes affect the stream corridor.

Section 2.E: Functions and Dynamic Equilibrium

The six major functions of stream corridors are: habitat, conduit, barrier, filter, source, and sink. The integrity of a stream corridor ecosystem depends on how well these functions operate. This section discusses these functions and how they relate to dynamic equilibrium.

2.A Hydrologic and Hydraulic Processes

The *hydrologic cycle* describes the continuum of the transfer of water from precipitation to surface water and ground water, to storage and runoff, and to the eventual return to the atmosphere by transpiration and evaporation (**Figure 2.2**).

Precipitation returns water to the earth's surface. Although most hydrologic processes are described in terms of rainfall events (or storm events), snowmelt is also an important source of water, especially for rivers that originate in high mountain areas and for continental regions that experience seasonal cycles of snowfall and snowmelt.

The type of precipitation that will occur is generally a factor of humidity and air temperature. Topographic relief and geographic location relative to large water bodies also affect the frequency and type of precipitation. Rainstorms occur more frequently along coastal and low-latitude areas with moderate temperatures and low relief. Snowfalls occur more frequently at high elevations and in mid-latitude areas with colder seasonal temperatures.

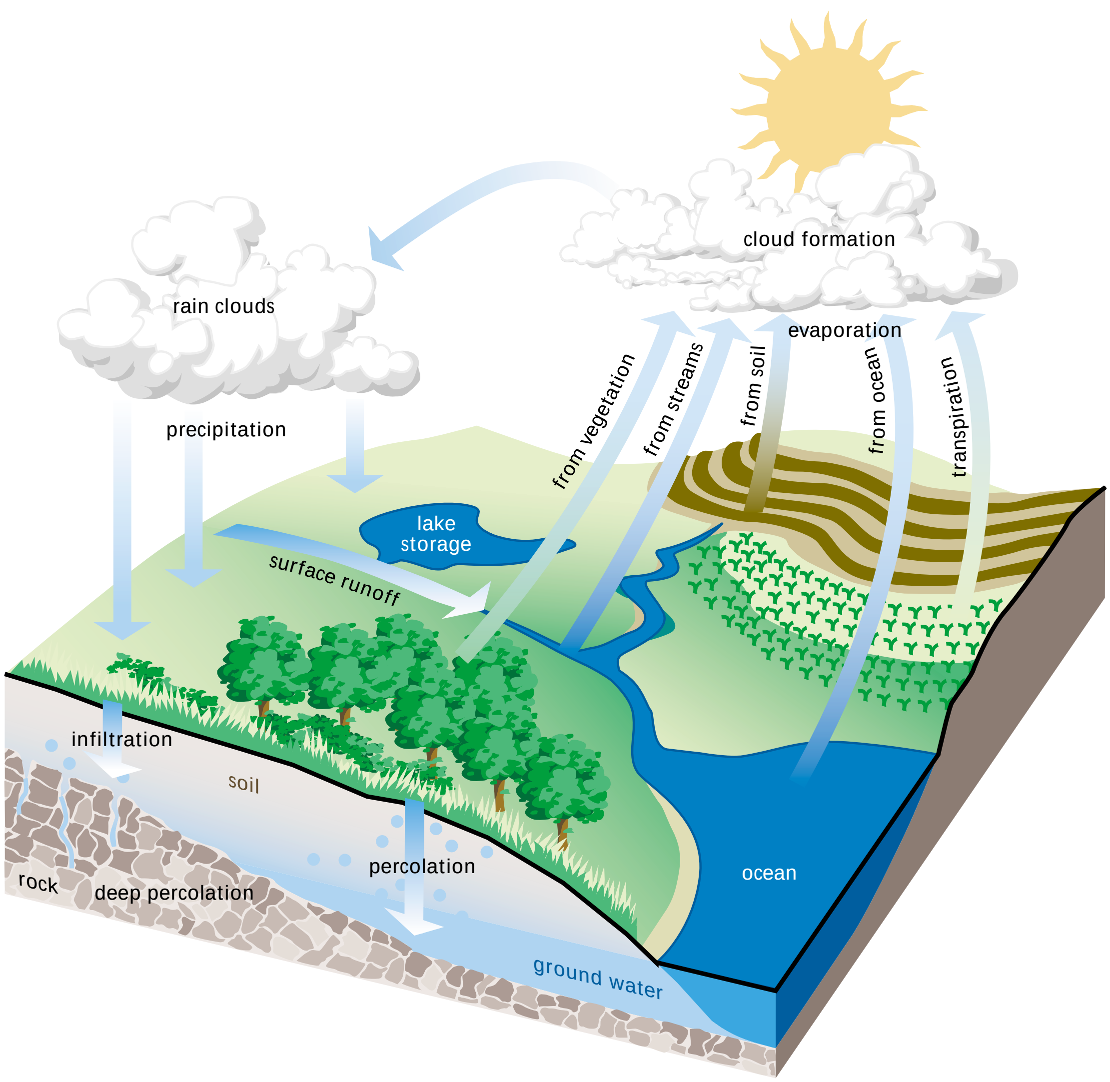


Figure 2.2: The hydrologic cycle. *The transfer of water from precipitation to surface water and ground water, to storage and runoff, and eventually back to the atmosphere is an ongoing cycle.*

Precipitation can do one of three things once it reaches the earth. It can return to the atmosphere; move into the soil; or run off the earth's surface into a stream, lake, wetland, or other water body. All three pathways play a role in determining how water moves into, across, and down the stream corridor.

This section is divided into two subsections. The first subsection focuses on hydrologic and hydraulic processes in the lateral dimension, namely, the movement of water from the land into the channel. The second subsection concentrates on water as it moves in the longitudinal dimension, specifically as streamflow in the channel.

Hydrologic and Hydraulic Processes Across the Stream Corridor

Key points in the hydrologic cycle serve as organizational headings in this subsection:

- Interception, transpiration, and evapotranspiration.
- Infiltration, soil moisture, and ground water.
- Runoff.

Interception, Transpiration, and Evapotranspiration

More than two-thirds of the precipitation falling over the United States evaporates to the atmosphere rather than being discharged as streamflow to the oceans. This "short-circuiting" of the hydrologic cycle occurs because of the two processes, interception and transpiration.

Interception

A portion of precipitation never reaches the ground because it is intercepted by vegetation and other natural and constructed surfaces. The amount of water intercepted in this manner is determined by the amount of interception storage available on the above-ground surfaces.

In vegetated areas, storage is a function of plant type and the form and density of leaves, branches, and stems (**Table 2.1**). Factors that affect storage in forested areas include:

- Leaf shape. Conifer needles hold water more efficiently than leaves. On leaf surfaces droplets run together and roll off. Needles, however, keep droplets separated.
- Leaf texture. Rough leaves store more water than smooth leaves.
- Time of year. Leafless periods provide less interception potential in the canopy than growing periods; however, more storage sites are created by leaf litter during this time.
- Vertical and horizontal density. The more layers of vegetation that precipitation must penetrate, the less likely it is to reach the soil.
- Age of the plant community. Some vegetative stands become more dense with age; others become less dense.

The intensity, duration, and frequency of precipitation also affect levels of interception.

Figure 2.3 shows some of the pathways rainfall can take in a forest. Rainfall at

Table 2.1: Percentage of precipitation intercepted for various vegetation types.
Source: Dunne and Leopold 1978.

Vegetative Type	% Precipitation Intercepted
Forests	
Deciduous	13
Coniferous	28
Crops	
Alfalfa	36
Corn	16
Oats	7
Grasses	10–20

the beginning of a storm initially fills interception storage sites in the canopy. As the storm continues, water held in these storage sites is displaced. The displaced water drops to the next lower layer of branches and limbs and fills storage sites there. This process is repeated until displaced water reaches the lowest layer, the leaf litter. At this point, water displaced off the leaf litter either infiltrates the soil or moves downslope as surface runoff.

Antecedent conditions, such as moisture still held in place from previous storms, affect the ability to intercept and store additional water. Evaporation will eventually remove water residing in interception sites. How fast this process occurs depends on climatic conditions that affect the evaporation rate.

Interception is usually insignificant in areas with little or no vegetation. Bare soil or rock has some small impermeable depressions that function as interception storage sites, but typically most of the precipitation either infiltrates the soil or moves downslope as surface runoff. In areas of frozen soil, interception storage sites are typically filled with frozen water. Consequently, additional rainfall is rapidly transformed into surface runoff.

Interception can be significant in large urban areas. Although urban drainage systems are designed to quickly move storm water off impervious surfaces, the urban landscape is rich with storage sites. These include flat rooftops, parking lots, potholes, cracks, and other rough surfaces that can intercept and hold water for eventual evaporation.

Transpiration and Evapotranspiration

Transpiration is the diffusion of water vapor from plant leaves to the atmosphere. Unlike intercepted water, which originates from precipitation, transpired

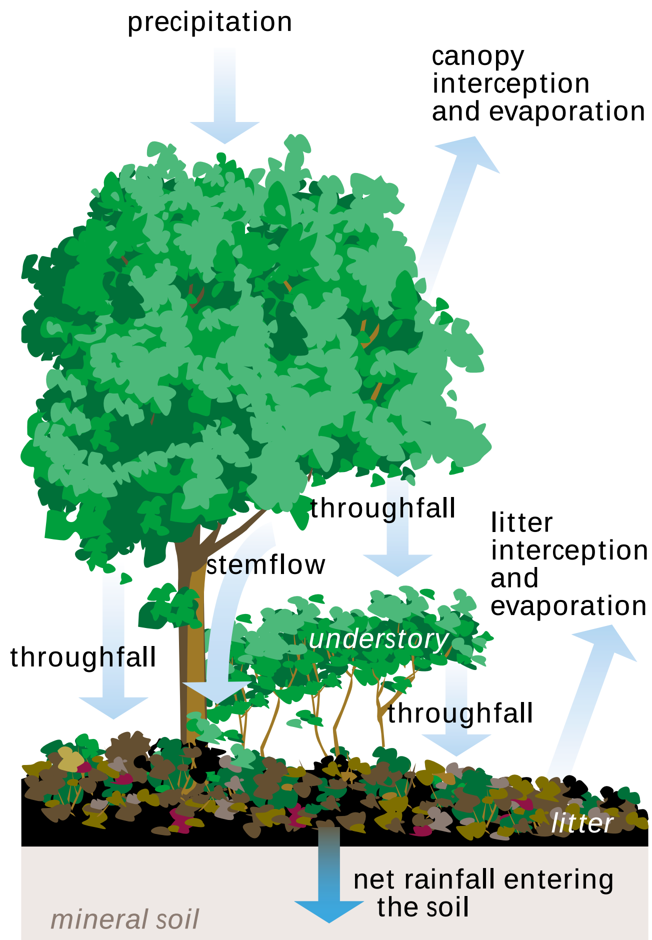


Figure 2.3: Typical pathways for forest rainfall. *A portion of precipitation never reaches the ground because it is intercepted by vegetation and other surfaces.*

water originates from water taken in by roots.

Transpiration from vegetation and evaporation from interception sites and open water surfaces, such as ponds and lakes, are not the only sources of water returned to the atmosphere. Soil moisture also is subject to evaporation. Evaporation of soil moisture is, however, a much slower process due to capillary and osmotic forces that keep the moisture in the soil and the fact that vapor must diffuse upward through soil pores to reach surface air at a lower vapor pressure.

Because it is virtually impossible to separate water loss due to transpiration

Evaporation

Water is subject to evaporation whenever it is exposed to the atmosphere. Basically this process involves:

- *The change of state of water from liquid to vapor*
- *The net transfer of this vapor to the atmosphere*

The process begins when some molecules in the liquid state attain sufficient kinetic energy (primarily from solar energy) to overcome the forces of surface tension and move into the atmosphere. This movement creates a vapor pressure in the atmosphere.

*The net rate of movement is proportional to the difference in vapor pressure between the water surface and the atmosphere above that surface. Once the pressure is equalized, no more evaporation can occur until new air, capable of holding more water vapor, displaces the old saturated air. Evaporation rates therefore vary according to latitude, season, time of day, cloudiness, and wind energy. Mean annual lake evaporation in the United States, for example, varies from 20 inches in Maine and Washington to about 86 inches in the desert Southwest (**Figure 2.4**).*

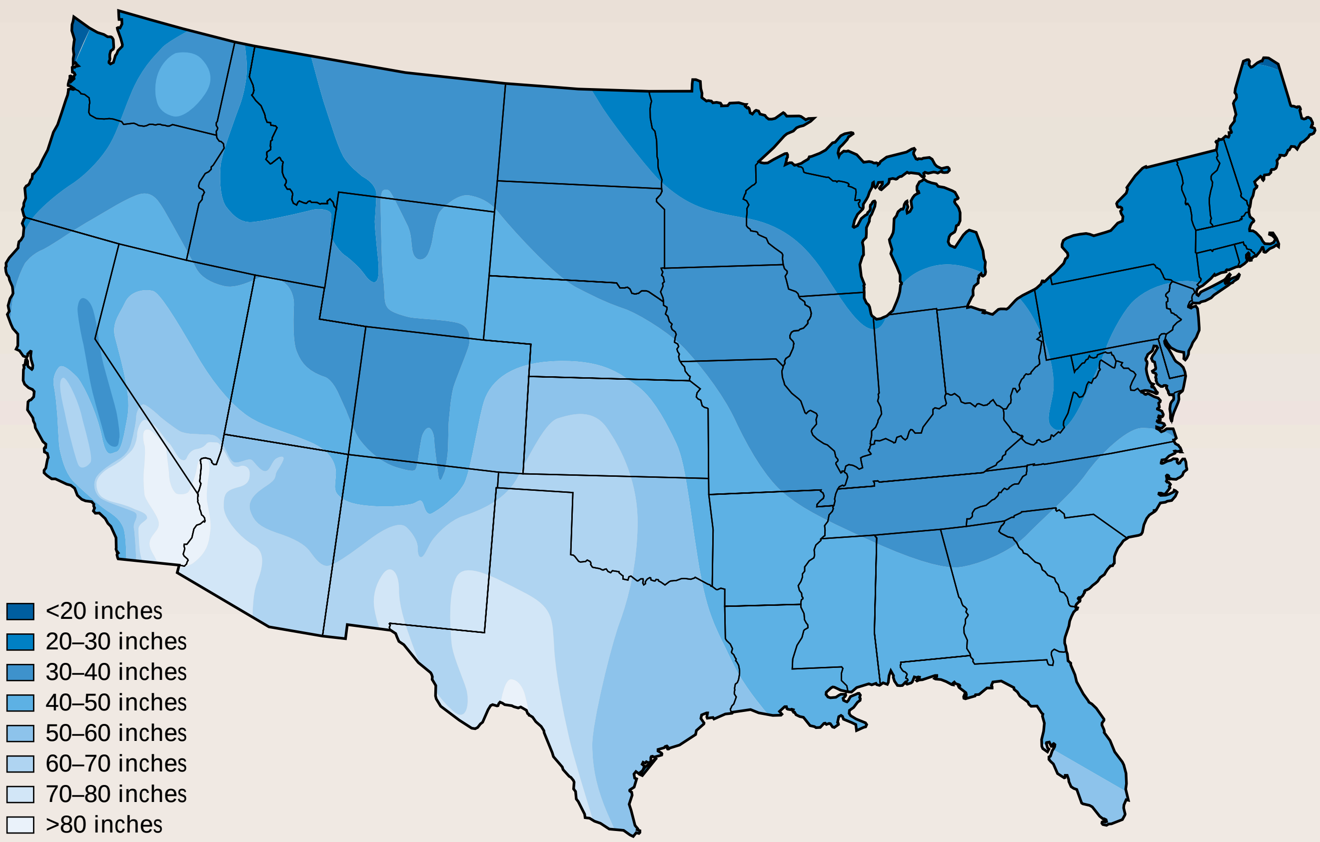


Figure 2.4: Mean annual lake evaporation for the period 1946–1955.
Source: Dunne and Leopold (1978) modified from Kohler et al. (1959).

from water loss due to evaporation, the two processes are commonly combined and labeled *evapotranspiration*. Evapotranspiration can dominate the water balance and can control soil moisture content, ground water recharge, and streamflow.

The following concepts are important when describing evapotranspiration:

- If soil moisture conditions are limiting, the actual rate of evapotranspiration is below its potential rate.
- When vegetation loses water to the atmosphere at a rate unlimited by the supply of water replenishing the roots, its actual rate of evapotranspiration is equal to its potential rate of evapotranspiration.

The amount of precipitation in a region drives both processes, however. Soil types and rooting characteristics also play important roles in determining the actual rate of evapotranspiration.

Infiltration, Soil Moisture, and Ground Water

Precipitation that is not intercepted or flows as surface runoff moves into the soil. Once there, it can be stored in the upper layer or move downward through the soil profile until it reaches an area completely saturated by water called the *phreatic zone*.

Infiltration

Close examination of the soil surface reveals millions of particles of sand, silt, and clay separated by channels of different sizes (**Figure 2.5**). These *macropores* include cracks, "pipes" left by decayed roots and wormholes, and pore spaces between lumps and particles of soil.

Water is drawn into the pores by gravity and capillary action. Gravity is the dominant force for water moving into the largest openings, such as worm or root holes. Capillary action is the domi-

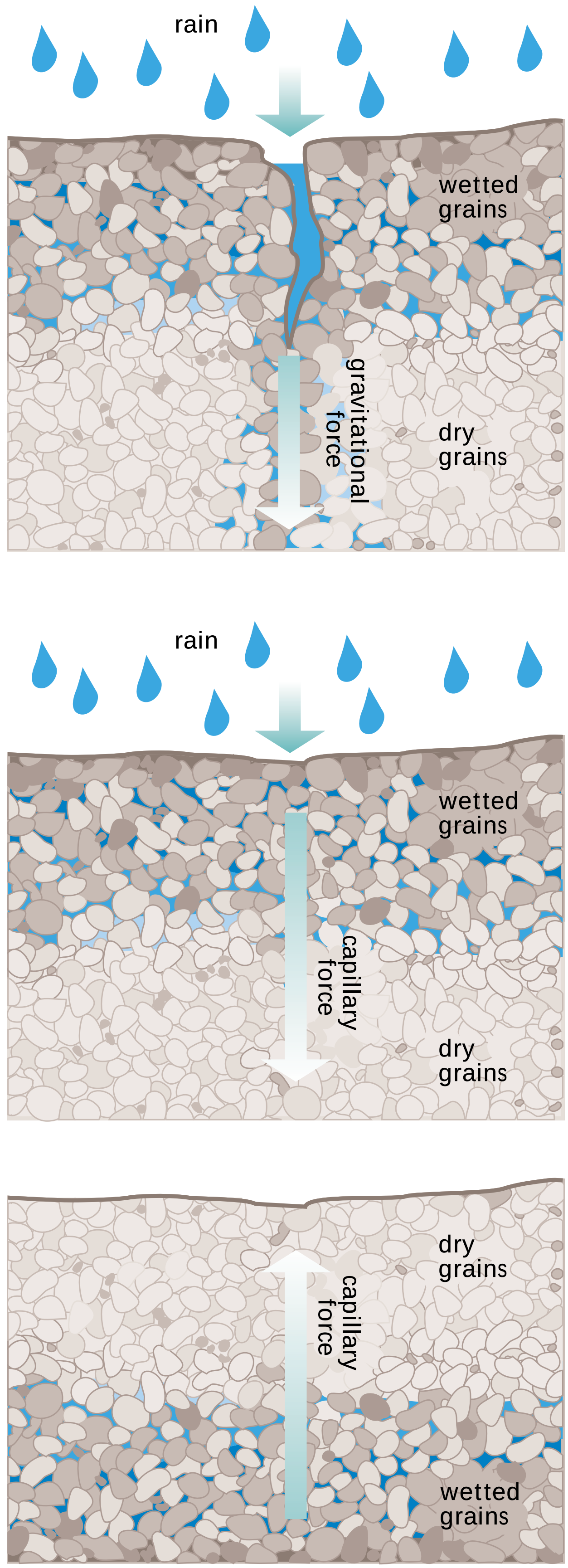


Figure 2.5: Soil profile. *Water is drawn into the pores in soil by gravity and capillary action.*

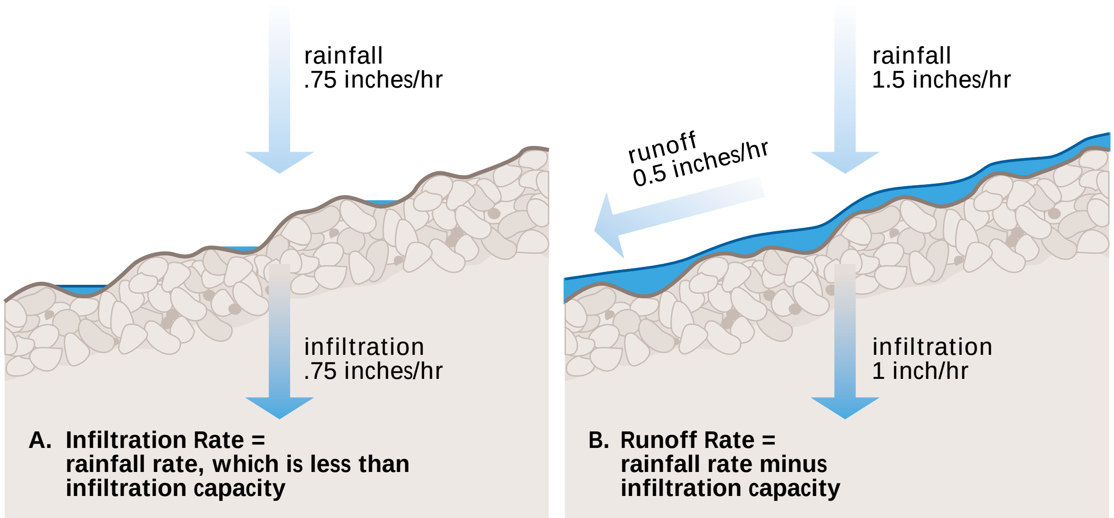


Figure 2.6: Infiltration and runoff. *Surface runoff occurs when rainfall intensity exceeds infiltration capacity.*

nant force for water moving into soils with very fine pores.

The size and density of these pore openings determine the water's rate of entry into the soil. *Porosity* is the term used to describe the percentage of the total soil volume taken up by spaces between soil particles. When all those spaces are filled with water, the soil is said to be saturated.

Soil characteristics such as texture and tilth (looseness) are key factors in determining porosity. Coarse-textured, sandy soils and soils with loose aggregates held together by organic matter or small amounts of clay have large pores and, thus, high porosity. Soils that are tightly packed or clayey have low porosity.

Infiltration is the term used to describe the movement of water into soil pores. The *infiltration rate* is the amount of water that soaks into soil over a given length of time. The maximum rate that water infiltrates a soil is known as the soil's *infiltration capacity*.

If rainfall intensity is less than infiltration capacity, water infiltrates the soil at a rate equal to the rate of rainfall. If the rainfall rate exceeds the infiltration capacity, the excess water either is detained in small depressions on the soil surface or travels downslope as surface runoff (**Figure 2.6**).

The following factors are important in determining a soil's infiltration rate:

- Ease of entry through the soil surface.
- Storage capacity within the soil.
- Transmission rate through the soil.

Areas with natural vegetative cover and leaf litter usually have high infiltration rates. These features protect the surface soil pore spaces from being plugged by fine soil particles created by raindrop splash. They also provide habitat for worms and other burrowing organisms and provide organic matter that helps bind fine soil particles together. Both of these processes increase porosity and the infiltration rate.

The rate of infiltration is not constant throughout the duration of a storm. The rate is usually high at the beginning of a storm but declines rapidly as gravity-fed storage capacity is filled. A slower, but stabilized, rate of infiltration is reached typically 1 or 2 hours into a storm. Several factors are involved in this stabilization process, including the following:

- Raindrops breaking up soil aggregates and producing finer material, which then blocks pore openings on the surface and reduces the ease of entry.
- Water filling fine pore spaces and reducing storage capacity.
- Wetted clay particles swelling and effectively reducing the diameter of pore spaces, which, in turn, reduces transmission rates.

Soils gradually drain or dry following a storm. However, if another storm occurs before the drying process is completed, there is less storage space for new water. Therefore, antecedent moisture conditions are important when analyzing available storage.

Soil Moisture

After a storm passes, water drains out of upper soils due to gravity. The soil remains moist, however, because some amount of water remains tightly held in fine pores and around particles by surface tension. This condition, called *field capacity*, varies with soil texture. Like porosity, it is expressed as a proportion by volume.

The difference between porosity and field capacity is a measure of unfilled pore space (**Figure 2.7**). Field capacity is an approximate number, however, because gravitation drainage continues in moist soil at a slow rate.

Soil moisture is most important in the context of evapotranspiration. Terrestrial plants depend on water stored in soil. As their roots extract water from progressively finer pores, the moisture content in the soil may fall below the field capacity. If soil moisture is not replenished, the roots eventually reach a point where they cannot create enough suction to extract the tightly held interstitial pore water. The moisture content of the soil at this point, which varies depending on soil characteristics, is called the *permanent wilting point* because plants can no longer withdraw water from the soil at a rate high enough to keep up with the demands of transpiration, causing the plants to wilt.

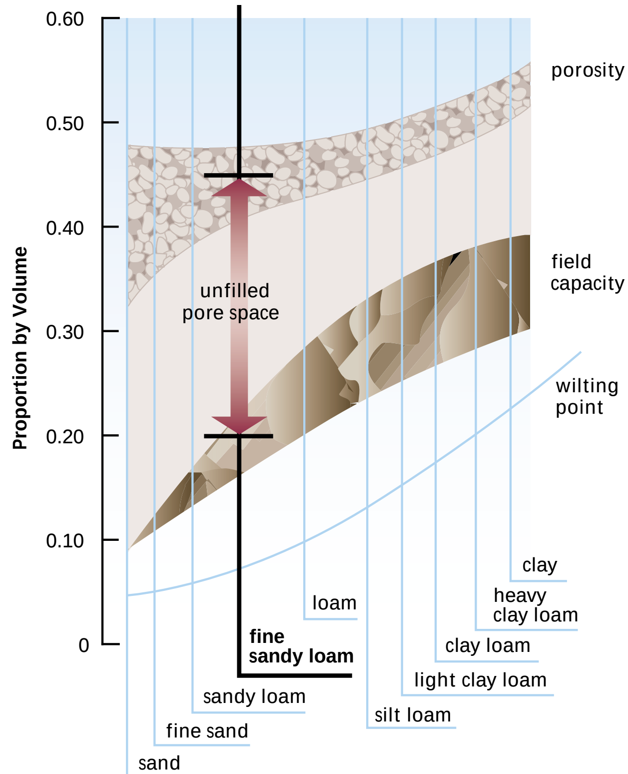


Figure 2.7: Water-holding properties of various soils. *Water-holding properties vary by texture. For a fine sandy loam the approximate difference between porosity, 0.45, and field capacity, 0.20, is 0.25, meaning that the unfilled pore space is 0.25 times the soil volume. The difference between field capacity and wilting point is a measure of unfilled pore space.*
Source: Dunne and Leopold 1978.

Deep percolation is the amount of water that passes below the root zone of crops, less any upward movement of water from below the root zone (Jensen et al. 1990).

Ground Water

The size and quantity of pore openings also determines the movement of water within the soil profile. Gravity causes water to move vertically downward. This movement occurs easily through larger pores. As pores reduce in size due to swelling of clay particles or filling of pores, there is a greater resistance to flow. Capillary forces eventually take over and cause water to move in any direction.

Water will continue to move downward until it reaches an area completely saturated with water, the *phreatic zone* or zone of saturation (**Figure 2.8**). The top of the phreatic zone defines the *ground water table* or phreatic surface. Just above the ground water table is an area called the *capillary fringe*, so named because the pores in this area are filled with water held by capillary forces.

In soils with tiny pores, such as clay or silt, the capillary forces are strong. Consequently, the capillary fringe can extend a large distance upward from the water table. In sandstone or soils with large pores, the capillary forces are weak and the fringe narrow.

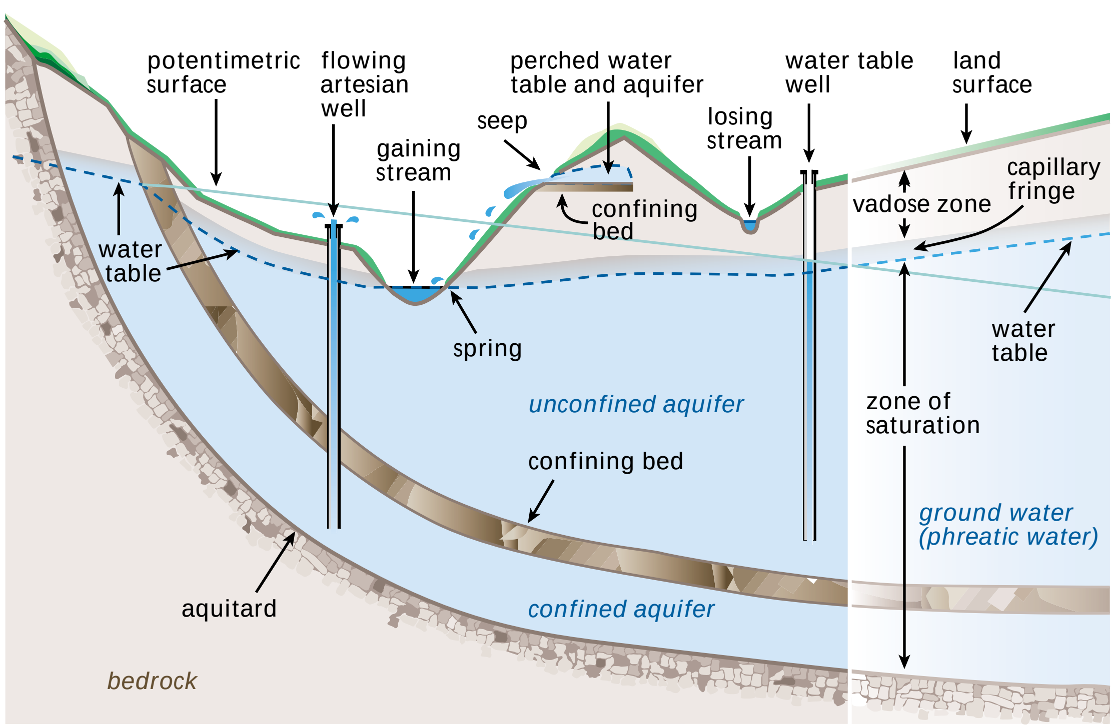
Between the capillary fringe and the soil surface is the *vadose zone*, or the zone of aeration. It contains air and microbial respiratory gases, capillary water, and water moving downward by gravity to the phreatic zone. *Pellicular water* is the film of ground water that adheres to individual particles above the ground water table. This water is held above the capillary fringe by molecular attraction.

If the phreatic zone provides a consistent supply of water to wells, it is known as an *aquifer*. Good aquifers usually have a large lateral and vertical extent relative to the amount of water withdrawn from wells and high porosity, which allows water to drain easily.

The opposite of an aquifer is an aquitard or confining bed. *Aquitards* or *confining beds* are relatively thin sediment or rock layers that have low permeability. Vertical water movement through an aquitard is severely restricted. If an aquifer has no confining layer overlying it, it is known as an *unconfined aquifer*. A *confined aquifer* is one confined by an aquitard.

The complexity and diversity of aquifers and aquitards result in a multitude of

igure 2.8: Ground vater related features and terminology. *Ground water elevation along the tream corridor can vary significantly over hort distances, depending on subsurface characteristics.* Source: USGS Water Supply Paper #1988, 1972, Definitions of Selected Ground Water Terms.



underground scenarios. For example, *perched ground water* occurs when a shallow aquitard of limited size prevents water from moving down to the phreatic zone. Water collects above the aquitard and forms a "mini-phreatic zone." In many cases, perched ground water appears only during a storm or during the wet season. Wells tapping perched ground water may experience a shortage of water during the dry season. Perched aquifers can, however, be important local sources of ground water.

Artesian wells are developed in confined aquifers. Because the hydrostatic pressure in confined aquifers is greater than atmospheric pressure, water levels in artesian wells rise to a level where atmospheric pressure equals hydrostatic pressure. If this elevation is above the ground surface, water can flow freely out of the well.

Water also will flow freely where the ground surface intersects a confined aquifer. The *piezometric surface* is the level to which water would rise in wells tapped into confined aquifers if the wells extended indefinitely above the ground surface. Phreatic wells draw water from below the phreatic zone in unconfined aquifers. The water level in a phreatic well is the same as the ground water table.

Practitioners of stream corridor restoration should be concerned with locations where ground water and surface water are exchanged. Areas that freely allow movement of water to the phreatic zone are called *recharge areas*. Areas where the water table meets the soil surface or where stream and ground water emerge are called *springs* or *seeps*.

The volume of ground water and the elevation of the water table fluctuate according to ground water recharge and discharge. Because of the fluctuation of water table elevation, a stream channel can function either as a recharge area (influent or "losing" stream) or a discharge area (effluent or "gaining" stream).

Runoff

When the rate of rainfall or snowmelt exceeds infiltration capacity, excess water collects on the soil surface and travels downslope as runoff. Factors that affect runoff processes include climate, geology, topography, soil characteristics, and vegetation. Average annual runoff in the contiguous United States ranges from less than 1 inch to more than 20 inches (**Figure 2.9**).

Three basic types of runoff are introduced in this subsection (**Figure 2.10**):

- Overland flow
- Subsurface flow
- Saturated overland flow

Each of these runoff types can occur individually or in some combination in the same locale.

Overland Flow

When the rate of precipitation exceeds the rate of infiltration, water collects on the soil surface in small depressions (**Figure 2.11**). The water stored in these spaces is called *depression storage*. It eventually is returned to the atmosphere through evaporation or infiltrates the soil surface.

After depression storage spaces are filled, excess water begins to move downslope as overland flow, either as a shallow sheet of water or as a series of small rivulets or rills. Horton (1933) was the first to describe this process in the literature. The term *Horton overland flow* or Hortonian flow is commonly used.

The sheet of water increases in depth and velocity as it moves downhill. As it travels, some of the overland flow is trapped on the hillside and is called *sur-*

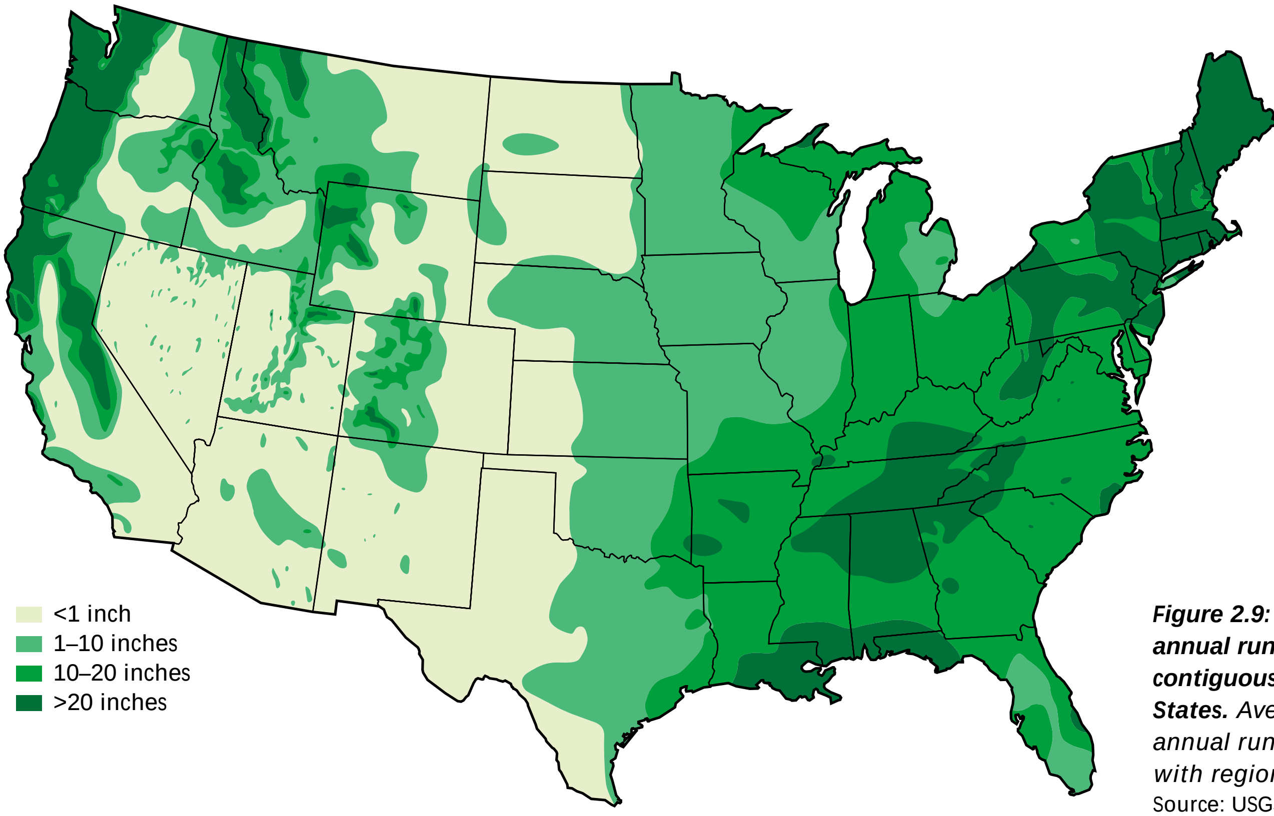


Figure 2.9: Average annual runoff in the contiguous United States. *Average annual runoff varies with regions.*
Source: USGS 1986.

face detention. Unlike depression storage, which evaporates to the atmosphere or enters the soil, surface detention is only temporarily detained from its journey downslope. It eventually runs off into the stream and is still considered part of the total volume of overland flow.

Overland flow typically occurs in urban and suburban settings with paved and impermeable surfaces. Paved areas and soils that have been exposed and compacted by heavy equipment or vehicles are also prime settings for overland flow. It is also common in areas of thin soils with sparse vegetative cover such as in mountainous terrain of arid or semiarid regions.

Subsurface Flow

Once in the soil, water moves in response to differences in hydraulic head (the potential for flow due to the gradient of hydrostatic pressure at different elevations). Given a simplified situation, the water table before a rainstorm has a parabolic surface that slopes toward a stream. Water moves downward and along this slope and into the stream channel. This portion of the flow is the baseflow. The soil below the water table is, of course, saturated. Assuming the hill slope has uniform soil characteristics, the moisture content of surface soils diminishes with distance from the stream.

During a storm, the soil nearest the stream has two important attributes as compared to soil upslope—a higher moisture content and a shorter distance to the water table. These attributes cause the water table to rise more rapidly in response to rainwater infiltration and causes the water table to steepen. Thus a new, storm-generated ground water component is added to baseflow. This new component, called *subsurface flow*, mixes with baseflow and increases ground water discharge to the channel.

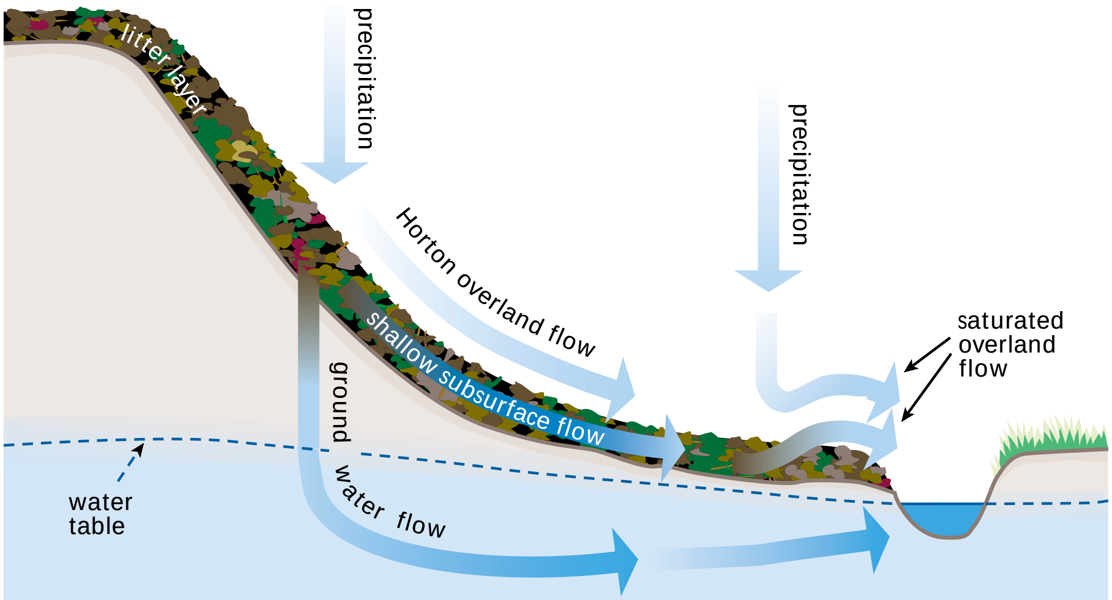


Figure 2.10: Flow paths of water over a surface. *The portion of precipitation that runs off or infiltrates to the ground water table depends on the soil's permeability rate; surface roughness; and the amount, duration, and intensity of precipitation.*

In some situations, infiltrated storm water does not reach the phreatic zone because of the presence of an aquitard. In this case, subsurface flow does not mix with baseflow, but also discharges water into the channel. The net result, whether mixed or not, is increased channel flow.

Saturated Overland Flow

If the storm described above continues, the slope of the water table surface can continue to steepen near the stream. Eventually, it can steepen to the point that the water table rises above the channel elevation. Additionally, ground water can break out of the soil and travel to the stream as overland flow. This type of runoff is termed *quick return flow*.

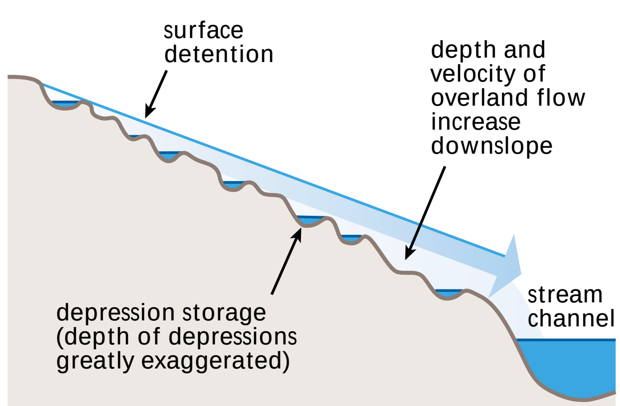
The soil below the ground water breakout is, of course, saturated. Consequently, the maximum infiltration rate is reached, and all of the rain falling on it flows downslope as overland runoff. The combination of this direct precipitation and quick return flow is called *saturated overland flow*. As the storm progresses, the saturated area expands further up the hillside. Because quick return flow and subsurface flow are so closely linked to overland flow, they are normally considered part of the overall runoff of surface water.

Hydrologic and Hydraulic Processes Along the Stream Corridor

Water flowing in streams is the collection of direct precipitation and water that has moved laterally from the land into the channel. The amount and timing of this lateral movement directly influences

Figure 2.11: Overland flow and depression storage. *Overland moves downslope as an irregular sheet.*

Source: Dunne and Leopold 1978.



FAST FORWARD

review Chap-
er 7, Section
A for more de-
ailed informa-
ion about
low duration
and frequency.

the amount and timing of streamflow, which in turn influences ecological functions in the stream corridor.

Flow Analysis

Flows range from no flow to flood flows in a variety of time scales. On a broad scale, historical climate records reveal occasional persistent periods of wet and dry years. Many rivers in the United States, for example, experienced a decline in flows during the "dust bowl" decade in the 1930s. Another similar decline in flows nationwide occurred in the 1950s. Unfortunately, the length of record regarding wet and dry years is short (in geologic time), making it is difficult to predict broad-scale persistence of wet or dry years.

Seasonal variations of streamflow are more predictable, though somewhat complicated by persistence factors. Because design work requires using historical information (period of record) as a basis for designing for the future, flow information is usually presented in a probability format. Two formats are especially useful for planning and designing stream corridor restoration:

- *Flow duration*, the probability a given streamflow was equaled or exceeded over a period of time.
- *Flow frequency*, the probability a given streamflow will be exceeded (or not exceeded) in a year. (Sometimes this concept is modified and expressed as the average number of years between exceeding [or not exceeding] a given flow.)

Figure 2.12 presents an example of a flow frequency expressed as a series of probability curves. The graph displays months on the x-axis and a range of mean monthly discharges on the y-axis. The curves indicate the probability that the mean monthly discharge will be less than the value indicated by the curve. For example, on about January 1, there is a 90 percent chance that the

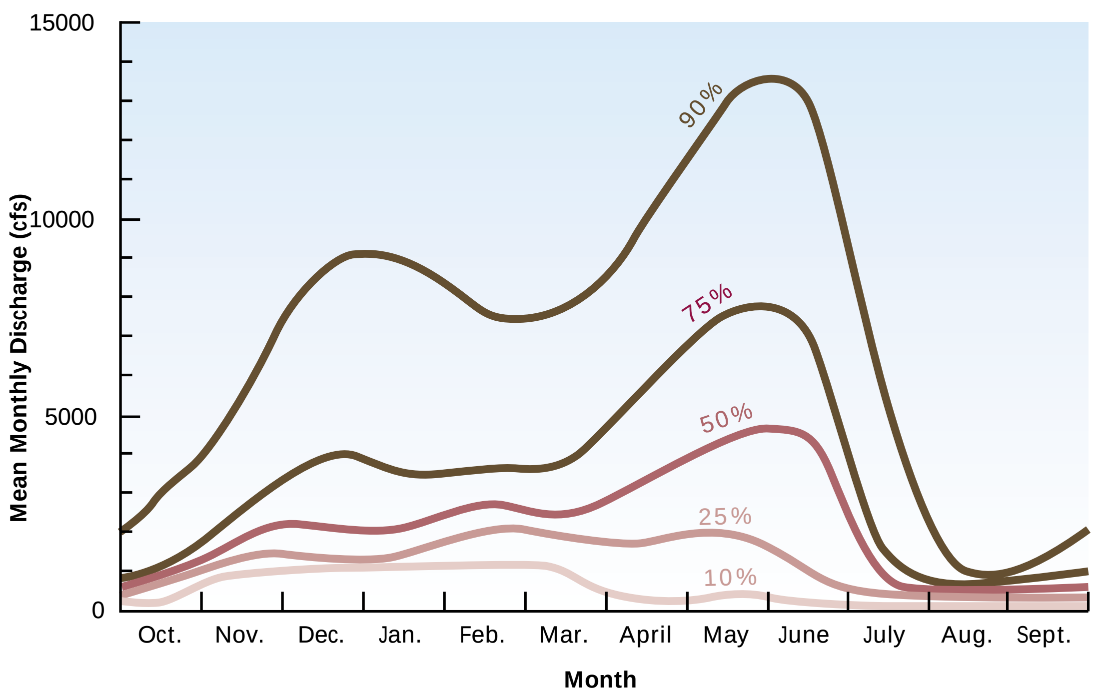


Figure 2.12: An example of monthly probability curves. *Monthly probability that the mean monthly discharge will be less than the values indicated. Yakima River near Parker, Washington. (Data from U.S. Army Corps of Engineers.)*
Source: Dunne and Leopold 1978.

discharge will be less than 9,000 cfs and a 50 percent chance it will be less than 2,000 cfs.

Ecological Impacts of Flow

The variability of streamflow is a primary influence on the biotic and abiotic processes that determine the structure and dynamics of stream ecosystems (Covich 1993). High flows are important not only in terms of sediment transport, but also in terms of reconnecting floodplain wetlands to the channel.

This relationship is important because floodplain wetlands provide spawning and nursery habitat for fish and, later in the year, foraging habitat for waterfowl. Low flows, especially in large rivers, create conditions that allow tributary fauna to disperse, thus maintaining populations of a single species in several locations.

In general, completion of the life cycle of many riverine species requires an array of different habitat types whose temporal availability is determined by the flow regime. Adaptation to this environmental dynamism allows riverine species to persist during periods of droughts and floods that destroy and recreate habitat elements (Poff et al. 1997).

2.B Geomorphic Processes

Geomorphology is the study of surface forms of the earth and the processes that developed those forms. The hydrologic processes discussed in the previous section drive the geomorphic processes described in this section. In turn, the geomorphic processes are the primary mechanisms for forming the drainage patterns, channel, floodplain, terraces, and other watershed and stream corridor features discussed in Chapter 1.

Three primary geomorphic processes are involved with flowing water, as follows:

- *Erosion*, the detachment of soil particles.
- *Sediment transport*, the movement of eroded soil particles in flowing water.
- *Sediment deposition*, settling of eroded soil particles to the bottom of a water body or left behind as water leaves. Sediment deposition can be transitory, as in a stream channel from one storm to another, or more or less permanent, as in a larger reservoir.

Since geomorphic processes are so closely related to the movement of water, this section is organized into subsections that mirror the hydrologic processes of surface storm water runoff and streamflow:

- Geomorphic Processes Across the Stream Corridor
- Geomorphic Processes Along the Stream Corridor

Geomorphic Processes Across the Stream Corridor

The occurrence, magnitude, and distribution of erosion processes in watersheds affect the yield of sediment and associated water quality contaminants to the stream corridor.

Soil erosion can occur gradually over a long period, or it can be cyclic or episodic, accelerating during certain seasons or during certain rainstorm events (**Figure 2.13**). Soil erosion can be caused by human actions or by natural processes. Erosion is not a simple process because soil conditions are continually changing with temperature, moisture content, growth stage and amount of vegetation, and the human manipulation of the soil for development or crop production. **Tables 2.2 and 2.3** show the basic processes that influence soil erosion and the different types of erosion found within the watershed.

Geomorphic Processes Along the Stream Corridor

The channel, floodplain, terraces, and other features in the stream corridor are formed primarily through the erosion, transport, and deposition of sediment by streamflow. This subsection describes the processes involved with transporting sediment loads downstream and how the channel and floodplain adjust and evolve through time.

Sediment Transport

Sediment particles found in the stream channel and floodplain can be categorized according to size. A boulder is the largest particle and clay is the smallest particle. Particle density depends on the size and composition of the particle (i.e., the specific gravity of the mineral content of the particle).

No matter the size, all particles in the channel are subject to being transported downslope or downstream. The size of the largest particle a stream can move under a given set of hydraulic conditions is referred to as *stream competence*. Often, only very high flows are competent to move the largest particles.

Closely related to stream competence is the concept of *tractive stress*, which creates lift and drag forces at the stream boundaries along the bed and banks. Tractive stress, also known as *shear stress*, varies as a function of flow depth and slope. Assuming constant density, shape, and surface roughness, the larger the particle, the greater the amount of tractive stress needed to dislodge it and move it downstream.

The energy that sets sediment particles into motion is derived from the effect of faster water flowing past slower water. This velocity gradient happens because the water in the main body of flow moves faster than water flowing at the boundaries. This is because bound-

Figure 2.13: Raindrop impact. *One of many types of erosion.*

aries are rough and create friction as flow moves over them which, in turn, slows flow.

The momentum of the faster water is transmitted to the slower boundary water. In doing so, the faster water tends to roll up the slower water in a spiral motion. It is this shearing motion, or shear stress, that also moves bed particles in a rolling motion downstream.

Particle movement on the channel bottom begins as a sliding or rolling motion, which transports particles along the streambed in the direction of flow (**Figure 2.14**). Some particles also may move above the bed surface by *saltation*, a skipping motion that occurs when one particle collides with another particle, causing it to bounce upward and then fall back toward the bed.

These rolling, sliding, and skipping motions result in frequent contact of the moving particles with the streambed and characterize the set of moving particles known as *bed load*. The weight of these particles relative to flow velocity causes them essentially to remain in contact with, and to be supported by, the streambed as they move downstream.

Table 2.2: Erosion processes.

Agent	Process
Raindrop impact	Sheet, interill
Surface water runoff	Sheet, interill, rill, ephemeral gully, classic gully
Channelized flow	Rill, ephemeral gully, classic gully, wind, streambank
Gravity	Classic gully, streambank, landslide, mass wasting
Wind	Wind
Ice	Streambank, lake shore
Chemical reactions	Solution, dispersion

Table 2.3: Erosion types vs. physical processes.

	Erosion/Physical Process			
Erosion Type	Sheet	Concentrated Flow	Mass Wasting	Combination
Sheet and rill	x	x		
Interill	x			
Rill	x	x		
Wind	x	x		
Ephemeral gully		x		
Classic gully		x	x	
Floodplain scour		x		
Roadside				x
Streambank		x	x	
Streambed		x		
Landslide			x	
Wave/shoreline				x
Urban, construction				x
Surface mine				x
Ice gouging				x

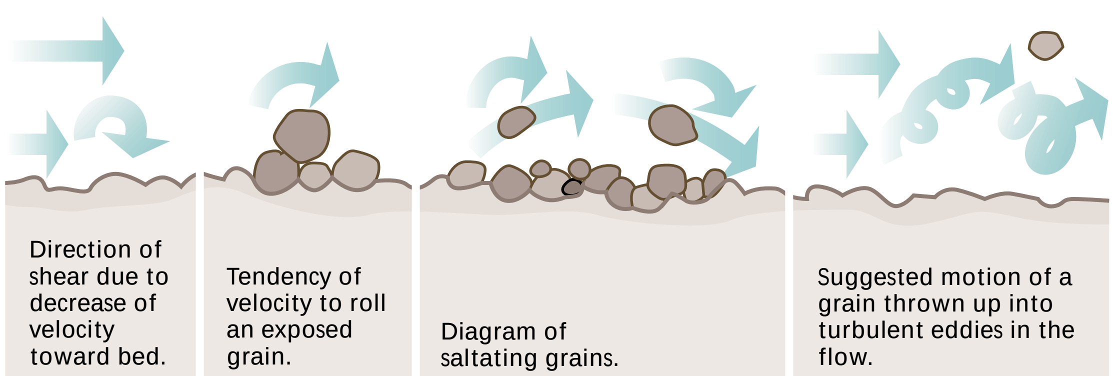


Figure 2.14: Action of water on particles near the streambed. *Processes that transport bed load sediments are a function of flow velocities, particle size, and principles of hydrodynamics.*
Source: *Water in Environmental Planning* by Dunne and Leopold © 1978 by W.H. Freeman and Company. Used with permission.

Wash Load and Bed-Material Load

One way to differentiate the sediment load of a stream is to characterize it based on the immediate source of the sediment in transport. The total sediment load in a stream, at any given time and location, is divided into two parts—wash load and bed-material load. The primary source of wash load is the watershed, including sheet and rill erosion, gully erosion, and upstream streambank erosion. The source of bed material load is primarily the streambed itself, but includes other sources in the watershed.

Wash load is composed of the finest sediment particles in transport. Turbulence holds the wash load in suspension. The concentration of wash load in suspension is essentially independent of hydraulic conditions in the stream and therefore cannot be calculated using measured or estimated hydraulic parameters such as velocity or discharge. Wash load concentration is normally a function of supply; i.e., the stream can carry as much wash load as the watershed and banks can deliver (for sediment concentrations below approximately 3000 parts per million).

Bed-material load is composed of the sediment of size classes found in the streambed. Bed-material load moves along the streambed by rolling, sliding, or jumping, and may be periodically entrained into the flow by turbulence, where it becomes a portion of the suspended load. Bed-material load is hydraulically controlled and can be computed using sediment transport equations discussed in Chapter 8.

Finer-grained particles are more easily carried into suspension by turbulent eddies. These particles are transported within the water column and are therefore called the *suspended load*. Although there may be continuous exchange of sediment between the bed load and suspended load of the river, as long as sufficient turbulence is present.

Part of the suspended load may be colloidal clays, which can remain in suspension for very long time periods, depending on the type of clay and water chemistry.

Sediment Transport Terminology

Sediment transport terminology can sometimes be confusing. Because of this confusion, it is important to define some of the more frequently used terms.

- *Sediment load*, the quantity of sediment that is carried past any cross section of a stream in a specified period of time, usually a day or a year. *Sediment discharge*, the mass or volume of sediment passing a stream cross section in a unit of time. Typical units for sediment load are tons, while sediment discharge units are tons per day.
- *Bed-material load*, part of the total sediment discharge that is composed of sediment particles that are the same size as streambed sediment.
- *Wash load*, part of the total sediment load that is comprised of particle sizes finer than those found in the streambed.
- *Bed load*, portion of the total sediment load that moves on or near the streambed by saltation, rolling, or sliding in the bed layer.
- *Suspended bed material load*, portion of the bed material load that is transported in suspension in the water column. The suspended bed material load and the bed load comprise the total bed material load.
- *Suspended sediment discharge* (or *suspended load*), portion of the total sediment load that is transported in suspension by turbulent fluctuations within the body of flowing water.

- *Measured load*, portion of the total sediment load that is obtained by the sampler in the sampling zone.
- *Unmeasured load*, portion of the total sediment load that passes beneath the sampler, both in suspension and on the bed. With typical suspended sediment samplers this is the lower 0.3 to 0.4 feet of the vertical.

The above terms can be combined in a number of ways to give the total sediment load in a stream (**Table 2.4**). However, it is important not to combine terms that are not compatible. For example, the suspended load and the bed material load are not complimentary terms because the suspended load may include a portion of the bed material load, depending on the energy available for transport. The total sediment load is correctly defined by the combination of the following terms:

Total Sediment Load =

Bed Material Load + Wash Load

or

Bed Load + Suspended Load

or

Measured Load + Unmeasured Load

Sediment transport rates can be computed using various equations or models. These are discussed in the *Stream Channel Restoration* section of Chapter 8.

Table 2.4: Sediment load terms.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Classification System</td></tr>
<tr><td>Based on Mechanism of Transport</td><td>Based on Particle Size</td></tr>
<tr><td rowspan="3">Total sediment load</td><td>Wash load</td><td rowspan="2">Suspended load</td><td>Wash load</td></tr>
<tr><td>Suspended bed-material load</td><td rowspan="2">Bed-material load</td></tr>
<tr><td>Bed load</td><td>Bed load</td></tr>
</table>

Stream Power

One of the principal geomorphic tasks of a stream is to transport particles out of the watershed (**Figure 2.15**). In this manner, the stream functions as a transporting "machine;" and, as a machine, its rate of doing work can be calculated as the product of available power multiplied by efficiency.

Stream power can be calculated as:

$$\varphi = \gamma Q S$$

Where:

φ = Stream power (foot-lbs/second-foot)

γ = Specific weight of water (lbs/ft^3)

Q = Discharge (ft^3/second)

S = Slope (feet/feet)

Sediment transport rates are directly related to stream power; i.e., slope and discharge. Baseflow that follows the highly sinuous thalweg (the line that marks the deepest points along the stream channel) in a meandering stream generates little stream power; therefore, the stream's ability to move sediment, *sediment-transport capacity,* is limited. At greater depths, the flow follows a straighter course, which increases slope, causing increased sediment transport rates. The stream builds its cross section to obtain depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel.

Runoff can vary from a watershed, either due to natural causes or land use practices. These variations may change the size distribution of sediments delivered to the stream from the watershed by preferentially moving particular particle sizes into the stream. It is not uncommon to find a layer of sand on top of a cobble layer. This often happens when accelerated erosion of sandy soils

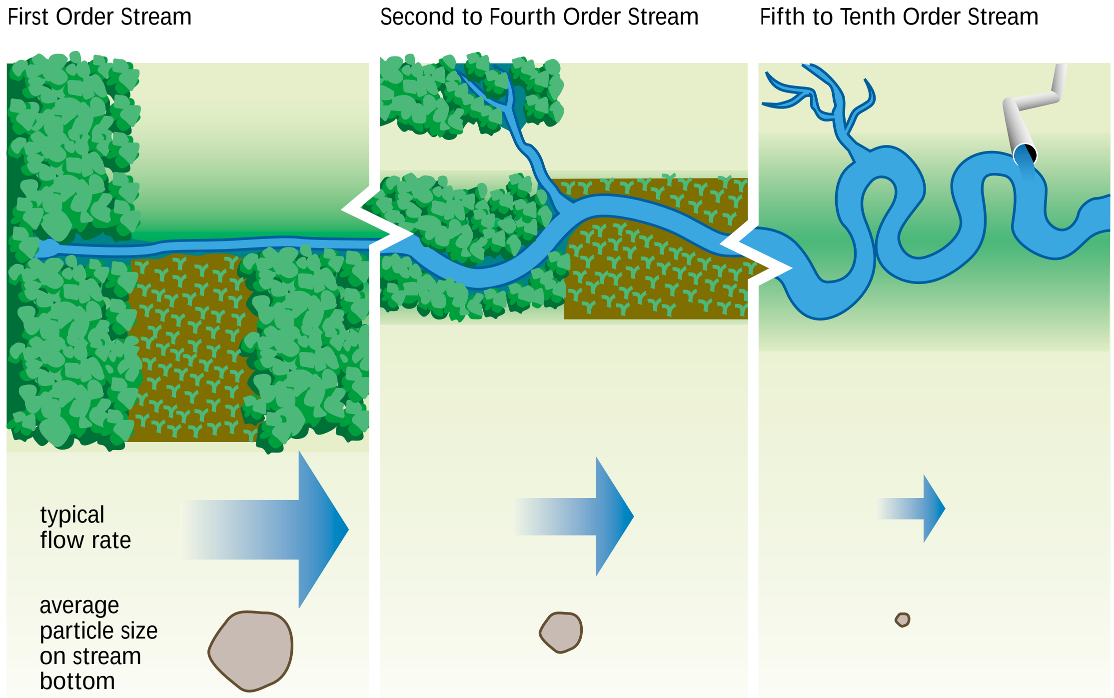


Figure 2.15: Particle transport. *A stream's total sediment load is the total of all sediment particles moving past a defined cross section over a specified time period. Transport rates vary according to the mechanism of transport.*

occurs in a watershed and the increased load of sand exceeds the transport capacity of the stream during events that move the sand into the channel.

Stream and Floodplain Stability

A question that normally arises when considering any stream restoration action is "Is it stable now and will it be stable after changes are made?" The answer may be likened to asking an opinion on a movie based on only a few frames from the reel. Although we often view streams based on a limited reference with respect to time, it is important that we consider the long-term changes and trends in channel cross section, longitudinal profile, and planform morphology to characterize channel stability.

Achieving channel stability requires that the average tractive stress maintains a stable streambed and streambanks. That is, the distribution of particle sizes in each section of the stream remains in equilibrium (i.e., new particles deposited are the same size and shape as particles displaced by tractive stress).

Yang (1971) adapted the basic theories described by Leopold to explain the longitudinal profile of rivers, the formation of stream networks, riffles, and pools, and river meandering. All these river characteristics and sediment transport are closely related. Yang (1971) developed the theory of average stream fall and the theory of least rate of energy expenditure, based on the entropy concept. These theories state that during the evolution toward an equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure per unit mass of flow along its course is a minimum.

Corridor Adjustments

Stream channels and their floodplains are constantly adjusting to the water and sediment supplied by the watershed. Successful restoration of degraded streams requires an understanding of watershed history, including both natural events and land use practices, and the adjustment processes active in channel evolution.

Channel response to changes in water and sediment yield may occur at differing times and locations, requiring various levels of energy expenditure. Daily changes in streamflow and sediment load result in frequent adjustment of bedforms and roughness in many streams with movable beds. Streams also adjust periodically to extreme high- and low-flow events, as floods not only remove vegetation but create and increase vegetative potential along the stream corridor (e.g., low flow periods allow vegetation incursion into the channel).

Similar levels of adjustment also may be brought about by changes in land use in the stream corridor and the upland watershed. Similarly, long-term changes in runoff or sediment yield from natural causes, such as climate change, wildfire, etc., or human causes, such as cultivation, overgrazing, or rural-to-urban conversions, may lead to long-term adjustments in channel cross section and planform that are frequently described as channel evolution.

Stream channel response to changes in flow and sediment load have been described qualitatively in a number of studies (e.g., Lane 1955, Schumm 1977). As discussed in Chapter 1, one of the earliest relationships proposed for explaining stream behavior was suggested by Lane (1955), who related mean annual streamflow (Q_w) and channel slope (S) to bed-material sediment load (Q_s) and median particle size on the streambed (D_{50}):

$$Q_s \bullet D_{50} \sim Q_w \bullet S$$

Lane's relationship suggests that a channel will be maintained in dynamic equilibrium when changes in sediment load and bed-material size are balanced by changes in streamflow or channel gradient. A change in one of these variables causes changes in one or more of the other variables such that dynamic equilibrium is reestablished.

FAST FORWARD

Preview Section E for a further discussion of dynamic equilibrium.

Additional qualitative relationships have been proposed for interpreting behavior of alluvial channels. Schumm (1977) suggested that width (b), depth (d), and meander wavelength (L) are directly proportional, and that channel gradient (S) is inversely proportional to streamflow (Q_w) in an alluvial channel:

$$Q_w \sim \frac{b,\ d,\ L}{S}$$

Schumm (1977) also suggested that width (b), meander wavelength (L), and channel gradient (S) are directly proportional, and that depth (d) and sinuosity (P) are inversely proportional to sediment discharge (Q_s) in alluvial streams:

$$Q_s \sim \frac{b,\ L,\ S}{d,\ P}$$

The above two equations may be rewritten to predict direction of change in channel characteristics, given an increase or decrease in streamflow or sediment discharge:

$$Q_w^+ \sim b^+, d^+, L^+, S^-$$

$$Q_w^- \sim b^-, d^-, L^-, S^+$$

$$Q_s^+ \sim b^+, d^-, L^+, S^+, P^-$$

$$Q_s^- \sim b^-, d^+, L^-, S^-, P^+$$

Combining the four equations above yields additional predictive relationships for concurrent increases or decreases in streamflow and/or sediment discharge:

$Q_w^+ Q_s^+ \sim b^+, d^{+/-}, L^+, S^{+/-}, P^-$

$Q_w^- Q_s^- \sim b^-, d^{+/-}, L^-, S^{+/-}, P^+$

$Q_w^+ Q_s^- \sim b^{+/-}, d^+, L^{+/-}, S^-, P^+$

$Q_w^- Q_s^+ \sim b^{+/-}, d^-, L^{+/-}, S^+, P^-$

Channel Slope

Channel slope, a stream's longitudinal profile, is measured as the difference in elevation between two points in the stream divided by the stream length between the two points. Slope is one of the most critical pieces of design information required when channel modifications are considered. Channel slope directly impacts flow velocity, stream competence, and stream power. Since these attributes drive the geomorphic processes of erosion, sediment transport, and sediment deposition, channel slope becomes a controlling factor in channel shape and pattern.

(See Figs. 1-27 and 1-28)

Most longitudinal profiles of streams are concave upstream. As described previously in the discussion of dynamic equilibrium, streams adjust their profile and pattern to try to minimize the time rate of expenditure of potential energy, or stream power, present in flowing water. The concave upward shape of a stream's profile appears to be due to adjustments a river makes to help minimize stream power in a downstream direction. Yang (1983) applied the theory of minimum stream power to explain why most longitudinal streambed profiles are concave upward. In order to satisfy the theory of minimum stream power, which is a special case of the general theory of minimum energy dissipation rate (Yang and Song 1979), the following equation must be satisfied:

$$\frac{dP}{dx} = \gamma Q \frac{dS}{dx} + S \frac{dQ}{dx} = 0$$

Where:

P = QS = Stream power

x = Longitudinal distance

Q = Water discharge

S = Water surface or energy slope

γ = Specific weight of water

Stream power has been defined as the product of discharge and slope. Since stream discharge typically increases in a downstream direction, slope must decrease in order to minimize stream power. The decrease in slope in a downstream direction results in the concave-up longitudinal profile.

Sinuosity is not a profile feature, but it does affect stream slope. Sinuosity is the stream length between two points on a stream divided by the valley length between the two points. For example, if a stream is 2,200 feet long from point A to point B, and if a valley length distance between those two points is 1,000 feet, that stream has a sinuosity of 2.2. A stream can increase its length by increasing its sinuosity, resulting in a decrease in slope. This impact of sinuosity on channel slope must always be considered if channel reconstruction is part of a proposed restoration.

Pools and Riffles

The longitudinal profile is seldom constant, even over a short reach. Differences in geology, vegetation patterns, or human disturbances can result in flatter and steeper reaches within an overall profile. Riffles occur where the stream bottom is higher relative to streambed elevation immediately upstream or downstream. These relatively deeper areas are considered pools. At normal flow, flow velocities decrease in pool areas, allowing fine grained deposition to occur, and increase atop riffles due to the increased bed slope between the riffle crest and the subsequent pool.

Longitudinal Profile Adjustments

A common example of profile adjustment occurs when a dam is constructed on a stream. The typical response to dam construction is channel degradation downstream and aggradation upstream. However, the specific response is quite complex as can be illustrated by considering Lane's relation. Dams typically reduce peak discharges and sediment supply in the downstream reach. According to Lane's relation, a decrease in discharge (Q) should be offset by an increase in slope, yet the decrease in sediment load (Q_s) should cause a decrease in slope. This response could be further complicated if armoring occurs (D_{50}^+), which would also cause an increase in slope. Impacts are not limited to the main channel, but can include aggradation or degradation on tributaries as well. Aggradation often occurs at the mouths of tributaries downstream of dams (and sometimes in the entire channel) due to the reduction of peak flows on the main stem. Obviously, the ultimate response will be the result of the integration of all these variables.

Channel Cross Sections

Figure 2.16 presents the type of information that should be recorded when collecting stream cross section data. In stable alluvial streams, the high points on each bank represent the top of the bankfull channel. The importance of the bankfull channel has been established. Channel cross sections need to include enough points to define the channel in relation to a portion of the floodplain on each side. A suggested guide is to include at least one stream width beyond the highest point on each bank for smaller stream corridors and at least enough of the floodplain on larger streams to clearly define its character in relation to the channel.

In meandering streams, the channel cross section should be measured in areas of riffles or crossovers. A riffle or crossover occurs between the apexes of two sequential meanders. The effects of differences in resistance to erosion of soil layers are prominent in the outside bends of meanders, and point bars on the insides of the meanders are constantly adjusting to the water and sediment loads being moved by the stream. The stream's cross section changes much more rapidly and frequently in the meander bends. There is more variability in pool cross sections than in riffle cross sections. The cross section in the crossover or riffle area is more uniform.

Resistance to Flow and Velocity

Channel slope is an important factor in determining streamflow velocity. Flow velocity is used to help predict what discharge a cross section can convey. As discharge increases, either flow velocity, flow area, or both must increase.

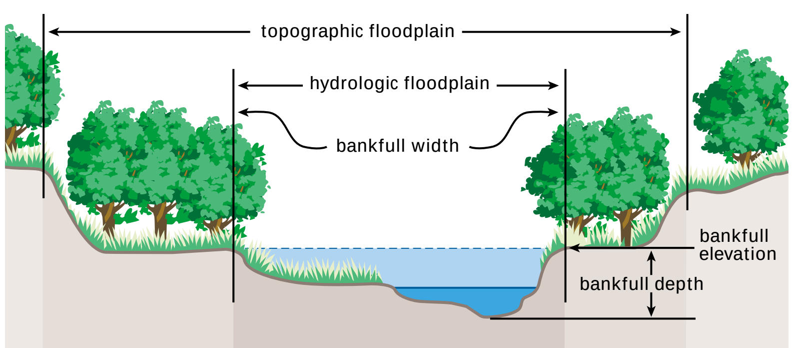


Figure 2.16: Channel cross section. *Information to record when collecting stream cross section data.*

Roughness plays an important r ole in streams. It helps determine the depth or stage of flow in a stream reach. As flow velocity slows in a stream reach due to roughness, the depth of flow has to increase to maintain the volume of flow that entered the upstream end of the reach (a concept known as flow continuity). Typical roughness along the boundaries of the stream includes the following:

- Sediment particles of different sizes.
- Bedforms.
- Bank irregularities.
- The type, amount, and distribution of living and dead vegetation.
- Other obstructions.

Roughness generally increases with increasing particle size. The shape and size of instream sediment deposits, or bedforms, also contribute to roughness.

Sand-bottom streams are good examples of how bedform roughness changes with discharge. At very low discharges, the bed of a sand stream may be dominated by ripple bedforms. As flow increases even more, sand dunes may begin to appear on the bed. Each of these bedforms increases the roughness of the stream bottom, which tends to slow velocity.

The depth of flow also increases due to increasing roughness. If discharge continues to increase, a point is reached when the flow velocity mobilizes the sand on the streambed and the entire bed converts again to a planar form. The depth of flow may actually decrease at this point due to the decreased roughness of the bed. If discharge increases further still, antidunes may form. These bedforms create enough friction to again cause the flow depth to increase. The depth of flow for a given discharge in sand-bed streams, therefore, depends on the bedforms present when that discharge occurs.

Vegetation can also contribute to roughness. In streams with boundaries consisting of cohesive soils, vegetation is usually the principal component of roughness. The type and distribution of vegetation in a stream corridor depends on hydrologic and geomorphic processes, but by creating roughness, vegetation can alter these processes and cause changes in a stream's form and pattern.

Meandering streams offer some resistance to flow relative to straight streams. Straight and meandering streams also have different distributions of flow velocity that are affected by the alignment of the stream, as shown in **Figure 2.17**. In straight reaches of a stream, the fastest flow occurs just below the surface near the center of the channel where flow resistance is lowest (see Figure 2.17 (a) Section G). In meanders, velocities are highest at the outside edge due to angular momentum (see Figure 2.17 (b) Section 3). The differences in flow velocity distribution in meandering streams result in both erosion and deposition at the meander bend. Erosion occurs at the outside of bends (cutbanks) from high velocity flows, while the slower velocities at the insides of bends cause deposition on the point bar (which also has been called the *slip-off slope*).

The angular momentum of flow through a meander bend increases the height or *super elevation* at the outside of the bend and sets up a secondary current of flow down the face of the cut bank and across the bottom of the pool toward the inside of the bend. This rotating flow is called *helical flow* and the direction of rotation is illustrated on the diagram on the following page by the arrows at the top and bottom of cross sections 3 and 4 in the figure.

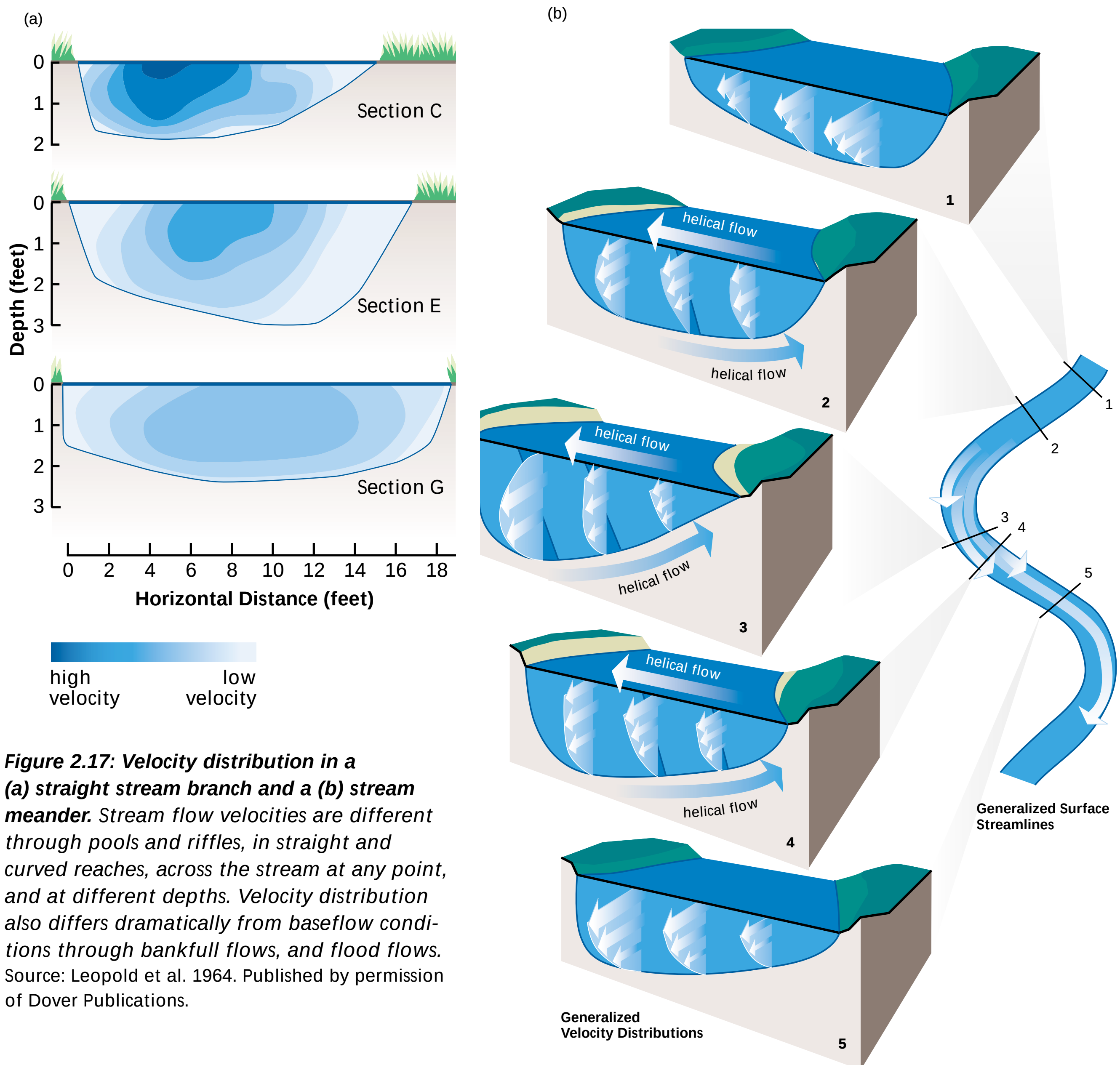


Figure 2.17: Velocity distribution in a (a) straight stream branch and a (b) stream meander. *Stream flow velocities are different through pools and riffles, in straight and curved reaches, across the stream at any point, and at different depths. Velocity distribution also differs dramatically from baseflow conditions through bankfull flows, and flood flows.*
Source: Leopold et al. 1964. Published by permission of Dover Publications.

The distribution of flow velocities in straight and meandering streams is important to understand when planning and designing modifications in stream alignment in a stream corridor restoration. Areas of highest velocities generate the most stream power, so where such velocities intersect the stream boundaries indicates where more durable protection may be needed.

As flow moves through a meander, the bottom water and detritus in the pool are rotated to the surface. This rotation is an important mechanism in moving drifting and benthic organisms past predators in pools. Riffle areas are not as deep as pools, so more turbulent flows occur in these shallow zones. The turbulent flow can increase the dissolved oxygen content of the water and may also increase the oxidation and volatilization of some chemical constituents in water.

Another extremely important function of roughness elements is that they create aquatic habitat. As one example, the deepest flow depths usually occur at the base of cutbanks. These scour holes or pools create very different habitat than occurs in the depositional environment of the slip-off slope.

Active Channels and Floodplains

Floodplains are built by two stream processes, lateral and vertical accretion. Lateral accretion is the deposition of sediment on point bars on the insides of bends of the stream. The stream laterally migrates across the floodplain as the outside of the meander bend erodes and the point bar builds with coarse-textured sediment. This naturally occurring process maintains the cross section needed to convey water and sediment from the watershed. Vertical accretion is the deposition of sediment on flooded surfaces. This sediment generally is finer textured than point bar sediments and is considered to be an overbank deposit. Vertical accretion occurs on top of the lateral accretion deposits in the point bars; however, lateral accretion is the dominant process. It typically makes up 60 to 80 percent of the total sediment deposits in floodplains (Leopold et al. 1964). It is apparent that lateral migration of meanders is an important natural process since it plays a critical role in reshaping floodplains.

2.C Physical and Chemical Characteristics

The quality of water in the stream corridor might be a primary objective of restoration, either to improve it to a desired condition or to sustain it. Establishing an appropriate flow regime and geomorphology in a stream corridor may do little to ensure a healthy ecosystem if the physical and chemical characteristics of the water are inappropriate. For example, a stream containing high concentrations of toxic materials or in which high temperatures, low dissolved oxygen, or other physical/chemical characteristics are inappropriate cannot support a healthy stream corridor. Conversely, poor condition of the stream corridor—such as lack of riparian shading, poor controls on erosion, or excessive sources of nutrients and oxygen-demanding waste—can result in degradation of the physical and chemical conditions within the stream.

This section briefly surveys some of the key physical and chemical characteristics of flowing waters. Stream water quality is a broad topic on which many books have been written. The focus here is on a few key concepts that are relevant to stream corridor restoration. The reader is referred to other sources (e.g., Thomann and Mueller 1987, Mills et al. 1985) for a more detailed treatment.

As in the previous sections, the physical and chemical characteristics of streams are examined in both the lateral and longitudinal perspectives. The lateral perspective refers to the influence of the watershed on water quality, with particular attention to riparian areas. The longitudinal perspective refers to processes that affect water quality during transport instream.

Physical Characteristics

Sediment

Section 2.B discussed total sediment loads in the context of the evolution of stream form and geomorphology. In addition to its role in shaping stream form, suspended sediment plays an important role in water quality, both in the water column and at the sediment-water interface. In a water quality context, sediment usually refers to soil particles that enter the water column from eroding land. Sediment consists of particles of all sizes, including fine clay particles, silt, and gravel. The term sedimentation is used to describe the deposition of sediment particles in waterbodies.

Although sediment and its transport occur naturally in any stream, changes in sediment load and particle size can have negative impacts (**Figure 2.18**). Fine sediment can severely alter aquatic communities. Sediment may clog and abrade fish gills, suffocate eggs and aquatic insect larvae on the bottom, and fill in the pore space between bottom cobbles where fish lay eggs. Sediment interferes with recreational activities and aesthetic enjoyment at waterbodies by reducing water clarity and filling in waterbodies. Sediment also may carry other pollutants into waterbodies. Nutrients and toxic chemicals may attach to sediment particles on land and ride the particles into surface waters where the pollutants may settle with the sediment or become soluble in the water column.

Studies have shown that fine sediment intrusion can significantly impact the quality of spawning habitat (Cooper 1965, Chapman 1988). Fine sediment intrusion into streambed gravels can reduce permeability and intragravel water velocities, thereby restricting the supply of oxygenated water to developing salmonid embryos and the removal of their metabolic wastes. Excessive fine sediment deposition can effectively smother incubating eggs and entomb alevins and fry. A sediment intrusion model (Alonso et al. 1996) has been developed, verified, and validated to predict the within-redd (spawning area) sediment accumulation and dissolved oxygen status.

Sediment Across the Stream Corridor

Rain erodes and washes soil particles off plowed fields, construction sites, logging sites, urban areas, and strip-mined lands into waterbodies. Eroding streambanks also deposit sediment into waterbodies. In sum, sediment quality in the stream represents the net result of erosion processes in the watershed.

The lateral view of sediment is discussed in more detail in Section 2.B. It is worth noting, however, that from a water quality perspective, interest may focus on specific fractions of the sediment load. For instance, controlling fine sediment load is often of particular concern for restoration of habitat for salmonid fish.

Restoration efforts may be useful for controlling loads of sediment and sediment-associated pollutants from the watershed to streams. These may range from efforts to reduce upland erosion to treatments that reduce sediment delivery through the riparian zone. Design of restoration treatments is covered in Chapter 8.

Figure 2.18: Stream sedimentation. *Although sediment and its transport occur naturally, changes in sediment load and particle size have negative impacts.*

FAST FORWARD

Preview Section D for more detail on the effects of cover on water temperature.

Sediment Along the Stream Corridor

The longitudinal processes affecting sediment transport from a water quality perspective are the same as those discussed from a geomorphic perspective in Section 2.B. As in the lateral perspective, interest from a water quality point of view may be focused on specific sediment size fractions, particularly the fine sediment fraction, because of its effect on water quality, water temperature, habitat, and biota.

Water Temperature

Water temperature is a crucial factor in stream corridor restoration for a number of reasons. First, dissolved oxygen solubility decreases with increasing water temperature, so the stress imposed by oxygen-demanding waste increases with higher temperatures. Second, temperature governs many biochemical and physiological processes in cold-blooded aquatic organisms, and increased temperatures can increase metabolic and reproductive rates throughout the food chain. Third, many aquatic species can tolerate only a limited range of temperatures, and shifting the maximum and minimum temperatures within a stream can have profound effects on species composition. Finally, temperature also affects many abiotic chemical processes, such as reaeration rate, sorption of organic chemicals to particulate matter, and volatilization rates. Temperature increases can lead to increased stress from toxic compounds, for which the dissolved fraction is usually the most bioactive fraction.

Water Temperature Across the Stream Corridor

Water temperature within a stream reach is affected by the temperature of water upstream, processes within the stream reach, and the temperature of influent water. The lateral view addresses the effects of the temperature of influent water.

The most important factor for temperature of influent water within a stream reach is the balance between water arriving via surface and ground water pathways. Water that flows over the land surface to a stream has the opportunity to gain heat through contact with surfaces heated by the sun. In contrast, ground water is usually cooler in summer and tends to reflect average annual temperatures in the watershed. Water flow via shallow ground water pathways may lie between the average annual temperature and ambient temperatures during runoff events.

Both the fraction of runoff arriving via surface pathways and the temperature of surface runoff are strongly affected by the amount of impervious surfaces within a watershed. For example, hot paved surfaces in a watershed can heat surface runoff and significantly increase the temperature of streams that receive the runoff.

Water Temperature Along the Stream Corridor

Water also is subject to thermal loading through direct effects of sunlight on streams. For the purposes of restoration, land use practices that remove overhead cover or that decrease baseflows can increase instream temperatures to levels that exceed critical thermal maxima for fishes (Feminella and Matthews 1984). Maintaining or restoring normal temperature ranges can therefore be an important goal for restoration.

Chemical Constituents

Previous chapters have discussed the physical journey of water as it moves through the hydrologic cycle. Rain percolates to the ground water table or becomes overland flow, streams collect this water and route it toward the ocean, and evapotranspiration occurs throughout the cycle. As water makes this journey, its chemistry changes. While in the air, water equilibrates with atmospheric gases. In shallow soils, it undergoes chemical exchanges with inorganic and organic matter and with soil gases. In ground water, where transit times are longer, there are more opportunities for minerals to dissolve. Similar chemical reactions continue along stream corridors. Everywhere, water interacts with everything it touches—air, rocks, bacteria, plants, and fish—and is affected by human disturbances.

Scientists have been able to define several interdependent cycles for many of the common dissolved constituents in water. Central among these cycles is the behavior of oxygen, carbon, and nutrients, such as nitrogen (N), phosphorus (P), sulfur (S), and smaller amounts of common trace elements.

Iron, for example, is an essential element in the metabolism of animals and plants. Iron in aquatic systems may be present in one of two oxidation states. Ferric iron (Fe^{3+}) is the more oxidized form and is very sparingly soluble in water. The reduced form, ferrous iron (Fe^{2+}), is more soluble by many orders of magnitude. In many aquatic systems, such as lakes for example, iron can cycle from the ferric state to the ferrous state and back again (**Figure 2.19**). The oxidation of ferrous iron followed by the precipitation of ferric iron results in iron coatings on the surfaces of some stream sediments. These coatings, along with organic coatings, play a substantial role in the aquatic chemistry of toxic trace elements and toxic organic chemicals. The chemistry of toxic organic chemicals and metals, along with the cycling and chemistry of oxygen, nitrogen, and phosphorus, will be covered later in this section.

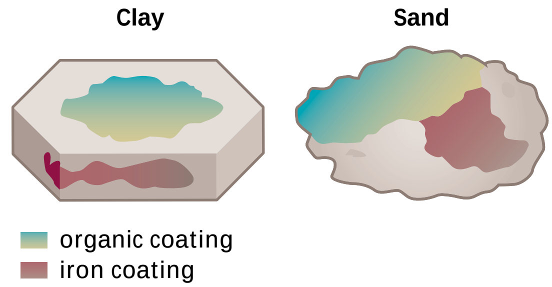


Figure 2.19: The organic coatings on suspended sediment from streams. *Water chemistry determines whether sediment will carry adsorbed materials or if stream sediments will be coated.*

The total concentration of all dissolved ions in water, also known as salinity, varies widely. Precipitation typically contains only a few parts per thousand (ppt) of dissolved solids, while the salinity of seawater averages about 35 ppt (**Table 2.5**). The concentration of dissolved solids in freshwater may vary from only 10 to 20 mg/L in a pristine mountain stream to several hundred mg/L in many rivers. Concentrations may exceed 1,000 mg/L in arid watersheds. A dissolved solids concentration of less than 500 mg/L is recommended for public drinking water, but this threshold is exceeded in many areas of the country. Some crops (notably fruit trees and beans) are sensitive to even modest salinity, while other crops, such as cotton, barley, and beets, tolerate high concentrations of dissolved solids. Agricultural return water from irrigation may increase salinity in streams, particularly in the west. Recommended salinity limits for livestock vary from 2,860 mg/L for poultry to 12,900 mg/L for adult sheep. Plants, fish, and other aquatic life also vary widely in their adaptation to different concentrations of dissolved solids. Most species have a maximum salinity tolerance, and few can live in very pure water of very low ionic concentration.

	Samples					
Constituent	1	2	3	4	5	6
SiO_2	0.0		1.2	0.3		0.1
Al	.01					
Fe	.00					.015
Ca	.0	.65	1.2	.8	1.41	.075
Mg	.2	.14	.7	1.2		.027
Na	.6	.56	.0	9.4	.42	.220
K	.6	.11	.0	.0		.072
NH_4	.0					
HCO_3	3		7	4		
SO_4	1.6	2.18	.7	7.6	2.14	1.1
Cl	.2	.57	.8	17	.22	
NO_2	.02		.00	.02		
NO_3	.1	.62	.2	.0		
Total dissolved solids	4.8		8.2	38		
pH	5.6		6.4	5.5		4.9

1. Snow, Spooner Summit. U.S. Highway 50, Nevada (east of Lake Tahoe) (Feth, Rogers, and Roberson, 1964).
2. Average composition of rain, August 1962 to July 1963, at 27 points in North Carolina and Virginia (Gambell and Fisher, 1966).
3. Rain, Menlo Park, Calif., 7:00 p.m. Jan. 9 to 8:00 a.m. Jan 10, 1958 (Whitehead and Feth, 1964).
4. Rain, Menlo Park, Calif., 8:00 a.m. to 2:00 p.m. Jan 10, 1958 (Whitehead and Feth, 1964).
5. Average for inland sampling stations in the United States for 1 year. Data from Junge and Werby (1958), as reported by Whitehead and Feth (1964).
6. Average composition of precipitation, Williamson Creek, Snohomish County, Wash., 1973-75. Also reported: As, 0.00045 mg/L; Cu 0.0025 mg/L; Pb, 0.0033 mg/L; Zn, 0.0036 mg/L (Deithier, D.P., 1977, Ph.D. thesis. University of Washington, Seattle).

Table 2.5: Composition, in milligrams per liter, of rain and snow.

pH, Alkalinity, and Acidity

Alkalinity, acidity, and buffering capacity are important characteristics of water that affect its suitability for biota and influence chemical reactions. The acidic or basic (alkaline) nature of water is commonly quantified by the negative logarithm of the hydrogen ion concentration, or pH. A pH value of 7 represents a neutral condition; a pH value less than 5 indicates moderately acidic conditions; a pH value greater than 9 indicates moderately alkaline conditions. Many biological processes, such as reproduction, cannot function in acidic or alkaline waters. In particular, aquatic organisms may suffer an osmotic imbalance under sustained exposure to low pH waters. Rapid fluctuations in pH also can stress aquatic organisms. Finally, acidic conditions also can aggravate toxic contamination problems through increased solubility, leading to the release of toxic chemicals stored in stream sediments.

pH, Alkalinity, and Acidity Across the Stream Corridor

The pH of runoff reflects the chemical characteristics of precipitation and the land surface. Except in areas with significant ocean spray, the dominant ion in most precipitation is bicarbonate (HCO_3^-). The bicarbonate ion is produced by carbon dioxide reacting with water:

$$H_2O + CO_2 = H^+ + HCO_3^-$$

This reaction also produces a hydrogen ion (H^+), thus increasing the hydrogen ion concentration and acidity and lowering the pH. Because of the presence of CO_2 in the atmosphere, most rain is naturally slightly acidic, with a pH of about 5.6. Increased acidity in rainfall can be caused by inputs, particularly from burning fossil fuels.

As water moves through soils and rocks, its pH may increase or decrease as additional chemical reactions occur. The carbonate buffering system controls the acidity of most waters. Carbonate buffering results from chemical equilibrium between calcium, carbonate, bicarbonate, carbon dioxide, and hydrogen ions in the water and carbon dioxide in the atmosphere. Buffering causes waters to resist changes in pH (Wetzel 1975). Alkalinity refers to the acid-neutralizing capacity of water and usually refers to those compounds that shift the pH in an alkaline direction (APHA 1995, Wetzel 1975). The amount of buffering is related to the alkalinity and primarily determined by carbonate and bicarbonate concentration, which are introduced into the water from dissolved calcium carbonate (i.e., limestone) and similar minerals present in the watershed. For example, when an acid interacts with limestone, the following dissolution reaction occurs:

$$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$

This reaction consumes hydrogen ions, thus raising the pH of the water. Conversely, runoff may acidify when all alkalinity in the water is consumed by acids, a process often attributed to the input of strong mineral acids, such as sulfuric acid, from acid mine drainage, and weak organic acids, such as humic and fulvic acids, which are naturally produced in large quantities in some types of soils, such as those associated with coniferous forests, bogs, and wetlands. In some streams, pH levels can be increased by restoring degraded wetlands that intercept acid inputs, such as acid mine drainage, and help neutralize acidity by converting sulfates from sulfuric acid to insoluble nonacidic metal sulfides that remain trapped in wetland sediments.

pH, Alkalinity, and Acidity Along the Stream Corridor

Within a stream, similar reactions occur between acids in the water, atmospheric CO_2, alkalinity in the water column, and streambed material. An additional characteristic of pH in some poorly buffered waters is high daily variability in pH levels attributable to biological processes that affect the carbonate buffering system. In waters with large standing crops of aquatic plants, uptake of carbon dioxide by plants during photosynthesis removes carbonic acid from the water, which can increase pH by several units. Conversely, pH levels may fall by several units during the night when photosynthesis does not occur and plants give off carbon dioxide. Restoration techniques that decrease instream plant growth through increased shading or reduction in nutrient loads or that increase reaeration also tend to stabilize highly variable pH levels attributable to high rates of photosynthesis.

The pH within streams can have important consequences for toxic materials. High acidity or high alkalinity tend to convert insoluble metal sulfides to soluble forms and can increase the concentration of toxic metals. Conversely, high pH can promote ammonia toxicity. Ammonia is present in water in two forms, unionized (NH_3) and ionized (NH_4^+). Of these two forms of ammonia, un-ionized ammonia is relatively highly toxic to aquatic life, while ionized ammonia is relatively negligibly toxic. The proportion of un-ionized ammonia is determined by the pH and temperature of the water (Bowie et al. 1985)—as pH or temperature increases, the proportion of un-ionized ammonia and the toxicity also increase. For example, with a pH of 7 and a temperature of 68°F, only about 0.4 percent of the total ammonia is in the un-ionized form, while at a pH of 8.5 and a temperature of 78°F, 15 percent of the total ammonia is in the un-ionized form, representing 35 times greater potential toxicity to aquatic life.

Dissolved Oxygen

Dissolved oxygen (DO) is a basic requirement for a healthy aquatic ecosystem. Most fish and aquatic insects “breathe” oxygen dissolved in the water column. Some fish and aquatic organisms, such as carp and sludge worms, are adapted to low oxygen conditions, but most sport fish species, such as trout and salmon, suffer if DO concentrations fall below a concentration of 3 to 4 mg/L. Larvae and juvenile fish are more sensitive and require even higher concentrations of DO (USEPA 1997).

Many fish and other aquatic organisms can recover from short periods of low

FAST FORWARD

Preview Section ? for more information on DO.

DO in the water. However, prolonged episodes of depressed dissolved oxygen concentrations of 2 mg/L or less can result in "dead" waterbodies. Prolonged exposure to low DO conditions can suffocate adult fish or reduce their reproductive survival by suffocating sensitive eggs and larvae, or can starve fish by killing aquatic insect larvae and other prey. Low DO concentrations also favor anaerobic bacteria that produce the noxious gases or foul odors often associated with polluted waterbodies.

Water absorbs oxygen directly from the atmosphere, and from plants as a result of photosynthesis. The ability of water to hold oxygen is influenced by temperature and salinity. Water loses oxygen primarily by respiration of aquatic plants, animals, and microorganisms. Due to their shallow depth, large surface exposure to air, and constant motion, undisturbed streams generally contain an abundant DO supply. However, external loads of oxygen-demanding wastes or excessive plant growth induced by nutrient loading followed by death and decomposition of vegetative material can deplete oxygen.

Dissolved Oxygen Across the Stream Corridor

Oxygen concentrations in the water column fluctuate under natural conditions, but oxygen can be severely depleted as a result of human activities that introduce large quantities of biodegradable organic materials into surface waters. Excess loading of nutrients also can deplete oxygen when plants within a stream produce large quantities of plant biomass.

Loads of oxygen-demanding waste usually are reported as *biochemical oxygen demand (BOD)*. BOD is a measure of the amount of oxygen required to oxidize organic material in water by biological activity. As such, BOD is an equivalent indicator rather than a true physical or chemical substance. It measures the total concentration of DO that eventually would be demanded as wastewater degrades in a stream.

BOD also is often separated into carbonaceous and nitrogenous components. This is because the two fractions tend to degrade at different rates. Many water quality models for dissolved oxygen require as input estimates of ultimate carbonaceous BOD ($CBOD_u$) and either ultimate nitrogenous BOD ($NBOD_u$) or concentrations of individual nitrogen species.

Oxygen-demanding wastes can be loaded to streams by point source discharges, nonpoint loading, and ground water. BOD loads from major point sources typically are controlled and monitored and thus are relatively easy to analyze. Nonpoint source loads of BOD are much more difficult to analyze. In general, any loading of organic material from a watershed to a stream results in an oxygen demand. Excess loads of organic material may arise from a variety of land use practices, coupled with storm events, erosion, and washoff. Some agricultural activities, particularly large-scale animal operations and improper manure application, can result in significant BOD loads. Land-disturbing activities of silviculture and construction can result in high organic loads through the erosion of organic topsoil. Finally, urban runoff often is loaded with high concentrations of organic materials derived from a variety of sources.

Dissolved Oxygen Along the Stream Corridor

Within a stream, DO content is affected by reaeration from the atmosphere, production of DO by aquatic plants as a by-product of photosynthesis, and consumption of DO in respiration by plants, animals, and, most importantly, microorganisms.

Major processes affecting the DO balance within a stream are summarized in **Figure 2.20**. This includes the following components:

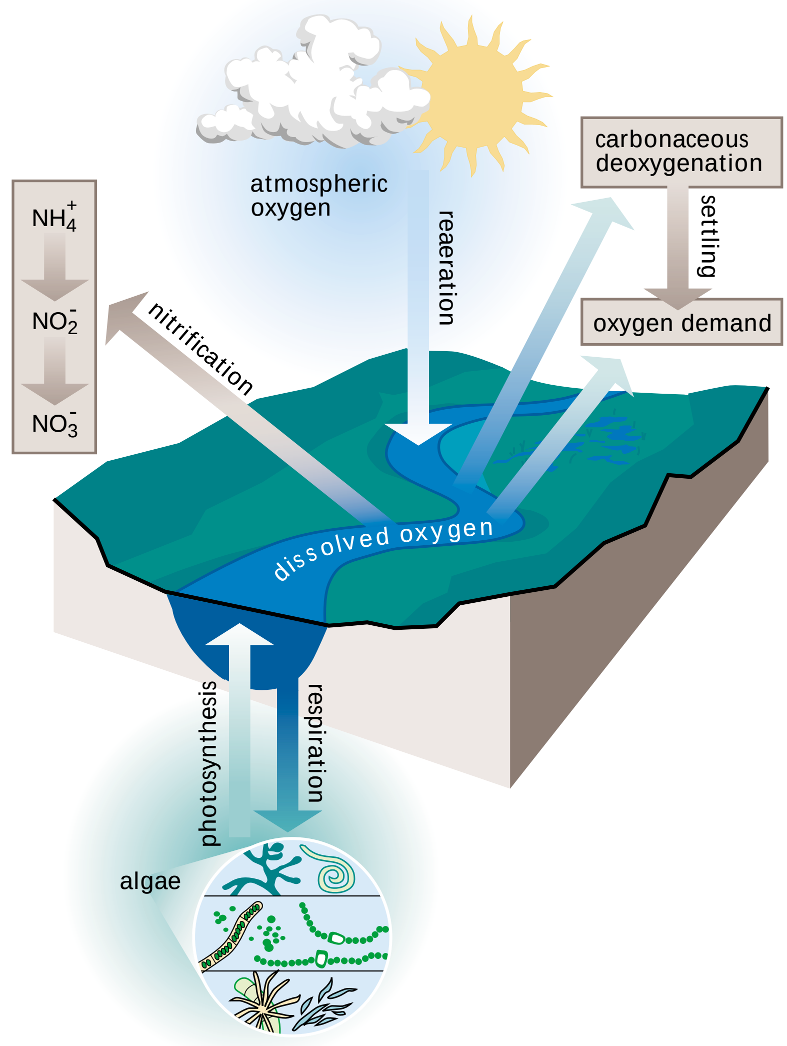
- Carbonaceous deoxygenation
- Nitrogenous deoxygenation (nitrification)
- Reaeration
- Sediment oxygen demand
- Photosynthesis and respiration of plants.

Reaeration is the primary route for introducing oxygen into most waters. Oxygen gas (O_2) constitutes about 21 percent of the atmosphere and readily dissolves in water. The saturation concentration of DO in water is a measure of the maximum amount of oxygen that water can hold at a given temperature. When oxygen exceeds the saturation concentration, it tends to degas to the atmosphere. When oxygen is below the saturation concentration, it tends to diffuse from the atmosphere to water. The saturation concentration of oxygen decreases with temperature according to a complex power function equation (APHA 1995). In addition to temperature, the saturation concentration is affected by water salinity and the atmospheric pressure. As the salinity of water increases, the saturation concentration decreases. As the atmospheric pressure increases the saturation concentration also increases.

Interactions between atmospheric and DO are driven by the partial pressure gradient in the gas phase and the concentration gradient in the liquid phase (Thomann and Mueller 1987). Turbulence and mixing in either phase decrease these gradients and increase reaeration, while a quiescent, stagnant surface or films on the surface reduce reaeration. In general, oxygen transfer in natural waters depends on the following:

- Internal mixing and turbulence due to velocity gradients and fluctuation
- Temperature
- Wind mixing
- Waterfalls, dams, and rapids
- Surface films
- Water column depth.

Figure 2.20: Interrelationship of major kinetic processes for BOD and DO as represented by water quality models. *Complex, interacting physical and chemical processes can sometimes be simplified by models in order to plan a restoration.*



Stream restoration techniques often take advantage of these relationships, for instance by the installation of artificial cascades to increase reaeration. Many empirical formulations have been developed for estimating stream reaeration rate coefficients; a detailed summary is provided in Bowie et al. (1985).

In addition to reaeration, oxygen is produced instream by aquatic plants. Through photosynthesis, plants capture energy from the sun to fix carbon dioxide into reduced organic matter:

$$6\ CO_2 + 6\ H_2O = C_6H_{12}O_6 + 6\ O_2$$

Note that photosynthesis also produces oxygen. Plants utilize their simple photosynthetic sugars and other nutrients (notably nitrogen [N], phosphorus [P], and sulfur [S] with smaller amounts of several common and trace elements) to operate their metabolism and to build their structures.

Most animal life depends on the release of energy stored by plants in the photosynthetic process. In a reaction that is the reverse of photosynthesis, animals consume plant material or other animals and oxidize the sugars, starches, and proteins to fuel their metabolism and build their own structure. This process is known as respiration and consumes dissolved oxygen. The actual process of respiration involves a series of energy converting oxidation-reduction reactions. Higher animals and many microorganisms depend on sufficient dissolved oxygen as the terminal electron acceptor in these reactions and cannot survive without it. Some microorganisms are able to use other compounds (such as nitrate and sulfate) as electron acceptors in metabolism and can survive in anaerobic (oxygen-depleted) environments.

Detailed information on analysis and modeling of DO and BOD in streams is contained in a number of references (e.g., Thomann and Mueller 1987), and a variety of well-tested computer models are available. Most stream water quality models account for CBOD in the water column separately from NBOD (which is usually represented via direct mass balance of nitrogen species) and *sediment oxygen demand* or *SOD*. SOD represents the oxygen demand of sediment organism respiration and the benthic decomposition of organic material. The demand of oxygen by sediment and benthic organisms can, in some instances, be a significant fraction of the total oxygen demand in a stream. This is particularly true in small streams. The effects may be particularly acute during low-flow and high-temperature conditions, as microbial activity tends to increase with increased temperature.

The presence of toxic pollutants in the water column can indirectly lower oxygen concentrations by killing algae, aquatic weeds, or fish, which provide an abundance of food for oxygen-consuming bacteria. Oxygen depletion also can result from chemical reactions that do not involve bacteria. Some pollutants trigger chemical reactions that place a chemical oxygen demand on receiving waters.

Nutrients

In addition to carbon dioxide and water, aquatic plants (both algae and higher plants) require a variety of other elements to support their bodily structures and metabolism. Just as with terrestrial plants, the most important of these elements are nitrogen and phosphorus. Additional nutrients, such as potassium, iron, selenium, and silica, are needed in smaller amounts and generally are not limiting factors to plant growth. When these chemicals are limited, plant growth may be limited. This is an important consideration in stream management. Plant biomass (either created instream or loaded from the watershed) is necessary to support the food chain. However, excessive growth of algae and other aquatic plants instream can result in nuisance conditions, and the depletion of dissolved oxygen during nonphotosynthetic periods by the respiration of plants and decay of dead plant material can create conditions unfavorable to aquatic life.

Phosphorus in freshwater systems exists in either a particulate phase or a dissolved phase. Both phases include organic and inorganic fractions. The organic particulate phase includes living and dead particulate matter, such as plankton and detritus. Inorganic particulate phosphorus includes phosphorus precipitates and phosphorus adsorbed to particulates. Dissolved organic phosphorus includes organic phosphorus excreted by organisms and colloidal phosphorus compounds. The soluble inorganic phosphate forms $H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}, collectively known as *soluble reactive phosphorus (SRP)* are readily available to plants. Some condensed phosphate forms, such as those found in detergents, are inorganic but are not directly available for plant uptake. Aquatic plants require nitrogen and phosphorus in different amounts. For phytoplankton, as an example, cells contain approximately 0.5 to 2.0 µg phosphorus per µg chlorophyll, and 7 to 10 µg nitrogen per µg chlorophyll. From this relationship, it is clear that the ratio of nitrogen and phosphorus required is in the range of 5 to 20 (depending on the characteristics of individual species) to support full utilization of available nutrients and maximize plant growth. When the ratio deviates from this range, plants cannot use the nutrient present in excess amounts. The other nutrient is then said to be the limiting nutrient on plant growth. In streams experiencing excessive nutrient loading, resource managers often seek to control loading of the limiting nutrient at levels that prevent nuisance conditions.

In the aquatic environment, nitrogen can exist in several forms—dissolved nitrogen gas (N_2), ammonia and ammonium ion (NH_3 and NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and organic nitrogen as proteinaceous matter or in dissolved or particulate phases. The most important forms of nitrogen in terms of their immediate impacts on water quality are the readily available ammonia ions, nitrites, and nitrates. Because they must be converted to a form more usable by plants, particulate and organic nitrogen are less important in the short term.

It may seem unusual that nitrogen could limit plant growth, given that the atmosphere is about 79 percent nitrogen gas. However, only a few life-forms (for example, certain bacteria and blue-green algae) have the ability to fix nitrogen gas from the atmosphere. Most plants can use nitrogen only if it is available as ammonia (NH_3, commonly present in water as the ionic form ammonium, NH_4^+) or as nitrate (NO_3^-) (**Figure 2.21**). However, in freshwater systems, growth of aquatic plants is more commonly limited by phosphorus than by nitrogen. This limitation occurs because phosphate (PO_4^{3-}) forms insoluble complexes with common constituents in water (Ca^{++} and variable amounts of OH^-, Cl^-, and F^-). Phosphorus also sorbs to iron coatings on clay and other sediment surfaces and is therefore removed from the water column by chemical processes, resulting in the reduced ability of the water body to support plant growth.

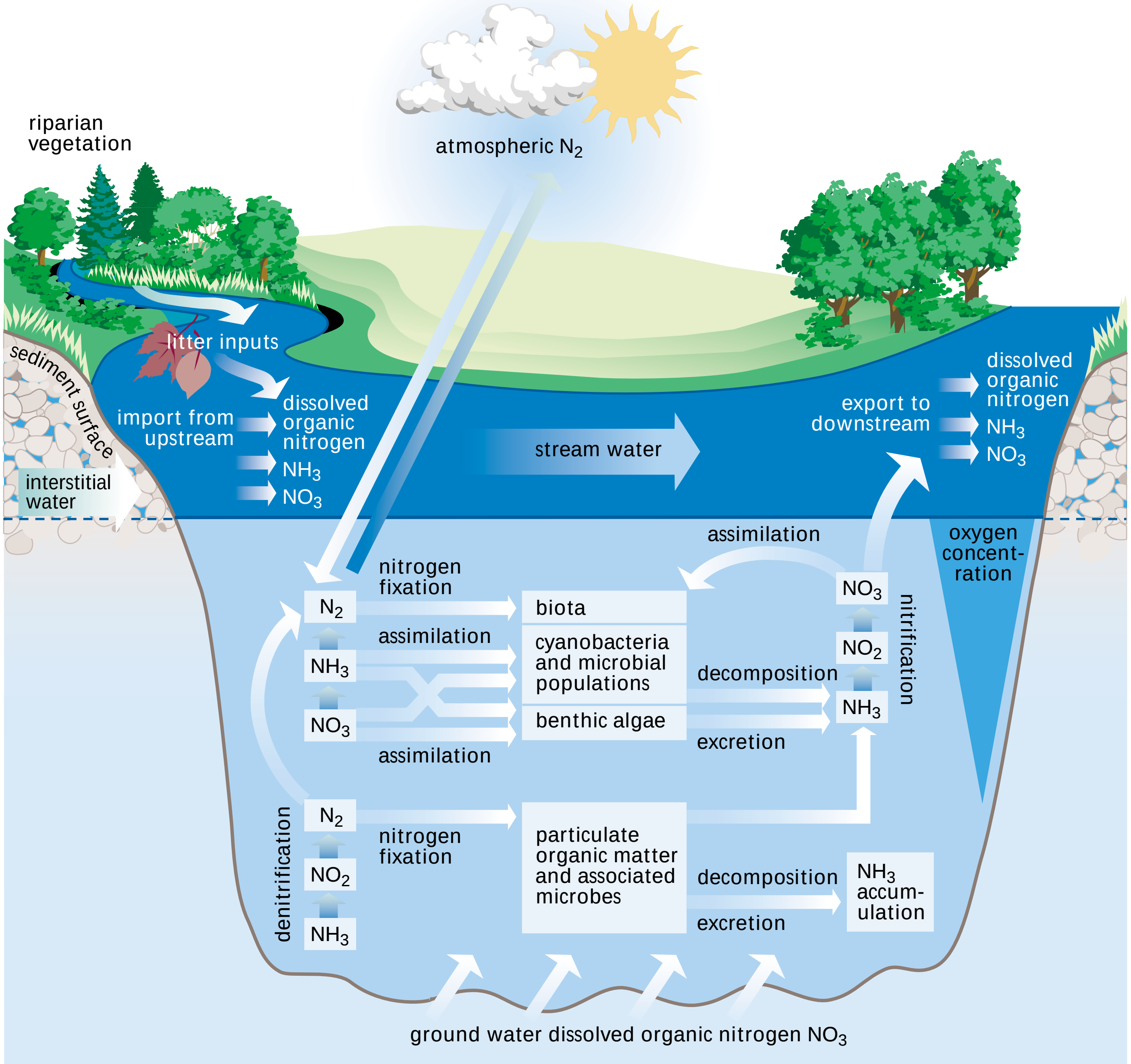


Figure 2.21: Dynamics and transformations of nitrogen in a stream ecosystem. *Nutrient cycling from one form to another occurs with changes in nutrient inputs, as well as temperature and oxygen available.*

Nutrients Across the Stream Corridor

Both nitrogen and phosphorus are delivered to surface waters at an elevated rate as a result of human activities, including point source discharges of treated wastewater and nonpoint sources, such as agriculture and urban development. In many developed watersheds, a major source of nutrients is the direct discharge of treated waste from wastewater treatment plants, as well as combined sewer overflows (CSOs). Such point source discharges are regulated under the National Pollutant Discharge Elimination System (NPDES) and usually are well characterized by monitoring. The NPDES requires permitted dischargers to meet both numeric and narrative water quality standards in streams. While most states do not have numeric standards for nutrients, point source discharges of nutrients are recognized as a factor leading to stream degradation and failure to achieve narrative water quality standards. As a result, increasingly stringent limitations on nutrient concentrations in wastewater treatment plant effluent (particularly phosphorus) have been imposed in many areas.

In many cases the NPDES program has significantly cleaned up rivers and streams; however, many streams still do not meet water quality standards, even with increasingly stringent regulatory standards. Scientists and regulators now understand that the dominant source of nutrients in many streams is from nonpoint sources within the stream's watershed, not from point sources such as wastewater treatment plants. Typical land uses that contribute to the nonpoint contamination of streams are the application of fertilizers to agricultural fields and suburban lawns, the improper handling of animal wastes from livestock operations, and the disposal of human waste in septic systems. Storm runoff from agricultural fields can contribute nutrients to a stream in dissolved forms as well as particulate forms.

Because of its tendency to sorb to sediment particles and organic matter, phosphorus is transported primarily in surface runoff with eroded sediments. Inorganic nitrogen, on the other hand, does not sorb strongly and can be transported in both particulate and dissolved phases in surface runoff. Dissolved inorganic nitrogen also can be transported through the unsaturated zone (interflow) and ground water to waterbodies. **Table 2.6** presents common point and nonpoint sources of nitrogen and phosphorus loading and shows the approximate concentrations delivered. Note that nitrates are naturally occurring in some soils.

Nutrients Along the Stream Corridor

Nitrogen, because it does not sorb strongly to sediment, moves easily between the substrate and the water column and cycles continuously. Aquatic organisms incorporate dissolved and particulate inorganic nitrogen into proteinaceous matter. Dead organisms decompose and nitrogen is released as ammonia ions and then converted to nitrite and nitrate, where the process begins again.

Phosphorus undergoes continuous transformations in a freshwater environment. Some phosphorus will sorb to

Table 2.6: Sources and concentrations of pollutants from common point and nonpoint sources.

Source	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)
Urban runoff[a]	3–10	0.2–1.7
Livestock operations[a]	6–800[b]	4–5
Atmosphere (wet deposition)[a]	0.9	0.015[c]
90% forest[d]	0.06–0.19	0.006–0.012
50% forest[d]	0.18–0.34	0.013–0.015
90% agriculture[d]	0.77–5.04	0.085–0.104
Untreated wastewater[a]	35	10
Treated wastewater[a,e]	30	10

[a] Novotny and Olem (1994).
[b] As organic nitrogen.
[c] Sorbed to airborne particulate.
[d] Omernik (1987).
[e] With secondary treatment.

sediments in the water column or substrate and be removed from circulation. The SRP (usually as orthophosphate) is assimilated by aquatic plants and converted to organic phosphorus. Aquatic plants then may be consumed by detritivores and grazers, which in turn excrete some of the organic phosphorus as SRP. Continuing the cycle, the SRP is rapidly assimilated by aquatic plants.

Toxic Organic Chemicals

Pollutants that cause toxicity in animals or humans are of obvious concern to restoration efforts. *Toxic organic chemicals (TOC)* are synthetic compounds that contain carbon, such as polychlorinated biphenyls (PCBs) and most pesticides and herbicides. Many of these synthesized compounds tend to persist and accumulate in the environment because they do not readily break down in natural ecosystems. Some of the most toxic synthetic organics, DDT and PCBs, have been banned from use in the United States for decades yet continue to cause problems in the aquatic ecosystems of many streams.

Toxic Organic Chemicals Across the Stream Corridor

TOCs may reach a water body via both point and nonpoint sources. Because permitted NPDES point sources must meet water quality standards instream and because of whole effluent toxicity requirements, continuing TOC problems in most streams are due to nonpoint loading, recycling of materials stored in stream and riparian sediments, illegal dumping, or accidental spills. Two important sources of nonpoint loading of organic chemicals are application of pesticides and herbicides in connection with agriculture, silviculture, or suburban lawn care, and runoff from potentially polluted urban and industrial land uses.

The movement of organic chemicals from the watershed land surface to a water body is largely determined by the characteristics of the chemical, as discussed below under the longitudinal perspective. Pollutants that tend to sorb strongly to soil particles are primarily transported with eroded sediment. Controlling sediment delivery from source area land uses is therefore an effective management strategy. Organic chemicals with significant solubility may be transported directly with the flow of water, particularly stormflow from impervious urban surfaces.

Toxic Organic Chemicals Along the Stream Corridor

Among all the elements of the earth, carbon is unique in its ability to form a virtually infinite array of stable covalent bonds with itself: long chains, branches and rings, spiral helixes. Carbon molecules can be so complex that they are able to encode information for the organization of other carbon structures and the regulation of chemical reactions.

The chemical industry has exploited this to produce many useful organic chemicals: plastics, paints and dyes, fuels, pesticides, pharmaceuticals, and other items of modern life. These products and their associated wastes and byproducts can interfere with the health of aquatic ecosystems. Understanding the transport and fate of *synthetic organic compounds (SOC)* in aquatic environments continues to challenge scientists. Only a general overview of the processes that govern the behavior of these chemicals along stream corridors is presented here.

Solubility

It is the nature of the carbon-carbon bond that electrons are distributed relatively uniformly between the bonded atoms. Thus a chained or ringed hydrocarbon is a fairly nonpolar compound.

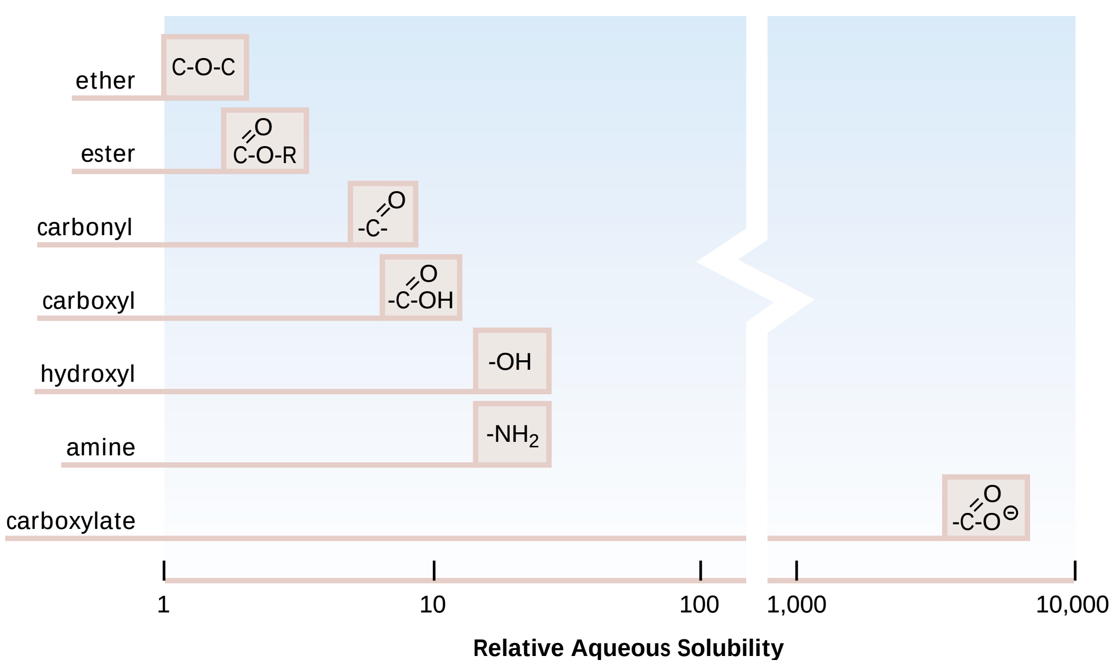
This nonpolar nature is dissimilar to the molecular structure of water, which is a very polar solvent.

On the general principle that "like dissolves like," dissolved constituents in water tend to be polar. Witness, for example, the ionic nature of virtually all inorganic constituents discussed thus far in this chapter. How does an organic compound become dissolved in water? There are several ways. The compound can be relatively small, so it minimizes its disturbance of the polar order of things in aqueous solution. Alternatively, the compound may become more polar by adding polar functional groups (**Figure 2.22**). Alcohols are organic compounds with -OH groups attached; organic acids are organic compounds with attached -COOH groups. These functional groups are highly polar and increase the solubility of any organic compound. Even more solubility in water is gained by ionic functional groups, such as $-COO^-$.

Another way that solubility is enhanced is by increased aromaticity. Aromaticity refers to the delocalized bonding structure of a ringed compound like benzene (**Figure 2.23**). (Indeed, all aromatic compounds can be considered derivatives of benzene.) Because electrons are free to "dance around the ring" of the benzene molecule, benzene and its derivatives are more compatible with the polar nature of water.

A simple example will illustrate the factors enhancing aqueous solubility of organic compounds. Six compounds, each having six carbons, are shown in **Table 2.7**. Hexane is a simple hydrocarbon, an alkane whose solubility is 10 mg/L. Simply by adding a single -OH group, which converts hexane to the alcohol hexanol, solubility is increased to 5,900 mg/L. You can bend hexane into a ringed alkane structure called cyclohexane. Forming the ring makes cyclohexane smaller than hexane and increases its solubility, but only to 55 mg/L. Making the ring aromatic by forming the six-carbon benzene molecule increases solubility all the way to 1,780 mg/L. Adding an -OH to benzene to form a phenol leads to another dra-

Figure 2.22: Relative aqueous solubility of different functional groups. *The solubility of a contaminant in water largely determines the extent to which it will impact water quality.*



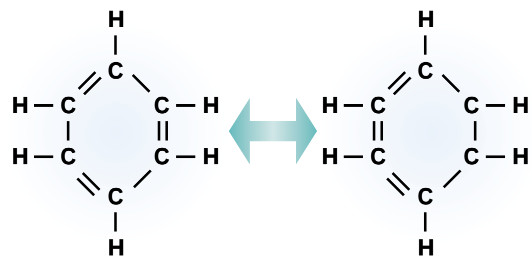


Figure 2.23: ***Aromatic hydrocarbons.*** *Benzene is soluble in water because of its "aromatic" structure.*

matic increase in solubility (to 82,000 mg/L). Adding a chloride atom to the benzene ring diminishes its aromatic character (chloride inhibits the dancing electrons), and thus the solubility of chlorobenzene (448 mg/L) is less than benzene.

Sorption

In the 1940s, a young pharmaceutical industry sought to develop medicines that could be transported in digestive fluids and blood (both of which are essentially aqueous solutions) and could also diffuse across cell membranes (which have, in part, a rather nonpolar character). The industry developed a parameter to quantify the polar versus nonpolar character of potential drugs, and they called that parameter the octanol-water partition coefficient. Basically they put water and octanol (an eight-carbon alcohol) into a vessel, added the organic compound of interest, and shook the combination up. After a period of rest, the water and octanol separate (neither is very soluble in the other), and the concentration of the organic compound can be measured in each phase. The *octanol-water partition coefficient*, or K_{ow}, is defined simply as:

$$K_{ow} = \text{concentration in octanol / concentration in water}$$

Table 2.7: Solubility of six-carbon compounds.

Compound	Solubility
Hexane	10 mg/L
Hexanol	5,900 mg/L
Cyclohexane	55 mg/L
Benzene	1,780 mg/L
Phenol	82,000 mg/L
Chlorobenzene	448 mg/L

The relation between water solubility and K_{ow} is shown in **Figure 2.24**. Generally we see that very insoluble compounds like DDT and PCBs have very high values of K_{ow}. Alternatively, organic acids and small organic solvents like TCE are relatively soluble and have low K_{ow} values.

The octanol-water partition coefficient has been determined for many compounds and can be useful in understanding the distribution of SOC between water and biota, and between water and sediments. Compounds with high K_{ow} tend to accumulate in fish tissue (**Figure 2.25**). The *sediment-water distribution coefficient*, often expressed as K_d, is defined in a sediment-water mixture at equilibrium as the ratio of the concentration in the sediment to the concentration in the water:

$$K_d = \text{concentration in sediment / concentration in water}$$

One might ask whether this coefficient is constant for a given SOC. Values of K_d for two polyaromatic hydrocarbons in various soils are shown in **Figure 2.26**. For pyrene (which consists of four benzene rings stuck together), the K_d ratios vary from about 300 to 1500. For phenanthrene (which consists of three benzene rings stuck together), K_d varies from about 10 to 300. Clearly K_d is not a constant value for either compound. But, K_d does appear to bear a relation to the fraction of organic carbon in the various sediments. What appears to be constant is not K_d itself, but the ratio of K_d to the fraction of organic carbon in the sediment. This ratio is referred to as K_{oc}:

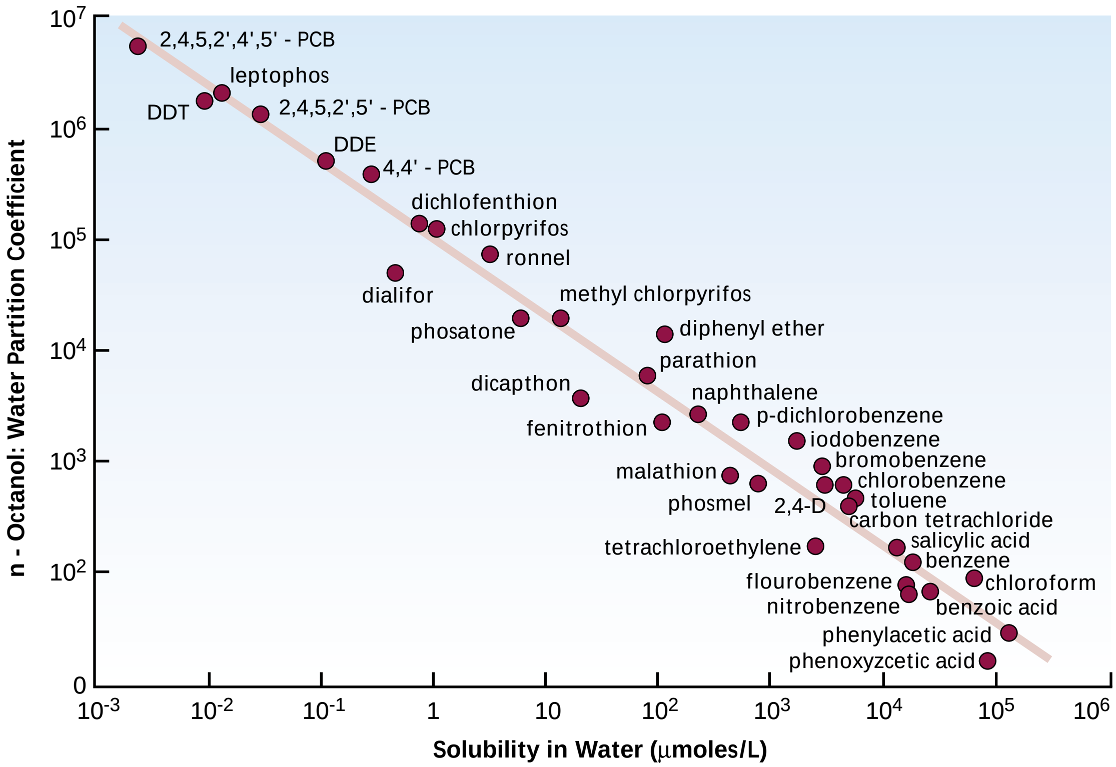


Figure 2.24: Relationship between octanol/H_2O partition coefficient and aqueous solubility. *The relative solubility in water is a substance's "Water Partition Coefficient."*

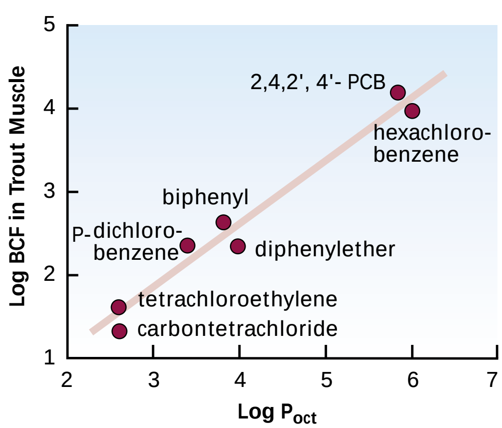


Figure 2.25: Relationship between octanol/water partition (P_{oct}) coefficient and bioaccumulation factor (BCF) in trout muscle. *Water quality can be inferred by the accumulation of contaminants in fish tissue.*

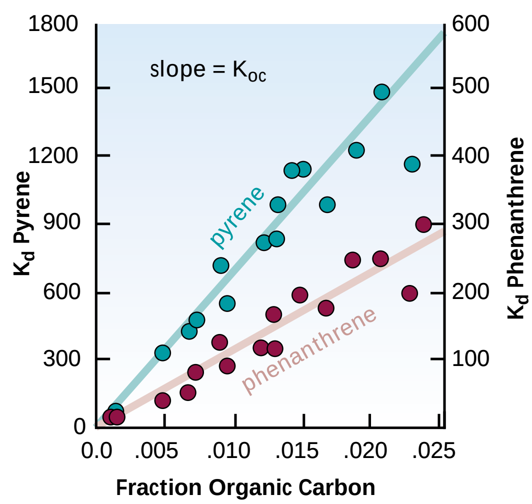


Figure 2.26: Relationship between pyrene, phenanthrene, and fraction organic carbon. *Contaminant concentrations in sediment vs. water (K_d) are related to the amount of organic carbon available.*

$K_{oc} = K_d$ / fraction of organic carbon in sediment

Various workers have related K_{oc} to K_{ow} and to water solubility (**Table 2.8**).

Using K_{ow}, K_{oc}, and K_d to describe the partitioning of an SOC between water and sediment has shown some utility, but this approach is not applicable to the sorption of all organic molecules in all systems. Sorption of some SOC occurs by hydrogen bonding, such as occurs in cation exchange or metal sorption to sediments (**Figure 2.27**). Sorption is not always reversible; or at least after sorption occurs, desorption may be very slow.

Volatilization

Organic compounds partition from water into air by the process of volatilization. An air-water distribution coefficient, the Henry's Law constant (H), has been defined as the ratio of the concentration of an SOC in air in equilibrium with its concentration in water:

H = SOC concentration in air / SOC concentration in water

"SOC" = synthetic organic compounds

A Henry's Law constant for an SOC can be estimated from the ratio of the compound's vapor pressure to its water solubility. Organic compounds that are inherently volatile (generally low molecular weight solvents) have very high Henry's Law constants. But even compounds with very low vapor pressure can partition into the atmosphere. DDT and PCBs for example, have modest Henry's Law constants because their solubility in water is so low. These SOC also have high K_d values and so may be-

Table 2.8: Regression equations for sediment adsorption coefficients (K_{oc}) for various contaminants.

Equation[a]	No.[b]	r^2[c]	Chemical Classes Represented
$\log K_{oc} = -0.55 \log S + 3.64$ (S in mg/L)	106	0.71	Wide variety, mostly pesticides
$\log K_{oc} = -0.54 \log S + 0.44$ (S in mole fraction)	10	0.94	Mostly aromatic or polynuclear aromatics; two chlorinated
$\log K_{oc} = -0.557 \log S + 4.277$ (S in μ moles/L)[d]	15	0.99	Chlorinated hydrocarbons
$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	45	0.74	Wide variety, mostly pesticides
$\log K_{oc} = 0.937 \log K_{ow} - 0.006$	19	0.95	Aromatics, polynuclear aromatics, triazines, and dinitroaniline herbicides
$\log K_{oc} = 1.00 \log K_{ow} - 0.21$	10	1.00	Mostly aromatic or polynuclear aromatics; two chlorinated
$\log K_{oc} = 0.95 \log K_{ow} + 0.02$	9	e	S-triazines and dinitroaniline herbicides
$\log K_{oc} = 1.029 \log K_{ow} - 0.18$	13	0.91	Variety of insecticides, herbicides, and fungicides
$\log K_{oc} = 0.524 \log K_{ow} + 0.855$[d]	30	0.84	Substituted phenylureas and alkyl-N-phenylcarbamates
$\log K_{oc} = 0.0067 (p - 45N) + 0.237$[d,f]	29	0.69	Aromatic compounds, urea, 1.3.5-triazines, carbamates, and uracils
$\log K_{oc} = 0.681 \log 8CF(f) + 1.963$	13	0.76	Wide variety, mostly pesticides
$\log K_{oc} = 0.681 \log 8CF(t) + 1.886$	22	0.83	Wide variety, mostly pesticides

[a] K_{oc} = soil (or sediment) adsorption coefficient; S = water solubility; K_{ow} = octanol-water partition coefficient; BCF(f) = bioconcentration factor from flowing-water tests; BCF(t) = bioconcentration factor from model ecosystems; P = parachor; N = number of sites in molecule which can participate in the formation of a hydrogen bond.

[b] No. = number of chemicals used to obtain regression equation.

[c] r^2 = correlation coefficient for regression equation.

[d] Equation originally given in terms of K_{om}. The relationship $K_{om} = K_{oc}/1.724$ was used to rewrite the equation in terms of K_{oc}.

[e] Not available.

[f] Specific chemicals used to obtain regression equation not specified.

come airborne in association with particulate matter.

Degradation

SOC can be transformed into a variety of degradation products. These degradation products may themselves degrade. Ultimate degradation, or mineralization, results in the oxidation of organic carbon to carbon dioxide. Major transformation processes include photolysis, hydrolysis, and oxidation-reduction reactions. The latter are commonly mediated by biological systems.

Photolysis refers to the destruction of a compound by the energy of light. The energy of light varies inversely with its wavelength (**Figure 2.28**). Long-wave light lacks sufficient energy to break chemical bonds. Short wave light (x-rays and gamma rays) is very destructive; fortunately for life on earth, this type of radiation largely is removed by our upper atmosphere. Light near the visible spectrum reaches the earth's surface and can break many of the bonds common in SOC. The fate of organic solvents following volatilization is usually photolysis in the earth's atmosphere. Photolysis also can be important in the degradation of SOC in stream water.

Hydrolysis refers to the splitting of an organic molecule by water. Essentially water enters a polar location on a molecule and inserts itself, with an H^+ going to one part of the parent molecule and an OH^- going to the other. The two parts then separate. A group of SOC called esters are particularly vulnerable to degradation by hydrolysis. Many esters have been produced as pesticides or plasticizers.

Oxidation-reduction reactions are what fuels most metabolism in the biosphere. SOC are generally considered as sources of reduced carbon. In such situations, what is needed for degradation is a metabolic system with the appro-

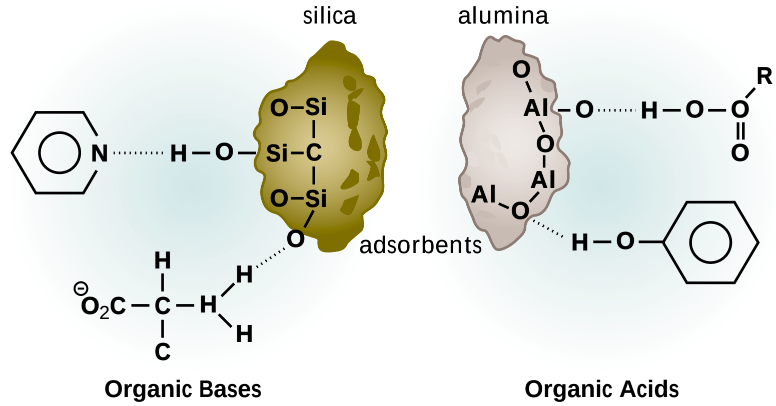
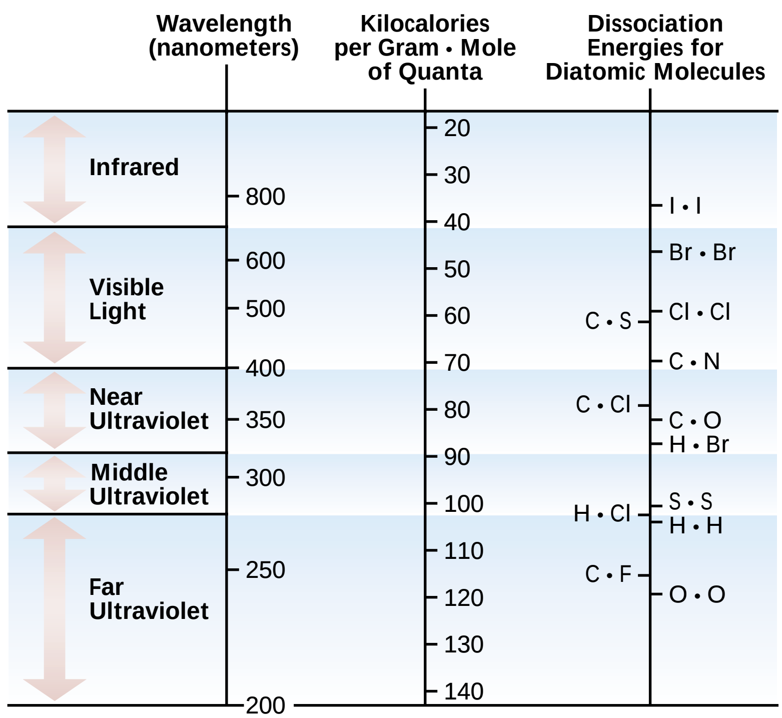


Figure 2.27: Two important types of hydrogen bonding involving natural organic matter and mineral surfaces. *Some contaminants are carried by sediment particles that are sorbed onto their surfaces by chemical bonding.*

Figure 2.28: Energy of electromagnetic radiation compared with some selected bond energies. *Light breaks chemical bonds of some compounds through photolysis.*



priate enzymes for the oxidation of the compound. A sufficient supply of other nutrients and a terminal electron acceptor are also required.

The *principle of microbial infallibility* informally refers to the idea that given a supply of potential food, microbial communities will develop the metabolic capability to use that food for biochemical energy. Not all degradation reactions, however, involve the oxidation of SOC. Some of the most problematic organic contaminants are chlorinated compounds.

Chlorinated SOC do not exist naturally, so microbial systems generally are not adapted for their degradation. Chlorine is an extremely electronegative element. The electronegativity of chlorine refers to its penchant for sucking on electrons. This tendency explains why chloride exists as an anion and why an attached chloride diminishes the solubility of an aromatic ring. Given this character, it is difficult for biological systems to oxidize chlorinated compounds. An initial step in that degradation, therefore, is often reductive dechlorination. The chlorine is removed by reducing the compound (i.e., by giving it electrons). After the chlorines are removed, degradation may proceed along oxidative pathways. The degradation of chlorinated SOC thus may require a sequence of reducing and oxidizing environments, which water may experience as it moves between stream and hyporheic zones.

The overall degradation of SOC often follows complex pathways. **Figure 2.29** shows a complex web of metabolic reaction for a single parent pesticide. Hydrolysis, reduction, and oxidation are all involved in the degradation of SOC, and the distribution and behavior of degradation products can be extremely variable in space and time.

Chemical consequences are rarely the immediate goal of most restoration actions. Plans that alter chemical processes and attributes are usually focused on changing the physical and biological characteristics that are vital to the restoration goals.

Toxic Concentrations of Bioavailable Metals

A variety of naturally occurring metals, ranging from arsenic to zinc, have been established to be toxic to various forms of aquatic life when present in sufficient concentrations. The primary mechanisms for water column toxicity of most metals is adsorption at the gill surface. While some studies indicate that particulate metals may contribute to toxicity, perhaps because of factors such as desorption at the gill surface, the dissolved metal concentration most closely approximates the fraction of metal in the water column that is bioavailable. Accordingly, current EPA policy is that dissolved metal concentrations should be used to set and measure compliance with water quality standards (40 CFR 22228-22236, May 4, 1995). For most metals, the dissolved fraction is equivalent to the inorganic ionic fraction. For certain metals, most notably mercury, the dissolved fraction also may include the metal complexed with organic binding agents (e.g., methyl mercury, which can be produced in sediments by methanogenic bacteria, is soluble and highly toxic, and can accumulate through the food chain).

Toxic Concentrations of Bioavailable Metals Across the Stream Corridor

Unlike synthetic organic compounds, toxic metals are naturally occurring. In common with synthetic organics, metals may be loaded to waterbodies from both point and nonpoint sources. Pollutants such as copper, zinc, and lead are often of concern in effluent from wastewater treatment plants but are required under the NPDES program to meet numeric water quality standards.

Many of the toxic metals are present at significant concentrations in most soils but in sorbed nonbioavailable forms. Sediment often introduces significant concentrations of metals such as zinc into waterbodies. It is then a matter of whether instream conditions promote bioavailable dissolved forms of the metal.

Nonpoint sources of metals first reflect the characteristics of watershed soils. In addition, many older industrial areas have soil concentrations of certain metals that are elevated due to past industrial practices. Movement of metals from soil to watershed is largely a function of the erosion and delivery of sediment.

In certain watersheds, a major source of metals loading is provided by acid mine drainage. High acidity increases the solubility of many metals, and mines tend to be in mineral-rich areas. Abandoned mines are therefore a continuing source of toxic metals loading in many streams.

Toxic Concentrations of Bioavailable Metals Along the Stream Corridor

Most metals have a tendency to leave the dissolved phase and attach to suspended particulate matter or form insoluble precipitates. Conditions that partition metals into particulate forms (presence of suspended sediments, dissolved and particulate organic carbon, carbonates, bicarbonates, and other ions that complex metals) reduce potential bioavailability of metals. Also, calcium reduces metal uptake, apparently by competing with metals for active uptake sites on gill membranes. pH is also an important water quality factor in metal bioavailability. In general, metal solubilities are lower at near neutral pH's than in acidic or highly alkaline waters.

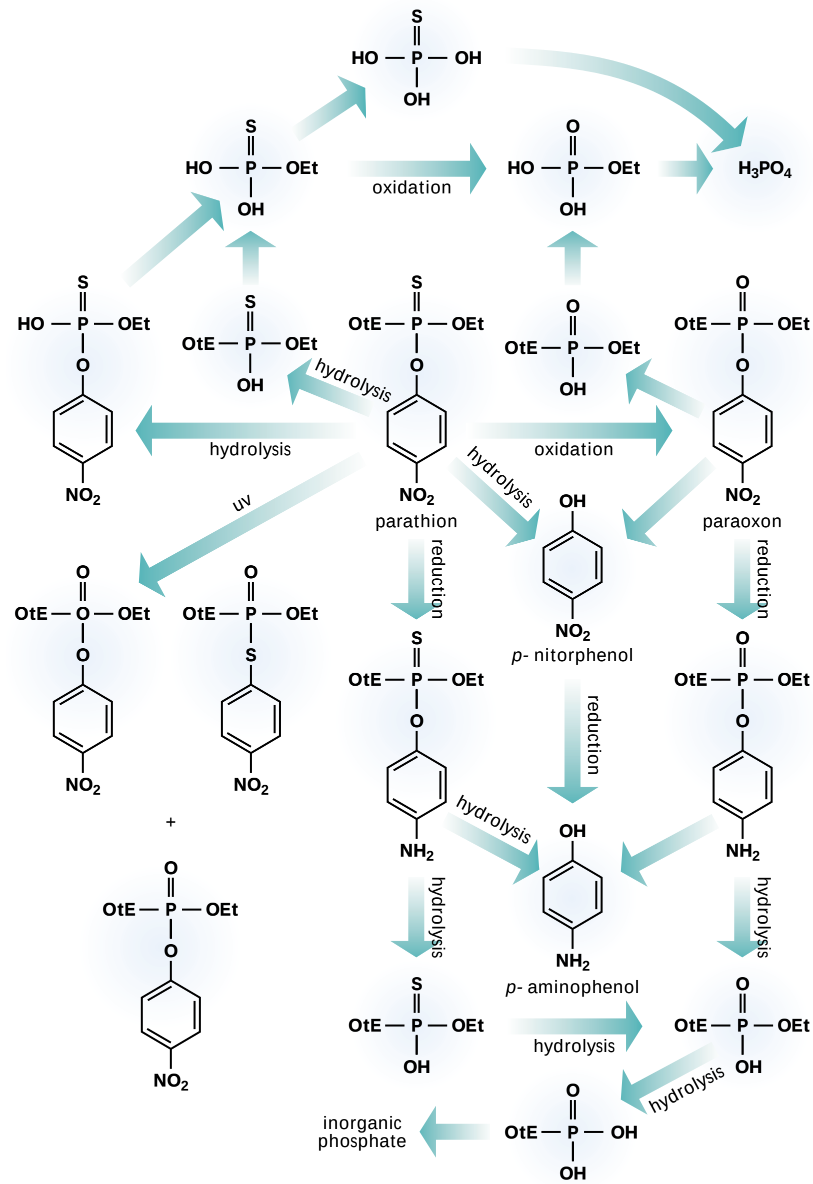


Figure 2.29: Metabolic reactions for a single parent pesticide. *Particles break down through processes of hydrolysis, oxidation, reduction, and photolysis.*

Ecological Functions of Soils

Soil is a living and dynamic resource that supports life. It consists of inorganic mineral particles of differing sizes (clay, silt, and sand), organic matter in various stages of decomposition, numerous species of living organisms, various water soluble ions, and various gases and water. These components each have their own physical and chemical characteristics which can either support or restrict a particular form of life.

Soils can be mineral or organic depending on which material makes up the greater percentage in the soil matrix. Mineral soils develop in materials weathered from rocks while organic soils develop in decayed vegetation. Both soils typically develop horizons or layers that are approximately parallel to the soil surface. The extreme variety of specific niches or conditions soil can create has enabled a large variety of fauna and flora to evolve and live under those conditions.

Soils, particularly riparian and wetland soils, contain and support a very high diversity of flora and fauna both above and below the soil surface. A large variety of specialized organisms can be found below the soil surface, outnumbering those above ground by several orders of magnitude. Generally, organisms seen above ground are higher forms of life such as plants and wildlife. However, at and below ground, the vast majority of life consists of plant roots having the responsibility of supporting the above ground portion of the plant; many insects, mollusks, and fungi living on dead organic matter; and an infinite number of bacteria which can live on a wide variety of energy sources found in soil.

It is important to identify soil boundaries and to understand the differences in soil properties and functions occurring within a stream corridor in order to identify opportunities and limitations for restoration. Floodplain and terrace soils are often areas of dense population and intensive agricultural development due to their flat slopes, proximity to water, and natural fertility. When planning stream corridor restoration initiatives in developed areas, it is important to recognize these alterations and to consider their impacts on goals.

Soils perform vital functions throughout the landscape. One of the most important functions of soil is to provide a physical, chemical, and biological setting for living organisms. Soils support biological activity and diversity for plant and animal productivity. Soils also regulate and partition the flow of water and the storage and cycling of nutrients and other elements in the landscape. They filter, buffer, degrade, immobilize, and detoxify organic and inorganic materials and provide the mechanical support living organisms need. These hydrologic, geomorphic, and biologic functions involve processes that help build and sustain stream corridors.

Soil Microbiology

Organic matter provides the main source of energy for soil microorganisms. Soil organic matter normally makes up 1 to 5 percent of the total weight in a mineral topsoil. It consists of original tissue, partially decomposed tissue, and humus. Soil organisms consume roots and vegetative detritus for energy and to build tissue. As the original organic matter is decomposed and modified by microorganisms, a gelatinous, more resistant compound is formed. This material is called *humus*. It is generally black or brown in color and exists as a colloid, a group of small, insoluble particles suspended in a gel. Small amounts of humus greatly increase a soil's ability to hold water and nutrient ions which enhances plant production. Humus is an indicator of a large and viable population of microorganisms in the soil and it increases the options available for vegetative restoration.

Bacteria play vital roles in the organic transactions that support plant growth. They are responsible for three essential transformations: denitrification, sulfur oxidation, and nitrogen fixation. Microbial reduction of nitrate to nitrite and then to gaseous forms of nitrogen is termed denitrification. A water content of 60 percent generally limits denitrification and the process only occurs at soil temperatures between 5°C and 75°C. Other soil properties optimizing the rate of denitrification include a pH between 6 and 8, soil aeration below the biological oxygen demand of the organisms in the soil, sufficient amounts of water-soluble carbon compounds, readily available nitrate in the soil, and the presence of enzymes needed to start the reaction.

Landscape and Topographic Position

Soil properties change with topographic position. Elevation differences generally mark the boundaries of soils and drainage conditions in stream corridors. Different landforms generally have different types of sediment underlying them. Surface and subsurface drainage patterns also vary with landforms.

- *Soils of active channels.* The active channel forms the lowest and usually youngest surfaces in the stream corridor. There is generally no soil developed on these surfaces since the unconsolidated materials forming the stream bottom and banks are constantly being eroded, transported, and redeposited.
- *Soils of active floodplains.* The next highest surface in the stream corridor is the flat, depositional surface of the active floodplain. This surface floods frequently, every 2 out of 3 years, so it receives sediment deposition.
- *Soils of natural levees.* Natural levees are built adjacent to the stream by deposition of coarser, suspended sediment dropping out of overbank flows during floods. A gentle backslope occurs on the floodplain side of the natural levee, so the floodplain becomes lowest at a point far from the river. Parent materials decrease in grain size away from the river due to the decrease in sediment-transport capacity in the slackwater areas.
- *Soils of topographic floodplains.* Slightly higher areas within and outside the active floodplain are defined as the topographic floodplain. They are usually inundated less frequently than the active floodplain, so soils may exhibit more profile development than the younger soils on the active floodplain.
- *Soils of terraces.* Abandoned floodplains, or terraces, are the next highest surfaces in stream corridors. These surfaces rarely flood. Terrace soils, in general, are coarser textured than floodplain soils, are more freely drained, and are separated from stream processes.

Upon close examination, floodplain deposits can reveal historical events of given watersheds. Soil profile development offers clues to the recent and geologic history at a site. Intricate and complex analysis methods such as carbon dating, pollen analysis, ratios of certain isotopes, etc. can be used to piece together an area's history. Cycles of erosion or deposition can at times be linked to catastrophic events like forest fires or periods of high or low precipitation. Historical impacts of civilization, such as extensive agriculture or denudation of forest cover will at times also leave identifiable evidence in soils.

Soil Temperature and Moisture Relationships

Soil temperature and moisture control biological processes occurring in soil. Average and expected precipitation and temperature extremes are critical pieces of information when considering goals for restoration initiatives. The mean annual soil temperature is usually very similar to the mean annual air temperature. Soil temperatures do experience daily, seasonal, and annual fluctuations caused by solar radiation, weather patterns, and climate. Soil temperatures are also affected by aspect, latitude, and elevation.

Soil moisture conditions change seasonally. If changes in vegetation species and composition are being considered as part of a restoration initiative, a graph comparing monthly precipitation and evapotranspiration for the vegetation should be constructed. If the water table and capillary fringe is below the predicted rooting depth, and the graph indicates a deficit in available water, irrigation may be required. If no supplemental water is available, different plant species must be considered.

The soil moisture gradient can decrease from 100 percent to almost zero along the transriparian continuum as one progresses from the stream bottom, across the riparian zone, and into the higher elevations of the adjacent uplands (Johnson and Lowe 1985), which results in vast differences in moisture available to vegetation. This gradient in soil moisture directly influences the characteristics of the ecological communities of the riparian, transitional, and upland zones. These ecological differences result in the presence of two ecotones along the stream corridor—an aquatic-wetland/riparian ecotone and a non-wetland riparian/floodplain ecotone—which increase the edge effect of the riparian zone and, therefore, the biological diversity of the region.

Wetland Soils

Wet or "hydric" soils present special challenges to plant life. Hydric soils are present in wetlands areas, creating such drastic changes in physical and chemical conditions that most species found in uplands cannot survive. Hence the composition of flora and fauna in wetlands are vastly different and unique, especially in wetlands subject to permanent or prolonged saturation or flooding.

Hydric soils are defined as those that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part. These anaerobic conditions affect the reproduction, growth, and survival of plants. The driving process behind the formation of hydric soils is flooding and/or soil saturation near the surface for prolonged periods (usually more the seven days) during the growing season (Tiner and Veneman 1989).

The following focuses primarily on mineral hydric soil properties, but organic soils such as peat and muck may be present in the stream corridor.

In aerated soil environments, atmospheric oxygen enters surface soils through gas diffusion, as soil pores are mostly filled with air. Aerated soils are found in well drained uplands, and generally all areas having a water table well below the root zone. In saturated soils, pores are filled with water, which diffuse gases very slowly compared to the atmosphere. Only small amounts of oxygen can dissolve in soil moisture, which then disperses into the top few inches of soil. Here, soil microbes quickly deplete all available free oxygen in oxidizing organic residue to carbon dioxide. This reaction produces an anaerobic chemically reducing environment in which oxidized compounds are changed to reduced compounds that are soluble and also toxic to many plants. The rate of diffusion is so slow that oxygenated conditions cannot be reestablished under such circumstances. Similar microbial reactions involving decomposition of organic matter in waterlogged anaerobic environments produce ethylene gas, which is highly toxic to plant roots and has an even stronger effect than a lack of oxygen. After all free oxygen is utilized, anaerobic microbes reduce other chemical constituents of the soil including nitrates, manganese oxides, and iron oxides, creating a further reduced condition in the soil.

Prolonged anaerobic reducing conditions result in the formation of readily visible signs of reduction. The typical gray colors encountered in wet soils are the result of reduced iron, and are known as *gleyed* soils. After iron oxides are depleted, sulfates are reduced to sulfides, producing the rotten egg odor of wet soils. Under extremely waterlogged conditions, carbon dioxide can be reduced to methane. Methane gas, also known as “swamp gas” can be seen at night, as it fluoresces.

Some wetland plants have evolved special mechanisms to compensate for having their roots immersed in anoxic environments. Water lilies, for example, force a gas exchange within the entire plant by closing their stomata during the heat of the day to raise the air pressure within special conductive tissue (aerenchyma). This process tends to introduce atmospheric oxygen deep into the root crown, keeping vital tissues alive. Most emergent wetland plants simply keep their root systems close to the soil surface to avoid anaerobic conditions in deeper strata. This is true of sedges and rushes, for example.

When soils are continually saturated throughout, reactions can occur equally throughout the soil profile as opposed to wet soils where the water level fluctuates. This produces soils with little zonation, and materials tend to be more uniform. Most differences in texture encountered with depth are related to stratification of sediments sorted by size during deposition by flowing water. Clay formation tends to occur in place and little translocation happens within the profile, as essentially no water moves through the soil to transport the particles. Due to the reactivity of wet soils, clay formation tends to progress much faster than in uplands.

Soils which are seasonally saturated or have a fluctuating water table result in distinct horizonation within the profile. As water regularly drains through the profile, it translocates particles and transports soluble ions from one layer to another, or entirely out of the profile. Often, these soils have a thick horizon near the surface which is stripped of all soluble materials including iron; known as a *depleted matrix*. Seasonally saturated soils usually have substantial organic matter accumulated at the surface, nearly black in color. The organics add to the cation exchange capacity of the soil, but base saturation is low due to stripping and overabundance of hydrogen ions. During non-saturated times, organic materials are exposed to atmospheric oxygen, and aerobic decomposition can take place which results in massive liberation of hydrogen ions. Seasonally wet soils also do not retain base metals well, and can release high concentrations of metals in wet cycles following dry periods.

Wet soil indicators will often remain in the soil profile for long periods of time (even after drainage), revealing the historical conditions which prevailed. Examples of such indicators are rust colored iron deposits which at one time were translocated by water in reduced form. Organic carbon distribution from past fluvial deposition cycles or zones of stripped soils resulting from wetland situations are characteristics which are extremely long lived.

Summary

This section provides only a brief overview of the diverse and complex chemistry; nevertheless, two key points should be evident to restoration practitioners:

- *Restoring physical habitat cannot restore biological integrity of a system if there are water quality constraints on the ecosystem.*
- *Restoration activities may interact in a variety of complex ways with water quality, affecting both the delivery and impact of water quality stressors.*

***Table 2.9** shows how a sample selection of common stream restoration and watershed management practices may interact with the water quality parameters described in this section.*

Table 2.9: Potential water quality impacts of selected stream restoration and watershed management practices.

Restoration Activities	Fine Sediment Loads	Water Temperature	Salinity	pH	Dissolved Oxygen	Nutrients	Toxics
Reduction of land-disturbing activities	Decrease	Decrease	Decrease	Increase/ decrease	Increase	Decrease	Decrease
Limit impervious surface area in the watershed	Decrease	Decrease	Negligible effect	Increase	Increase	Decrease	Decrease
Restore riparian vegetation	Decrease	Decrease	Decrease	Decrease	Increase	Decrease	Decrease
Restore wetlands	Decrease	Increase/ decrease	Increase/ decrease	Increase/ decrease	Decrease	Increase	Increase
Stabilize channel and restore under-cut banks	Decrease	Decrease	Decrease	Decrease	Increase	Decrease	Negligible effect
Create drop structures	Increase	Negligible effect	Negligible effect	Increase/ decrease	Increase	Negligible effect	Decrease
Reestablish riffle substrate	Negligible effect	Negligible effect	Negligible effect	Increase/ decrease	Increase	Negligible effect	Negligible effect

2.D Biological Community Characteristics

Successful stream restoration is based on an understanding of the relationships among physical, chemical, and biological processes at varying time scales. Often, human activities have accelerated the temporal progression of these processes, resulting in unstable flow patterns and altered biological structure and function of stream corridors. This section discusses the biological structure and functions of stream corridors in relation to geomorphologic, hydrologic, and water quality processes. The interrelations between the watershed and the stream, as well as the cause and effects of disturbances to these interrelationships are also discussed. Indices and approaches for evaluating stream corridor functions are provided in Chapter 7.

Terrestrial Ecosystems

The biological community of a stream corridor is determined by the characteristics of both terrestrial and aquatic ecosystems. Accordingly, the discussion of biological communities in stream corridors begins with a review of terrestrial ecosystems.

Ecological Role of Soil

Terrestrial ecosystems are fundamentally tied to processes within the soil. The ability of a soil to store and cycle nutrients and other elements depends on the properties and microclimate (i.e., moisture and temperature) of the soil, and the soil's community of organisms (**Table 2.10**). These factors also determine its effectiveness at filtering, buffering, degrading, immobilizing, and detoxifying other organic and inorganic materials.

Terrestrial Vegetation

The ecological integrity of stream corridor ecosystems is directly related to the integrity and ecological characteristics of the plant communities that make up and surround the corridor. These plant communities are a valuable source of energy for the biological communities, provide physical habitat, and moderate solar energy fluxes to and from the surrounding aquatic and terrestrial ecosystems. Given adequate moisture, light, and temperature, the vegetative community grows in an annual cycle of active growth/production, senescence, and relative dormancy. The growth period is subsidized by incidental solar radiation, which drives the photosynthetic process through which inorganic carbon is converted to organic plant materials. A portion of this organic material is stored as above- and below-ground biomass, while a significant fraction of organic matter is lost annually via senescence, fractionation, and leaching to the organic soil layer in the form of leaves, twigs, and decaying roots. This organic fraction, rich in biological activity of microbial flora and microfauna, represents a major storage and cycling pool of available carbon, nitrogen, phosphorus, and other nutrients.

The distribution and characteristics of vegetative communities are determined by climate, water availability, topographic features, and the chemical and physical properties of the soil, including moisture and nutrient content. The characteristics of the plant communities directly influence the diversity and integrity of the faunal communities. Plant communities that cover a large area and that are diverse in their vertical and horizontal structural characteristics can support far more diverse faunal com-

REVERSE

Review Section C for further discussion of the ecological functions of soils.

Animals		
Macro	**Subsisting largely on plant materials**	
		Small mammals—squirrels, gophers, woodchucks, mice, shrews
		Insects—springtails, ants, beetles, grubs, etc.
		Millipedes
		Sowbugs (woodlice)
		Mites
		Slugs and snails
		Earthworms
	Largely predatory	
		Moles
		Insects—many ants, beetles, etc.
		Mites, in some cases
		Centipedes
		Spiders
Micro	**Predatory or parasitic or subsisting on plant residues**	
		Nematodes
		Protozoa
		Rotifers

Plants		
Roots of higher plants		
Algae		
	Green	
	Blue-green	
	Diatoms	
Fungi		
	Mushroom fungi	
	Yeasts	
	Molds	
Actinomycetes of many kinds		
Bacteria		
	Aerobic	Autotrophic
		Heterotrophic
	Anaerobic	Autotrophic
		Heterotrophic

Table 2.10: Groups of organisms commonly present in soils.

munities than relatively homogenous plant communities, such as meadows. As a result of the complex spatial and temporal relationships that exist between floral and faunal communities, current ecological characteristics of these communities reflect the recent historical (100 years or less) physical conditions of the landscape.

The quantity of terrestrial vegetation, as well as its species composition, can directly affect stream channel characteristics. Root systems in the streambank can bind bank sediments and moderate erosion processes. Trees and smaller woody debris that fall into the stream can deflect flows and induce erosion at some points and deposition at others. Thus woody debris accumulation can influence pool distribution, organic matter and nutrient retention, and the formation of microhabitats that are important fish and invertebrate aquatic communities.

Streamflow also can be affected by the abundance and distribution of terrestrial vegetation. The short-term effects of removing vegetation can result in an immediate short-term rise in the local water table due to decreased evapotranspiration and additional water entering the stream. Over the longer term, however, after removal of vegetation, the baseflow of streams can decrease and water temperatures can rise, particularly in low-order streams. Also, removal of vegetation can cause changes in soil temperature and structure, resulting in decreased movement of water into and through the soil profile. The loss of surface litter and the gradual loss of organic matter in the soil also contribute to increased surface runoff and decreased infiltration.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishing corridors that are structurally different from native systems or that are inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and, where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages (Knopf et al. 1988).

Landscape Scale

The ecological characteristics and distribution of plant communities in a watershed influence the movement of water, sediment, nutrients, and wildlife. Stream corridors provide links with other features of the landscape. Links may involve continuous corridors between headwater and valley floor ecosystems or periodic interactions between terrestrial systems. Wildlife use corridors to disperse juveniles, to migrate, and to move between portions of their home range. Corridors of a natural origin are preferred and include streams and rivers, riparian strips, mountain passes, isthmuses, and narrow straits (Payne and Bryant 1995).

It is important to understand the differences between a stream-riparian ecosystem and a river-floodplain ecosystem. Flooding in the stream-riparian ecosystem is brief and unpredictable. The riparian zone supplies nutrients, water, and sediment to the stream channel, and riparian vegetation regulates temperature and light. In the river-floodplain ecosystem, floods are often more predictable and longer lasting, the river channel is the donor of water, sediment, and inorganic nutrients to the floodplain, and the influx of turbid and cooler channel water influences light penetration and temperature of the inundated floodplain.

Stream Corridor Scale

At the stream corridor scale, the composition and regeneration patterns of vegetation are characterized in terms of *horizontal complexity*. Floodplains along unconstrained channels typically are vegetated with a mosaic of plant communities, the composition of which varies in response to available surface and ground water, differential patterns of flooding, fire, and predominant winds, sediment deposition, and opportunities for establishing vegetation.

A broad floodplain of the southern, midwestern, or eastern United States may support dozens of relatively distinct forest communities in a complex mosaic reflecting subtle differences in soil type and flood characteristics (e.g., frequency, depth, and duration). In contrast, while certain western stream systems may support only a few woody species, these systems may be structurally complex due to constant reworking of substrates by the stream, which produces a mosaic of stands of varying ages. The presence of side channels, oxbow lakes, and other topographic variation can be viewed as elements of structural variation at the stream corridor level. Riparian areas along constrained stream channels may consist primarily of upland vegetation organized by processes largely unrelated to stream characteristics, but these areas may have considerable influence on the stream ecosystem.

The River Continuum Concept, as discussed in Chapter 1, is also generally applicable to the vegetative components of the riparian corridor. Riparian vegetation demonstrates both a transriparian gradient (across the valley) and an intra-riparian (longitudinal, elevational) gradient (Johnson and Lowe 1985). In the west, growth of riparian vegetation is increased by the "canyon effect" resulting when cool moist air spills downslope from higher elevations (**Figure 2.30**). This cooler air settles in canyons and creates a more moist microhabitat than occurs on the surrounding slopes. These canyons also serve as water courses. The combination of moist, cooler edaphic and atmospheric conditions is conducive to plant and animal species at lower than normal altitudes, often in disjunct populations or in regions where they would not otherwise occur (Lowe and Shannon 1954).

Plant Communities

The sensitivity of animal communities to vegetative characteristics is well recognized. Numerous animal species are associated with particular plant communities, many require particular developmental stages of those communities (e.g., old-growth), and some depend on particular habitat elements within those communities (e.g., snags). The structure of streamside plant communities also directly affects aquatic organisms by providing inputs of appropriate organic materials to the aquatic food web, by shading the water surface and providing cover along banks, and by influencing instream habitat structure through in-

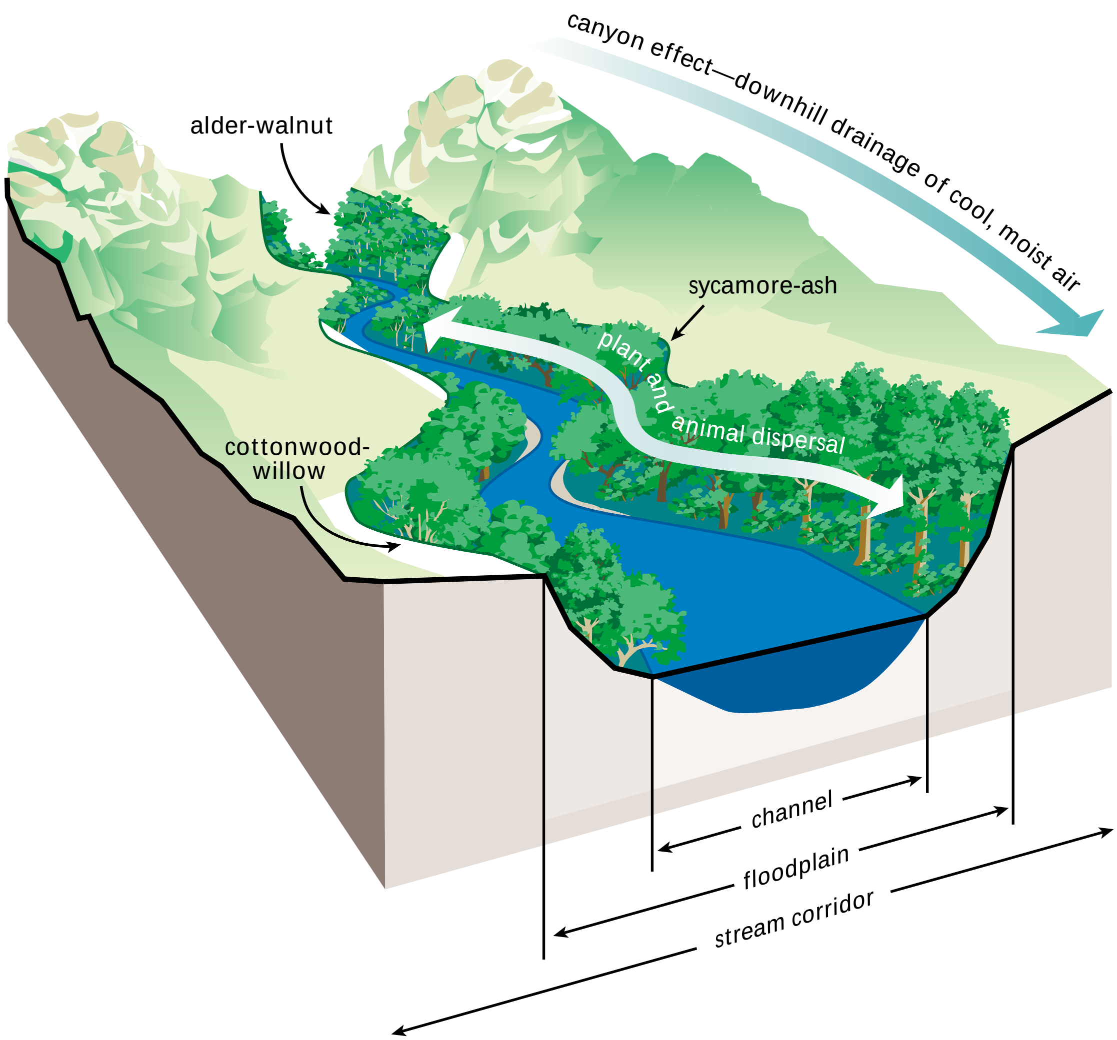


Figure 2.30: Canyon effect. *Cool moist air settles in canyons and creates microhabitat that occurs on surrounding slopes.*

puts of woody debris (Gregory et al. 1991).

Plant communities can be viewed in terms of their internal complexity (**Figure 2.31**). Complexity may include the number of layers of vegetation and the species comprising each layer; competitive interactions among species; and the presence of detrital components, such as litter, downed wood, and snags. Vegetation may contain tree, sapling, shrub (subtree), vine, and herbaceous subshrub (herb-grass-forb) layers. Microtopographic relief and the ability of water to locally pond also may be regarded as characteristic structural components.

Vertical complexity, described in the concept of diversity of strata or foliage height diversity in ecological literature, was important to studies of avian habitat by Carothers et al. (1974) along the Verde River, a fifth- or sixth-order stream in central Arizona. Findings showed a high correlation between riparian bird species diversity and foliage height diversity of riparian vegetation (Carothers et al. 1974). Short (1985) demonstrated that more structurally diverse vegetative habitats support a greater number of guilds (groups of species with closely related niches in a community) and therefore a larger number of species.

Species and age composition of vegetation structure also can be extremely important. Simple vegetative structure, such as an herbaceous layer without woody overstory or old woody riparian trees without smaller size classes, creates fewer niches for guilds. The fewer guilds there are, the fewer species there are. The quality and vigor of the vegetation can affect the productivity of fruits, seeds, shoots, roots, and other vegetative material, which provide food for wildlife. Poorer vigor can result in less food and fewer consumers (wildlife).

Increasing the patch size (area) of a streamside vegetation type, increasing the number of woody riparian tree size classes, and increasing the number of species and growth forms (herb, shrub, tree) of native riparian-dependent vegetation can increase the number of guilds and the amount of forage, resulting in increased species richness and biomass (numbers). Restoration techniques can change the above factors.

The importance of horizontal complexity within stream corridors to certain animal species also has been well established. The characteristic compositional, structural, and topographic complexity of southern floodplain forests, for example, provides the range of resources and foraging conditions required by many wintering waterfowl to meet particular requirements of their life cycles at the appropriate times (Fredrickson 1978); similar complex relationships have been reported for other vertebrates and invertebrates in floodplain habitats (Wharton et al. 1982). In parts of the arid West, the unique vegetation structure in riparian systems contrasts dra-

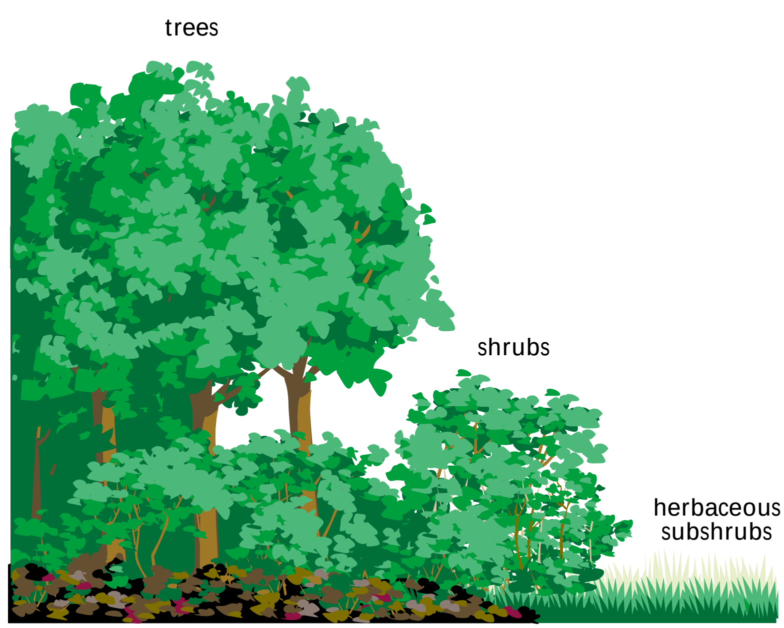


***Figure 2.31: Vertical complexity.** Complexity may include a number of layers of vegetation.*

matically with the surrounding uplands and provides essential habitat for many animals (Knopf et al. 1988). Even within compositionally simple riparian systems, different developmental stages may provide different resources.

Plant communities are distributed on floodplains in relation to flood depth, duration, and frequency, as well as variations in soils and drainage condition. Some plant species, such as cottonwood (*Populus* sp.), willows (*Salix* sp.), and silver maple (*Acer saccharinum*), are adapted to colonization of newly deposited sediments and may require very specific patterns of flood recession during a brief period of seedfall to be successfully established (Morris et al. 1978, Rood and Mahoney 1990). The resultant pattern is one of even-aged tree stands established at different intervals and locations within the active meander belt of the stream. Other species, such as the bald cypress (*Taxodium distichum*), are particularly associated with oxbow lakes formed when streams cut off channel segments, while still others are associated with microtopographic variations within floodplains that reflect the slow migration of a stream channel across the landscape.

Plant communities are dynamic and change over time. The differing regeneration strategies of particular vegetation types lead to characteristic patterns of plant succession following disturbances in which pioneer species well-adapted to bare soil and plentiful light are gradually replaced by longer-lived species that can regenerate under more shaded and protected conditions. New disturbances reset the successional process. Within stream corridors, flooding, channel migration, and, in certain biomes, fire, are usually the dominant natural sources of disturbance. Restoration practitioners should understand patterns of natural succession in a stream corridor and should take advantage of the successional process by planting hardy early-successional species to stabilize an eroding streambank, while planning for the eventual replacement of these species by longer-lived and higher-successional species.

Terrestrial Fauna

Stream corridors are used by wildlife more than any other habitat type (Thomas et al. 1979) and are a major source of water to wildlife populations, especially large mammals. For example, 60 percent of Arizona's wildlife species depend on riparian areas for survival (Ohmart and Anderson 1986). In the Great Basin area of Utah and Nevada, 288 of the 363 identified terrestrial vertebrate species depend on riparian zones (Thomas et al. 1979). Because of their wide suitability for upland and riparian species, midwestern stream corridors associated with prairie grasslands support a wider diversity of wildlife than the associated uplands. Stream corridors play a large role in maintaining biodiversity for all groups of vertebrates.

The faunal composition of a stream corridor is a function of the interaction of food, water, cover, and spatial arrangement (Thomas et al. 1979). These habitat components interact in multiple ways to provide eight habitat features of stream corridors:

- Presence of permanent sources of water.
- High primary productivity and biomass.
- Dramatic spatial and temporal contrasts in cover types and food availability.
- Critical microclimates.
- Horizontal and vertical habitat diversity.

- Maximized edge effect.
- Effective seasonal migration routes.
- High connectivity between vegetated patches.

Stream corridors offer the optimal habitat for many forms of wildlife because of the proximity to a water source and an ecological community that consists primarily of hardwoods in many parts of the country, which provide a source of food, such as nectar, catkins, buds, fruit, and seeds (Harris 1984). Upstream sources of water, nutrients, and energy ultimately benefit downstream locations. In turn, the fish and wildlife return and disperse some of the nutrients and energy to uplands and wetlands during their movements and migrations (Harris 1984).

Water is especially critical to fauna in areas such as the Southwest or Western Prairie regions of the U.S. where stream corridors are the only naturally occurring permanent sources of water on the landscape. These relatively moist environments contribute to the high primary productivity and biomass of the riparian area, which contrasts dramatically with surrounding cover types and food sources. In these areas, stream corridors provide critical microclimates that ameliorate the temperature and moisture extremes of uplands by providing water, shade, evapotranspiration, and cover.

The spatial distribution of vegetation is also a critical factor for wildlife. The linear arrangement of streams results in a maximized edge effect that increases species richness because a species can simultaneously access more than one cover (or habitat) type and exploit the resources of both (Leopold 1933). Edges occur along multiple habitat types including the aquatic, riparian, and upland habitats.

Forested connectors between habitats establish continuity between forested uplands that may be surrounded by unforested areas. These act as feeder lines for dispersal and facilitate repopulation by plants and animals. Thus, connectivity is very important for retaining biodiversity and genetic integrity on a landscape basis.

However, the linear distribution of habitat, or edge effect, is not an effective indicator of habitat quality for all species. Studies in island biogeography, using habitat islands rather than oceanic islands, demonstrate that a larger habitat island supports both a larger population of birds and also a larger number of species (Wilson and Carothers 1979). Although a continuous corridor is most desirable, the next preferable situation is minimal fragmentation, i.e., large plots (“islands”) of riparian vegetation with minimal spaces between the large plots.

Reptiles and Amphibians

Nearly all amphibians (salamanders, toads, and frogs) depend on aquatic habitats for reproduction and overwintering. While less restricted by the presence of water, many reptiles are found primarily in stream corridors and riparian habitats. Thirty-six of the 63 reptile and amphibian species found in west-central Arizona were found to use riparian zones. In the Great Basin, 11 of 22 reptile species require or prefer riparian zones (Ohmart and Anderson 1986).

Birds

Birds are the most commonly observed terrestrial wildlife in riparian corridors. Nationally, over 250 species have been reported using riparian areas during some part of the year.

The highest known density of nesting birds in North America occurs in southwestern cottonwood habitats (Carothers and Johnson 1971). Seventy-three percent of the 166 breeding bird species in the Southwest prefer riparian habitats (Johnson et al. 1977).

Bird species richness in midwestern stream corridors reflects the vegetative diversity and width of the corridor. Over half of these breeding birds are species that forage for insects on foliage (vireos, warblers) or species that forage for seeds on the ground (doves, orioles, grosbeaks, sparrows). Next in abundance are insectivorous species that forage on the ground or on trees (thrushes, woodpeckers).

Smith (1977) reported that the distribution of bird species in forested habitats of the Southeast was closely linked to soil moisture. Woodcock (*Scolopax minor*) and snipe (*Gallinago gallinago*), red-shouldered hawks (*Buteo lineatus*), hooded and prothonotary warblers (*Wilsonia citrina*, *Protonotaria citrea*), and many other passerines in the Southeast prefer the moist ground conditions found in riverside forests and shrublands for feeding. The cypress and mangrove swamps along Florida's waterways harbor many species found almost nowhere else in the Southeast.

Mammals

The combination of cover, water, and food resources in riparian areas make them desirable habitat for large mammals such as mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*), moose (*Alces alces*), and elk (*Cervus elaphus*) that can use multiple habitat types. Other mammals depend on riparian areas in some or all of their range. These include otter (*Lutra canadensis*), ringtail (*Bassarisdus astutus*), raccoon (*Procyon lotor*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), swamp rabbit (*Sylvilagus aquaticus*), short-tailed shrew (*Blarina brevicauda*), and mink (*Mustela vison*).

Riparian areas provide tall dense cover for roosts, water, and abundant prey for a number of bat species, including the little brown bat (*Myotis lucifugus*), big brown bat (*Eptesicus fuscus*), and the pallid bat (*Antrozous pallidus*). Brinson et al. (1981) tabulated results from several studies on mammals in riparian areas of the continental U.S. They concluded that the number of mammal species generally ranges from five to 30, with communities including several furbearers, one or more large mammals, and a few small to medium mammals.

Hoover and Wills (1984) reported 59 species of mammals in cottonwood riparian woodlands of Colorado, second only to pinyon-juniper among eight other forested cover types in the region. Fifty-two of the 68 mammal species found in west-central Arizona in Bureau of Land Management inventories use riparian habitats. Stamp and Ohmart (1979) and Cross (1985) found that riparian areas had a greater diversity and biomass of small mammals than adjacent upland areas.

The contrast between the species diversity and productivity of mammals in the riparian zone and that of the surrounding uplands is especially high in arid and semiarid regions. However, bottomland hardwoods in the eastern U.S. also have exceptionally high habitat values for many mammals. For example, bottomland hardwoods support white-tail deer populations roughly twice as large as equivalent areas of upland forest (Glasgow and Noble 1971).

Stream corridors are themselves influenced by certain animal activities (Forman 1995). For example, beavers build dams that cause ponds to form within a stream channel or in the floodplain. The pond kills much of the existing vegetation, although it does create wetlands and open water areas for fish and migratory waterfowl. If appropriate woody plants in the floodplain are scarce, beavers extend their cutting activities into the uplands and can significantly alter the riparian and stream corridors. Over time, the pond is replaced by a mudflat, which becomes a meadow and eventually gives way to woody successional stages. Beaver often then build a dam at a new spot, and the cycle begins anew with only a spatial displacement.

The sequence of beaver dams along a stream corridor may have major effects on hydrology, sedimentation, and mineral nutrients (Forman 1995). Water from stormflow is held back, thereby affording some measure of flood control. Silts and other fine sediments accumulate in the pond rather than being washed downstream. Wetland areas usually form, and the water table rises upstream of the dam. The ponds combine slow flow, near-constant water levels, and low turbidity that support fish and other aquatic organisms. Birds may use beaver ponds extensively. The wetlands also have a relatively constant water table, unlike the typical fluctuations across a floodplain. Beavers cutting trees diminish the abundance of such species as elm (*Ulmus* spp.) and ash (*Fraxinus* spp.) but enhance the abundance of rapidly sprouting species, such as alder (*Alnus* spp.), willow, and poplar (*Populus* spp.).

Aquatic Ecosystems

Aquatic Habitat

The biological diversity and species abundance in streams depend on the diversity of available habitats. Naturally functioning, stable stream systems promote the diversity and availability of habitats. This is one of the primary reasons stream stability and the restoration of natural functions are always considered in stream corridor restoration activities. A stream's cross-sectional shape and dimensions, its slope and confinement, the grain-size distribution of bed sediments, and even its planform affect aquatic habitat. Under less disturbed situations, a narrow, steep-walled cross section provides less physical area for habitat than a wider cross section with less steep sides, but may provide more biologically rich habitat in deep pools compared to a wider, shallower stream corridor. A steep, confined stream is a high-energy environment that may limit habitat occurrence, diversity, and stability. Many steep, fast flowing streams are coldwater salmonid streams of high value. Unconfined systems flood frequently, which can promote riparian habitat development. Habitat increases with stream sinuosity. Uniform sediment size in a streambed provides less potential habitat diversity than a bed with many grain sizes represented.

Habitat subsystems occur at different scales within a stream system (Frissell et al. 1986) (**Figure 2.32**). The grossest scale, the stream system itself, is measured in thousands of feet, while segments are measured in hundreds of feet and reaches are measured in tens of feet. A reach system includes combinations of debris dams, boulder cascades, rapids, step/pool sequences, pool/riffle sequences, or other types of streambed forms or "structures," each of which could be 10 feet or less in scale. Frissell's smallest scale habitat subsystem includes features that are a foot or less in size. Examples of these *microhabitats* include leaf or stick detritus, sand or silt over cobbles or other coarse material, moss on boulders, or fine gravel patches.

Steep slopes often form a step/pool sequence in streams, especially in cobble, boulder, and bedrock streams. Each step acts as a miniature grade stabilization structure. The steps and pools work

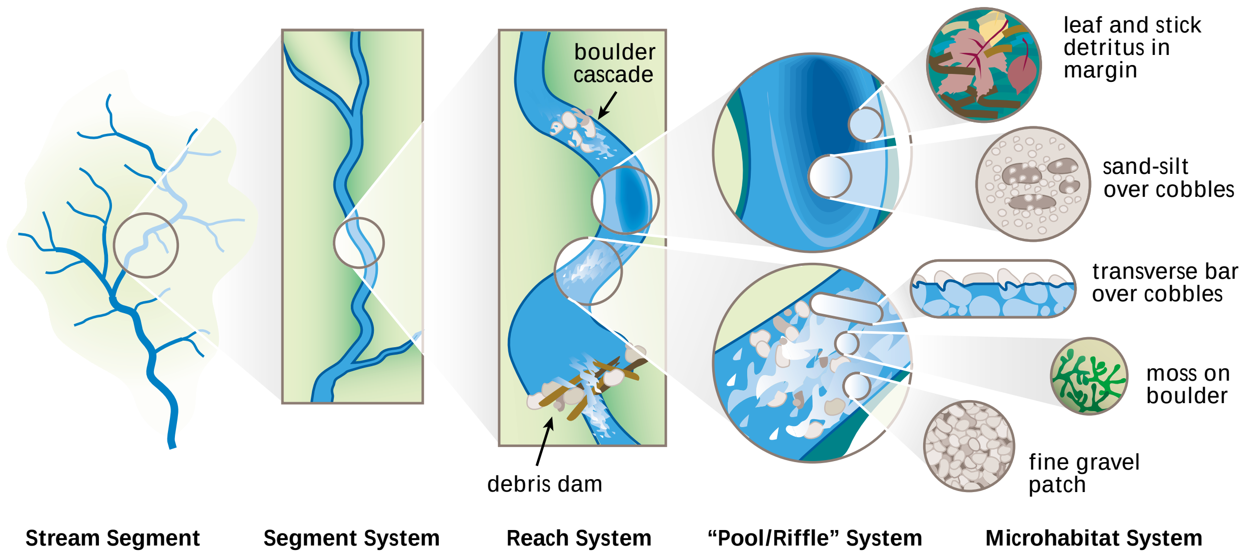


Figure 2.32: Hierarchical organization of a stream system and its habitat subsystems.
Approximate linear spatial scale, appropriate to second- or third-order mountain stream.

together to distribute the excess energy available in these steeply sloping systems. They also add diversity to the habitat available. Cobble- and gravel-bottomed streams at less steep slopes form pool/riffle sequences, which also increase habitat diversity. Pools provide space, cover, and nutrition to fish and they provide a place for fish to seek shelter during storms, droughts, and other catastrophic events. Upstream migration of many salmonid species typically involves rapid movements through shallow areas, followed by periods of rest in deeper pools (Spence et al. 1996).

Wetlands

Stream corridor restoration initiatives may include restoration of wetlands such as riverine-type bottomland hardwood systems or riparian wetlands. While wetland restoration is a specific topic better addressed in other references (e.g., Kentula et al. 1992), a general discussion of wetlands is provided here. Stream corridor restoration initiatives should be designed to protect or restore the functions of associated wetlands.

A wetland is an ecosystem that depends on constant or recurrent shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features that reflect recurrent sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where physicochemical, biotic, or anthropogenic factors have removed them or prevented their development (National Academy of Sciences 1995). Wetlands may occur in streams, riparian areas, and floodplains of the stream corridor. The riparian area or zone may contain both wetlands and non-wetlands.

Wetlands are transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water (Cowardin et al. 1979). For vegetated wetlands, water creates conditions that favor the growth of hydrophytes—plants growing in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content (Cowardin et al. 1979) and promotes the development of hydric soils—soils that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part (National Academy of Sciences 1995).

Wetland functions include fish and wildlife habitat, water storage, sediment trapping, flood damage reduction, water quality improvement/pollution control, and ground water recharge. Wetlands have long been recognized as highly productive habitats for threatened and endangered fish and wildlife species. Wetlands provide habitat for 60 to 70 percent of the animal species federally listed as threatened or endangered (Lohoefner 1997).

The Federal Geographic Data Committee has adopted the U.S. Fish and Wildlife Service's *Classification of Wetlands and Deepwater Habitats of the United States* (Cowardin et al. 1979) as the national standard for wetlands classification. The Service's National Wetlands Inventory (NWI) uses this system to carry out its congressionally mandated role of identifying, classifying, mapping, and digitizing data on wetlands and deepwater habitats. This system, which defines wetlands consistently with the National Academy of Science's reference definition, includes Marine, Estuarine, Riverine, Lacustrine, and Palustrine systems. The NWI has also developed protocols for classifying and mapping riparian habitats in the 22 coterminous western states.

The riverine system under Cowardin's classification includes all wetlands and deepwater habitats contained within a channel except wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens and habitats with water containing ocean-derived salts in excess of 0.5 parts per thousand (ppt).

It is bounded on the upstream end by uplands and on the downstream end at the interface with tidal wetlands having a concentration of ocean-derived salts that exceeds 0.5 ppt. Riverine wetlands

Riparian Mapping

The riparian zone is a classic example of the maximized value that occurs when two or more habitat types meet. There is little question of the substantial value of riparian habitats in the United States. The Fish and Wildlife Service has developed protocols to classify and map riparian areas in the West in conjunction with the National Wetlands Inventory (NWI). NWI will map riparian areas on a 100 percent user-pay basis. No formal riparian mapping effort has been initiated. The NWI is congressionally mandated to identify, classify, and digitize all wetlands and deepwater habitats in the United States. For purposes of riparian mapping, the NWI has developed a riparian definition that incorporates biological information consistent with many agencies and applies information according to cartographic principles. For NWI mapping and classification purposes, a final definition for riparian has been developed:

Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrological features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, and drainage ways). Riparian areas have one or both of the following characteristics: (1) distinctly different vegetative species than adjacent areas; and (2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetland and upland.

The definition applies primarily to regions of the lower 48 states in the arid west where the mean annual precipitation is 16 inches or less and the mean annual evaporation exceeds mean annual precipitation. For purposes of this mapping, the riparian system is subdivided into subsystems, classes, subclasses, and dominance types. (USFWS 1997) are bounded perpendicularly on the landward side by upland, the channel bank (including natural and manufactured levees), or by *Palustrine wetlands*. In braided streams, riverine wetlands are bounded by the banks forming the outer limits of the depression within which the braiding occurs.

Vegetated floodplain wetlands of the river corridor are classified as Palustrine under this system. The Palustrine system was developed to group the vegetated wetlands traditionally called by such names as marsh, swamp, bog, fen, and prairie pothole and also includes small, shallow, permanent, or intermittent water bodies often called ponds. Palustrine wetlands may be situated shoreward of lakes, river channels, or estuaries, on river floodplains, in isolated catchments, or on slopes. They also may occur as islands in lakes or rivers. The Palustrine system includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses and lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5 ppt. The Palustrine system is bounded by upland or by any of the other four systems. They may merge with non-wetland riparian habitat where hydrologic conditions cease to support wetland vegetation or may be totally absent where hydrologic conditions do not support wetlands at all (Cowardin et al. 1979).

The *hydrogeomorphic (HGM) approach* is a system that classifies wetlands into similar groups for conducting functional assessments of wetlands. Wetlands are classified based on geomorphology, water source, and hydrodynamics. This allows the focus to be placed on a group of wetlands that function much more similarly than would be the case without classifying them. Reference wetlands are used to develop reference standards against which a wetland is evaluated (Brinson 1995).

Under the HGM approach, riverine wetlands occur in floodplains and riparian corridors associated with stream channels. The dominant water sources are overbank flow or subsurface connections between stream channel and wetlands. Riverine wetlands lose water by surface and subsurface flow returning to the stream channel, ground water recharge, and evapotranspiration. At the extension closest to the headwaters, riverine wetlands often are replaced by slope or depressional wetlands where channel bed and bank disappear, or they may intergrade with poorly drained flats and uplands. Usually forested, they extend downstream to the intergrade with estuarine fringe wetlands. Lateral extent is from the edge of the channel perpendicularly to the edge of the floodplain. In some landscape situations, riverine wetlands may function hydrologically more like slope wetlands, and in headwater streams with little or no floodplain, slope wetlands may lie adjacent to the stream channel (Brinson et al. 1995). **Table 2.11** summarizes functions of riverine wetlands under the HGM approach. The U.S. Fish and Wildlife Service is testing an operational draft set of hydrogeomorphic type descriptors to help bridge the gap between the Cowardin system and the HGM approach (Tiner 1997).

For purposes of regulation under Section 404 of the Clean Water Act, only areas with wetland hydrology, hydrophytic vegetation, and hydric soils are classified as regulated wetlands. As such, they represent a subset of the areas classified as wetlands under the Cowardin system. However, many areas classified as wetlands under the Cowardin system, but not classified as wetlands for purposes of Section 404, are nevertheless subject to regulation because they are part of the Waters of the United States.

Aquatic Vegetation and Fauna

Stream biota are often classified in seven groups—bacteria, algae, macrophytes (higher plants), protists (amoebas, flagellates, ciliates), microinvertebrates (invertebrates less than 0.02 inch in length, such as rotifers, copepods, ostracods, and nematodes), macroinvertebrates (invertebrates greater than 0.02 inch in length, such as mayflies, stoneflies, caddisflies, crayfish, worms, clams, and snails), and vertebrates (fish, amphibians, reptiles, and mammals) (**Figure 2.33**). The discussion of the River Continuum Concept in Chapter 1, provides an overview of the major groups of organisms found in streams and how these assemblages change from higher order to lower order streams.

Undisturbed streams can contain a remarkable number of species. For example, a comprehensive inventory of stream biota in a small German stream, the Breitenbach, found more than 1,300 species in a 1.2-mile reach. Lists of algae, macroinvertebrates, and fish likely to be found at potential restoration sites may be obtained from state or regional inventories. The densities of such stream biota are shown in **Table 2.12**.

Aquatic plants usually consist of algae and mosses attached to permanent stream substrates. Rooted aquatic vegetation may occur where substrates are suitable and high currents do not scour the stream bottom. Luxuriant beds of vascular plants may grow in some areas such as spring-fed streams in Florida where water clarity, substrates, nutrients, and slow water velocities exist. Bedrock or stones that cannot be moved easily by stream currents are often covered by mosses and algae and various forms of

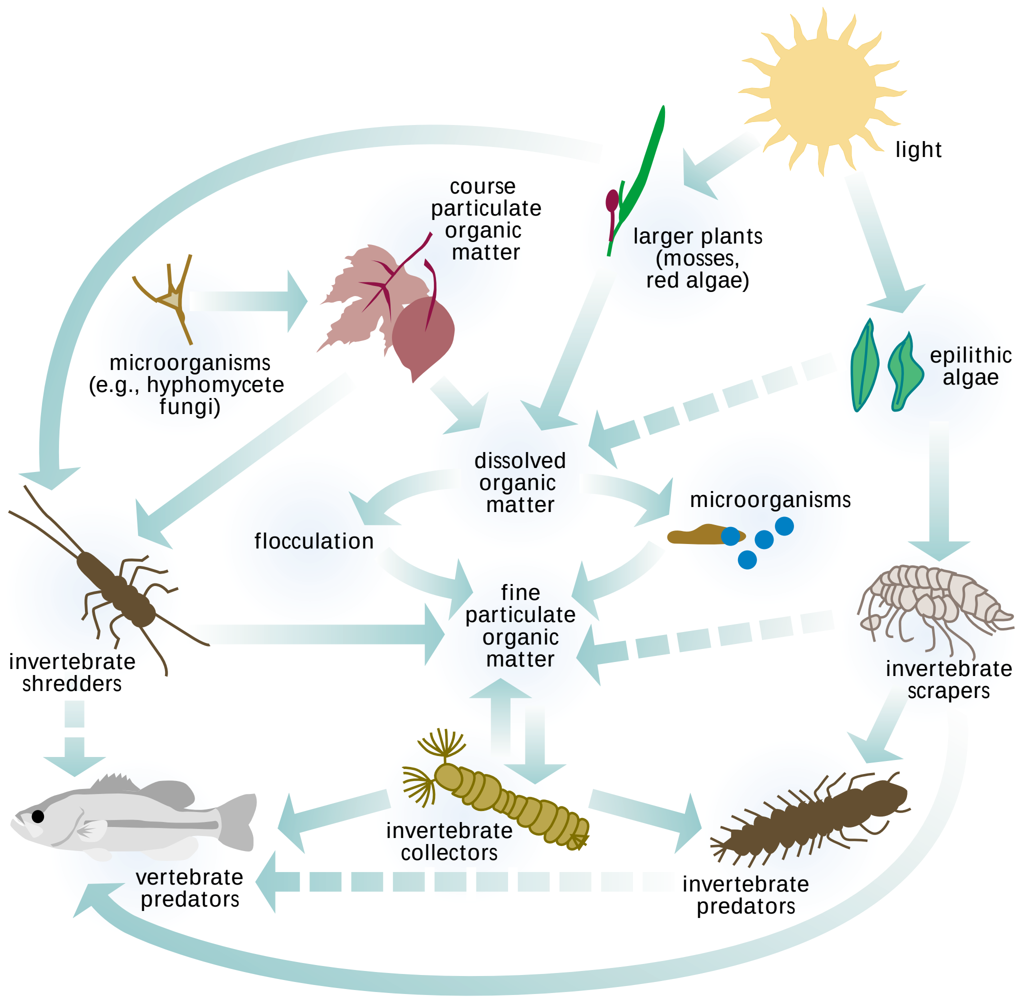
Hydrologic	Dynamic surface water storage
	Long-term surface water storage
	Subsurface storage of water
	Energy dissipation
	Moderation of ground-water flow or discharge
Biogeochemical	Nutrient cycling
	Removal of elements and compounds
	Retention of particulates
	Organic carbon export
Plant habitat	Maintain characteristic plant communities
	Maintain characteristic detrital biomass
Animal habitat	Maintain spatial habitat structure
	Maintain interspersion and connectivity
	Maintain distribution and abundance of invertebrates
	Maintain distribution and abundance of vertebrates

Table 2.11: Functions of riverine wetlands.
Source: Brinson et al. 1995.

micro- and macroinvertebrates (Ruttner 1963). Planktonic plant forms are usually limited but may be present where the watershed contains lakes, ponds, floodplain waters, or slow current areas (Odum 1971).

The benthic invertebrate community of streams may contain a variety of biota, including bacteria, protists, rotifers, bryozoans, worms, crustaceans, aquatic insect larvae, mussels, clams, crayfish, and other forms of invertebrates. Aquatic invertebrates are found in or on a multitude of microhabitats in streams including plants, woody debris, rocks, interstitial spaces of hard substrates, and soft substrates (gravel, sand, and muck). Invertebrate habitats exist at all vertical strata including the water surface, the water column, the bottom surface, and deep within the hyporheic zone.

Unicellular organisms and microinvertebrates are the most numerous biota in streams. However, larger macroinvertebrates are important to community structure because they contribute significantly to a stream's total invertebrate biomass (Morin and Nadon 1991,



igure 2.33: Stream iota. *Food relationhips typically found n streams.*

Bourassa and Morin 1995). Furthermore, the larger species often play important roles in determining community composition of other components of the ecosystem. For example, herbivorous feeding activities of caddisfly larvae (Lamberti and Resh 1983), snails (Steinman et al. 1987), and crayfish (Lodge 1991) can have a significant effect on the abundance and taxonomic composition of algae and periphyton in streams. Likewise, macroinvertebrate predators, such as stoneflies, can influence the abundance of other species within the invertebrate community (Peckarsky 1985).

Table 2.12: Ranges of densities commonly observed for selected groups of stream biota.

Biotic Component	Density (Individuals/Square Mile)
Algae	$10^9 – 10^{10}$
Bacteria	$10^{12} – 10^{13}$
Protists	$10^8 – 10^9$
Microinvertebrates	$10^3 – 10^5$
Macroinvertebrates	$10^4 – 10^5$
Vertebrates	$10^0 – 10^2$

Collectively, microorganisms (fungi and bacteria) and benthic invertebrates facilitate the breakdown of organic material, such as leaf litter, that enters the stream from external sources. Some invertebrates (insect larvae and amphipods) act as shredders whose feeding activities break down larger organic leaf litter to smaller particles. Other invertebrates filter smaller organic material from the water (blackfly larvae, some mayfly nymphs, and some caddisfly larvae), scrape material off surfaces (snails, limpets, and some caddisfly and mayfly nymphs), or feed on material deposited on the substrate (dipteran larvae and some mayfly nymphs) (Moss 1988). These feeding activities result in the breakdown of organic matter in addition to the elaboration of invertebrate tissue, which other consumer groups, such as fish, feed on.

Benthic macroinvertebrates, particularly aquatic insect larvae and crustaceans, are widely used as indicators of stream health and condition. Many fish species rely on benthic organisms as a food source either by direct browsing on the benthos or by catching benthic organisms that become dislodged and drift downstream (Walburg 1971).

Fish are ecologically important in stream ecosystems because they are usually the largest vertebrates and often are the apex predator in aquatic systems. The numbers and species composition of fishes in a given stream depends on the geographic location, evolutionary history, and such intrinsic factors as physical habitat (current, depth, substrates, riffle/pool ratio, wood snags, and undercut banks), water quality (temperature, dissolved oxygen, suspended solids, nutrients, and toxic chemicals), and biotic interactions (exploitation, predation, and competition).

There are approximately 700 native freshwater species of fish in North America (Briggs 1986). Fish species richness is highest in the Mississippi River Basin where most of the adaptive radiations have occurred in the United States (Allan 1995). In the Midwest, as many as 50 to 100 species can occur in a local area, although typically only half the species native to a region may be found at any one location (Horwitz 1978). Fish species richness generally declines as one moves westward across the United States, primarily due to extinction during and following the Pleistocene Age (Fausch et al. 1984). For example, 210 species are found west of the Continental Divide, but only 40 of these species are found on both sides of the continent (Minckley and Douglas 1991). The relatively depauperate fauna of the Western United States has been attributed to the isolating mechanisms of tectonic geology. Secondary biological, physical, and chemical factors may further reduce the species richness of a specific community (Minckley and Douglas 1991, Allan 1995).

Fish species assemblages in streams will vary considerably from the headwaters to the outlet due to changes in many hydrologic and geomorphic factors which control temperature, dissolved oxygen, gradient, current velocity, and substrate. Such factors combine to determine the degree of habitat diversity in a given stream segment. Fish species richness tends to increase downstream as gradient decreases and stream size increases. Species richness is generally lowest at small headwater streams due to increased gradient and small stream size, which increases the frequency and severity of environmental fluctuations (Hynes 1970, Matthews and Styron 1980). In addition, the high gradient and decreased links with tributaries reduces the potential for colonization and entry of new species.

Species richness increases in mid-order to lower stream reaches due to increased environmental stability, greater numbers of potential habitats, and increases in numbers of colonization sources or links between major drainages. As one proceeds downstream, pools and runs increase over riffles, allowing for an increase in fine bottom materials and facilitating the growth of macrophytic vegetation. These environments allow for the presence of fishes more tolerant of low oxygen and increased temperatures. Further, the range of body forms increases with the appearance of those species with less fusiform body shapes, which are ecologically adapted to areas typified by decreased water velocities. In higher order streams or large rivers the bottom substrates often are typified by finer sediments; thus herbivores, omnivores, and planktivores may increase in response to the availability of aquatic vegetation and plankton (Bond 1979).

Fish have evolved unique feeding and reproductive strategies to survive in the diverse habitat conditions of North America. Horwitz (1978) examined the structure of fish feeding guilds in 15 U.S. river systems and found that most fish species (33 percent) were benthic insectivores, whereas piscivores (16 percent), herbivores (7 percent), omnivores (6 percent), planktivores (3 percent), and other guilds contained fewer species. However, Allan (1995) indicated that fish frequently change feeding habits across habitats, life stages, and season to adapt to changing physical and biological conditions. Fish in smaller headwater streams tend to be insectivores or specialists, whereas the number of generalists and the range of feeding strategies increases downstream in response to increasing diversity of conditions.

Some fish species are migratory, returning to a particular site over long distances to spawn. Others may exhibit great endurance, migrating upstream against currents and over obstacles such as waterfalls. Many must move between salt water and freshwater, requiring great osmoregulatory ability (McKeown 1984). Species that return from the ocean environment into freshwater streams to spawn are called *anadromous* species.

Species generally may be referred to as cold water or warm water, and gradations between, depending on their temperature requirements (Magnuson et al. 1979). Fish such as salmonids are usually restricted to higher elevations or northern climes typified by colder, highly oxygenated water. These species tend to be specialists, with rather narrow thermal tolerances and rather specific reproductive requirements. For example, salmonids typically spawn by depositing eggs over or within clean gravels which remain oxygenated and silt-free due to upwelling of currents within the interstitial spaces. Reproductive movement and behavior is controlled by subtle thermal changes combined with increasing or decreasing day-length. Salmonid populations, therefore, are highly susceptible to many forms of habitat degradation, including alteration of flows, temperature, and substrate quality.

Numerous fish species in the U.S. are declining in number. Williams and Julien (1989) presented a list of North American fish species that the American Fisheries Society believed should be classified as endangered, threatened, or of special concern. This list contains 364 fish species warranting protection because of their rarity. Habitat loss was the primary cause of depletion for approximately 90 percent of the species listed. This study noted that 77 percent of the fish species listed were found in 25 percent of the states, with the highest concentrations in eight southwestern states. Nehlsen et al. (1991) provided a list of 214 native naturally spawning stocks of depleted Pacific salmon, steelhead, and sea-run cutthroat stocks from California, Oregon, Idaho, and Washington. Reasons cited for the declines were alteration of fish passage and migration due to dams, flow reduction associated with hydropower and agriculture, sedimentation and habitat loss due to logging and agriculture, overfishing, and negative interactions with other fish, including nonnative hatchery salmon and steelhead.

The widespread decline in the numbers of native fish species has led to current widespread interest in restoring the quality and quantity of habitats for fish. Restoration activities have frequently centered on improving local habitats, such as fencing or removing livestock from streams, constructing fish passages, or installing instream physical habitat. However, research has demonstrated that in most of these cases the success has been limited or questionable because the focus was too narrow and did not address restoration of the diverse array of habitat requirements and resources that are needed over the life span of a species.

Stream corridor restoration practitioners and others are now acutely aware that fish require many different habitats over the season and lifespan to fulfill needs for feeding, resting, avoiding predators, and reproducing. For example, Livingstone and Rabeni (1991) determined that juvenile smallmouth bass in the Jacks Fork River of southeastern Missouri fed primarily on small macroinvertebrates in littoral vegetation. Vegetation represented not only a source of food but a refuge from predators and a warmer habitat, factors that can collectively optimize chances for survival and growth (Rabeni and Jacobson 1993). Adult smallmouth bass, however, tended to occupy deeper pool habitats, and the numbers and biomass of adults at various sites were attributed to these specific deep-water habitats (McClendon and Rabeni 1987). Rabeni and Jacobson (1993) suggested that an understanding of these specific habitats, combined with an understanding of the fluvial hydraulics and geomorphology that form and maintain them, are key to developing successful stream restoration initiatives.

The emphasis on fish community restoration is increasing due to many ecological, economic, and recreational factors. In 1996 approximately 35 million Americans older than 16 participated in recreational fishing, resulting in over $36 billion in expenditures (Brouha 1997). Much of this activity is in streams, which justifies stream corridor restoration initiatives.

While fish stocks often receive the greatest public attention, preservation of other aquatic biota may also may be a goal of stream restoration. Freshwater mussels, many species of which are threatened and endangered, are often of particular concern. Mussels are highly sensitive to habitat disturbances and obviously benefit from intact, well-managed stream corridors. The south-central United States has the highest diversity of mussels in the world. Mussel ecology also is intimately linked with fish ecology, as fish function as hosts for mussel larvae (glochidia). Among the major threats they face are dams, which lead to direct habitat loss and fragmentation of remaining habitat, persistent sedimentation, pesticides, and introduced exotic species, such as fish and other mussel species.

Abiotic and Biotic Interrelations in the Aquatic System

Much of the spatial and temporal variability of stream biota reflects variations in both abiotic and biotic factors, including water quality, temperature, streamflow and flow velocity, substrate, the availability of food and nutrients, and predator-prey relationships. These factors influence the growth, survival, and reproduction of aquatic organisms. While these factors are addressed individually below, it is important to remember that they are often interdependent.

Flow Condition

The flow of water from upstream to downstream distinguishes streams from other ecosystems. The spatial and temporal characteristics of streamflow, such as fast versus slow, deep versus shallow, turbulent versus smooth, and flooding versus low flows, are described previously in this chapter. These flow characteristics can affect both micro- and macro-distribution patterns of numerous stream species (Bayley and Li 1992, Reynolds 1992, Ward 1992). Many organisms are sensitive to flow velocity because it represents an important mechanism for delivering food and nutrients yet also may limit the ability of organisms to remain in a stream segment. Some organisms also respond to temporal variations in flow, which can change the physical structure of the stream channel, as well as increase mortality, modify available resources, and disrupt interactions among species (Resh et al. 1988, Bayley and Li 1992).

The flow velocity in streams determines whether planktonic forms can develop and sustain themselves. The slower the currents in a stream, the more closely the composition and configuration of biota at the shore and on the bottom approach those of standing water (Ruttner 1963). High flows are cues for timing migration and spawning of some fishes. High flows also cleanse and sort streambed materials and scour pools. Extreme low flows may limit young fish production because such flows often occur during periods of recruitment and growth (Kohler and Hubert 1993).

Water Temperature

Water temperature can vary markedly within and among stream systems as a function of ambient air temperature, altitude, latitude, origin of the water, and solar radiation (Ward 1985, Sweeney 1993). Temperature governs many biochemical and physiological processes in cold-blooded aquatic organisms because their body temperature is the same as the surrounding water; thus, water temperature has an important role in determining growth, development, and behavioral patterns. Stream insects, for example, often grow and develop more rapidly in warmer portions of a stream or during warmer seasons. Where the thermal differences among sites are significant (e.g., along latitudinal or altitudinal gradients), it is possible for some species to complete two or more generations per year at warmer sites; these same species complete one or fewer generations per year at cooler sites (Sweeney 1984, Ward 1992). Growth rates for algae and fish appear to respond to temperature changes in a similar fashion (Hynes 1970, Reynolds 1992). The relationships between temperature and growth, development, and behavior can be strong enough to affect geographic ranges of some species (**Table 2.13**).

Water temperature is one of the most important factors determining the distribution of fish in freshwater streams, due both to direct impacts and influence on dissolved oxygen concentrations, and is influenced by local conditions, such as shade, depth and current. Many fish species can tolerate only a limited temperature range. Such fish as salmonids and sculpins dominate in cold water streams, whereas such species as largemouth bass, smallmouth bass, suckers, minnows, sunfishes and catfishes may be present in warmer streams (Walburg 1971).

Effects of Cover

For the purposes of restoration, land use practices that remove overhead

Table 2.13: Maximum weekly average temperatures for growth and short term maximum temperatures for selected fish (°F).
Source: Brungs and Jones 1977.

Species	Max. Weekly Average Temp. for Growth (Juveniles)	Max. Temp. for Survival of Short Exposure (Juveniles)	Max. Weekly Average Temp. for Spawning[a]	Max. Temp. for Embryo Spawning[b]
Atlantic salmon	68ºF	73ºF	41ºF	52ºF
Bluegill	90ºF	95ºF	77ºF	93ºF
Brook trout	66ºF	75ºF	48ºF	55ºF
Common carp			70ºF	91ºF
Channel catfish	90ºF	95ºF	81ºF	84ºF[c]
Largemouth bass	90ºF	93ºF	70ºF	81ºF[c]
Rainbow trout	66ºF	75ºF	48ºF	55ºF
Smallmouth bass	84ºF		63ºF	73ºF[c]
Sockeye salmon	64ºF	72ºF	50ºF	55ºF

[a] Optimum or mean of the range of spawning temperatures reported for the species.
[b] Upper temperature for successful incubation and hatching reported for the species.
[c] Upper temperature for spawning.

cover or decrease baseflows can increase instream temperatures to levels that exceed critical thermal maxima for fishes (Feminella and Matthews 1984). Thus, maintenance or restoration of normal temperature regimes can be an important endpoint for stream managers.

Riparian vegetation is an important factor in the attenuation of light and temperature in streams (Cole 1994). Direct sunlight can significantly warm streams, particularly during summer periods of low flow. Under such conditions, streams flowing through forests warm rapidly as they enter deforested areas, but may also cool somewhat when streams reenter the forest. In Pennsylvania (Lynch et al. 1980), average daily stream temperatures that increased 12°C through a clearcut area were substantially moderated after flow through 1,640 feet of forest below the clearcut. They attributed the temperature reduction primarily to inflows of cooler ground water.

A lack of cover also affects stream temperature during the winter. Sweeney (1993) found that, while average daily temperatures were higher in a second-order meadow stream than in a comparable wooded reach from April through October, the reverse was true from November through March. In a review of temperature effects on stream macroinvertebrates common to the Pennsylvania Piedmont, Sweeney (1992) found that temperature changes of 2 to 6 °C usually altered key life-history characteristics of the study species. Riparian forest buffers have been shown to prevent the disruption of natural temperature patterns as well as to mitigate the increases in temperature following deforestation (Brown and Krygier 1970, Brazier and Brown 1973).

The exact buffer width needed for temperature control will vary from site to site depending on such factors as stream orientation, vegetation, and width. Along a smaller, narrow headwater stream, the reestablishment of shrubs, e.g., willows and alders, may provide adequate shade and detritus to restore both the riparian and aquatic ecosystems. The planting and/or reestablishment of large trees, e.g., cottonwoods, willows, sycamores, ash, and walnuts (Lowe 1964), along larger, higher order rivers can improve the segment of the fishery closest to the banks, but has little total effect on light and temperature of wider rivers.

Heat budget models can accurately predict stream and river temperatures (e.g., Beschta 1984, Theurer et al. 1984). Solar radiation is the major factor influencing peak summer water temperatures and shading is critical to the overall temperature regime of streams in small watersheds.

Dissolved Oxygen

Oxygen enters the water by absorption directly from the atmosphere and by plant photosynthesis (Mackenthun 1969). Due to the shallow depth, large surface exposure to air and constant motion, streams generally contain an abundant dissolved oxygen supply even when there is no oxygen production by photosynthesis.

Dissolved oxygen at appropriate concentrations is essential not only to keep aquatic organisms alive but to sustain their reproduction, vigor, and development. Organisms undergo stress at reduced oxygen levels that make them less competitive in sustaining the species (Mackenthun 1969). Dissolved oxygen concentrations of 3.0 mg/L or less have been shown to interfere with fish populations for a number of reasons (Mackenthun 1969, citing several other sources) (**Table 2.14**).

Depletion of dissolved oxygen can result in the death of aquatic organisms, including fish. Fish die when the demand for oxygen by biological and chemical processes exceeds the oxygen input by reaeration and photosynthesis, resulting in fish suffocation. Oxygen depletion usually is associated with slow current, high temperature, extensive growth of rooted aquatic plants, algal blooms, or high concentrations of organic matter (Needham 1969).

Stream communities are susceptible to pollution that reduces the dissolved oxygen supply (Odum 1971). Major factors determining the amount of oxygen found in water are temperature, pressure, abundance of aquatic plants and the amount of natural aeration from contact with the atmosphere (Needham 1969). A level of 5 mg/L of

Table 2.14: Summary of dissolved oxygen concentrations (mg/L) generally associated with effects on fish in salmonid and nonsalmonid waters.
Source: USEPA 1987.

Level of Effect	Salmonid[a]	Nonsalmonid
Early life stages (eggs and fry)		
No production impairment	11 (8)	6.5
Slight production impairment	9 (6)	5.5
Moderate production impairment	8 (5)	5.0
Severe production impairment	7 (4)	4.5
Limit to avoid acute mortality	6 (3)	4.0
Other life stages		
No production impairment	8 (0)	6.0
Slight production impairment	6 (0)	5.0
Moderate production impairment	5 (0)	4.0
Severe production impairment	4 (0)	3.5
Limit to avoid acute mortality	3 (0)	3.0

[a] Values for salmonid early life stages are water column concentrations recommended to achieve the required concentration of dissolved oxygen in the gravel spawning substrate (shown in parentheses).

dissolved oxygen in water is associated with normal activity of most fish (Walburg 1971). Oxygen analyses of good trout streams show dissolved oxygen concentrations that range from 4.5 to 9.5 mg/L (Needham 1969).

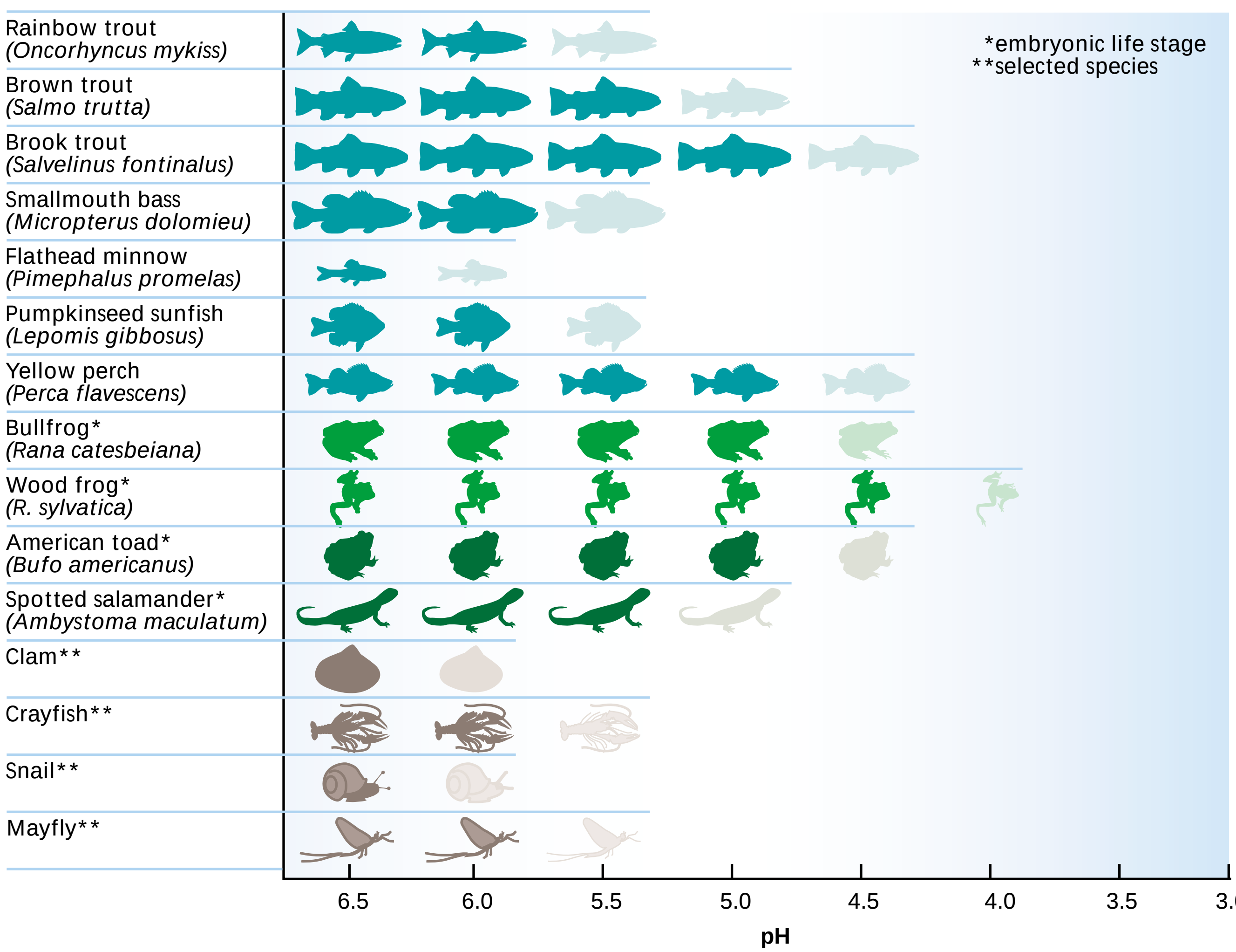
pH

Aquatic organisms from a wide range of taxa exist and thrive in aquatic systems with nearly neutral hydrogen ion activity (pH 7). Deviations, either toward a more basic or acidic environment, increase chronic stress levels and eventually decrease species diversity and abundance (**Figure 2.34**). One of the more widely recognized impacts of changes in pH has been attributed to increased acidity of rainfall in some parts of the United States, especially areas downwind of industrial and urban emissions (Schreiber 1995). Of particular concern are environments that have a reduced capacity to neutralize acid inputs because soils have a limited buffering capacity. Acidic rainfall can be especially harmful to environments such as the Adirondack region of upstate New York, where runoff already tends to be slightly acidic as a result of natural conditions.

Substrate

Stream biota respond to the many abiotic and biotic variables influenced by substrate. For example, differences in

Figure 2.34*: *Effects of acid rain on some aquatic species. *As acidity increases (and pH decreases) in lakes and streams, some species are lost.*



species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach (Benke et al. 1984, Smock et al. 1985, Huryn and Wallace 1987). This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams (Hackney et al. 1992).

Stream substrates can be viewed in the same functional capacity as soils in the terrestrial system; that is, stream substrates constitute the interface between water and the hyporheic subsurface of the aquatic system. The *hyporheic zone* is the area of substrate which lies below the substrate/water interface, and may range from a layer extending only inches beneath and laterally from the stream channel, to a very large subsurface environment. Alluvial floodplains of the Flathead River, Montana, have a hyporheic zone with significant surface water/ground water interaction which is 2 miles wide and 33 feet deep (Stanford and Ward 1988). Naiman et al. (1994) discussed the extent and connectivity of hyporheic zones around streams in the Pacific Northwest. They hypothesized that as one moves from low-order (small) streams to high-order (large) streams, the degree of hyporheic importance and continuity first increases and then decreases. In small streams, the hyporheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock. The hyporheic zones are generally not continuous. In mid-order channels with more extensive floodplains, the spatial connectivity of the hyporheic zone increases. In large order streams, the spatial extent of the hyporheic zone is usually greatest, but it tends to be highly discontinuous because of features associated with fluvial activities such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems (Naiman et al. 1994) (**Figure 2.35**).

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes (Minshall 1984). Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms (Odum 1971). As previously described, substrate size, heterogeneity, stability with respect to high and baseflow, and durability vary within streams, depending on particle size, density, and kinetic energy of flow. Inorganic substrates tend to be of larger size upstream than downstream and tend to be larger in riffles than in pools (Leopold et al. 1964). Likewise, the distribution and role of woody debris varies with stream size (Maser and Sedell 1994).

In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris that falls into the stream can increase the quantity and diversity of substrate and aquatic habitat or range (Bisson et al. 1987, Dolloff et al. 1994). Debris dams trap sediment behind them and often create scour holes immediately downstream. Eroded banks commonly occur at the boundaries of debris blockages.

Organic Material

Metabolic activity within a stream reach depends on autochthonous, allochthonous, and upstream sources of food and nutrients (Minshall et al. 1985). Autochthonous materials, such as algae and aquatic macrophytes, originate within the stream channel, whereas allochthonous materials such as wood, leaves, and dissolved organic carbon, originate outside the stream channel. Upstream materials may be of autochthonous or allochthonous origin and are transported by streamflow to downstream locations. Seasonal flooding provides allochthonous input of organic material to the stream channel and also can significantly increase the rate of decomposition of organic material.

The role of primary productivity of streams can vary depending on geographic location, stream size, and season (Odum 1957, Minshall 1978). The river continuum concept (Vannote et al. 1980) (see *The River Continuum Concept* in section 1.E in Chapter 1) hypothesizes that primary productivity is of minimal importance in shaded headwater streams but increases in significance as stream size increases and riparian vegetation no longer limits the entry of light to stream periphyton. Numerous researchers have demonstrated that primary productivity is of greater importance in certain ecosystems, including streams in grassland and desert ecosystems. Flora of streams can range from diatoms in high mountain streams to dense stands of macrophytes in low gradient streams of the Southeast.

As discussed in Section 2.C, loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as *eutrophication*. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems in waterbodies.

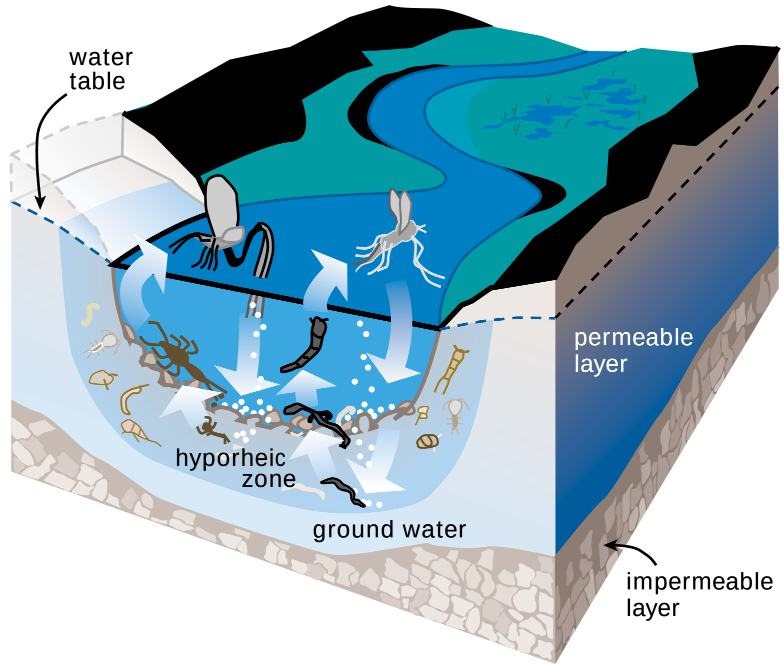


Figure 2.35: Hyporheic zone. *Summary of the different means of migration undergone by members of the stream benthic community.*

Eutrophication in lakes and reservoirs is indirectly measured as standing crops of phytoplankton biomass, usually represented by planktonic chlorophyll a concentration. However, phytoplankton biomass is usually not the dominant portion of plant biomass in smaller streams, due to periods of energetic flow and high substrate to volume ratios that favor the development of periphyton and macrophytes on the stream bottom. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures (**Figure 2.36**). Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

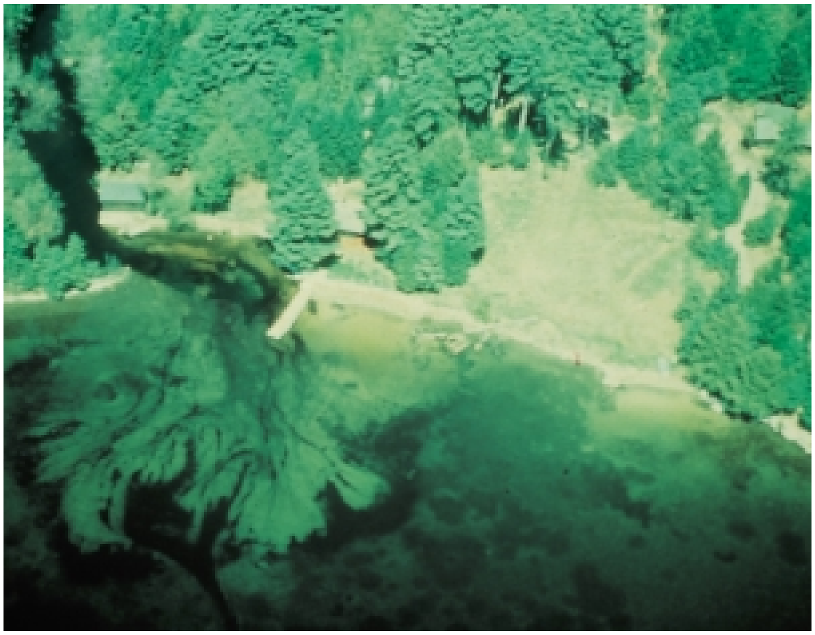


***Figure 2.36**: Stream eutrophication.*
Eutrophication can result in oxygen depletion.

In many streams, shading or turbidity limit the light available for algal growth, and biota depend highly on allochthonous organic matter, such as leaves and twigs produced in the surrounding watershed. Once leaves or other allochthonous materials enter the stream, they undergo rapid changes (Cummins 1974). Soluble organic compounds, such as sugars, are removed via leaching. Bacteria and fungi subsequently colonize the leaf materials and metabolize them as a source of carbon. The presence of the microbial biomass increases the protein content of the leaves, which ultimately represents a high quality food resource for shredding invertebrates.

The combination of microbial decomposition and invertebrate shredding/scraping reduces the average particle size of the organic matter, resulting in the loss of carbon both as respired CO_2 and as smaller organic particles transported downstream. These finer particles, lost from one stream segment, become the energy inputs to the downstream portions of the stream. This unidirectional movement of nutrients and organic matter in lotic systems is slowed by the temporary retention, storage, and utilization of nutrients in leaf packs, accumulated debris, invertebrates, and algae.

Organic matter processing has been shown to have nutrient-dependent relationships similar to primary productivity. Decomposition of leaves and other forms of organic matter can be limited by either nitrogen or phosphorus, with predictive N:P ratios being similar to those for growth of algae and periphyton. Leaf decomposition occurs by a sequential combination of microbial decomposition, invertebrate shredding, and physical fractionation. Leaves and organic matter itself are generally low in protein value. However, the colonization of organic matter by bacteria and fungi increases the net content of nitrogen and phosphorus due to the accumulation of proteins and lipids contained in microbial biomass. These compounds are a major nutritive source for aquatic invertebrates. Decaying organic matter represents a major storage component for nutrients in streams, as well as a primary pathway of energy and nutrient transfer within the food web. Ultimately, the efficiency of retention and utilization is reflected at the top of the food web in the form of fish biomass.

Organisms often respond to variations in the availability of autochthonous, allochthonous, and upstream sources. For example, herbivores are relatively more common in streams having open riparian canopies and high algal productivity compared to streams having closed canopies and accumulated leaves as the primary food resource (Minshall et al. 1983). Similar patterns can be observed longitudinally within the same stream (Behmer and Hawkins 1986).

Terrestrial and Aquatic Ecosystem Components for Stream Corridor Restoration

The previous sections presented the biological components and functional processes that shape stream corridors. The terrestrial and aquatic environments were discussed separately for the sake of simplicity and ease of understanding. Unfortunately, this is frequently the same approach taken in environmental restoration initiatives, with efforts placed separately on the uplands, riparian area, or instream channel. The stream corridor must be viewed as a single functioning unit or ecosystem with numerous connections and interactions between components. Successful stream corridor restoration cannot ignore these fundamental relationships.

The structure and functions of vegetation are interrelated at all scales. They are also directly tied to ecosystem dynamics. Particular vegetation types may have characteristic regeneration strategies (e.g., fire, treefall gaps) that maintain those types within the landscape at all times. Similarly, certain topographic settings may be more likely than others to be subject to periodic, dramatic changes in hydrology and related vegetation structure as a result of massive debris jams or occupation by beavers. However, in the context of stream corridor ecosystems, some of the most fundamental dynamic interactions relate to stream flooding and channel migration.

Many ecosystem functions are influenced by the structural characteristics of vegetation. In an undeveloped watershed, the movement of water and other materials is moderated by vegetation and detritus, and nutrients are mobilized and conserved in complex patterns that generally result in balanced interactions between terrestrial and aquatic systems. As the character and distribution of vegetation is altered by removal of biomass, agriculture, livestock grazing, development, and other land uses, and the flow patterns of water, sediment, and nutrients are modified, the interactions among system components become less efficient and effective. These problems can become more pronounced when they are aggravated by introductions of excess nutrients and synthetic toxins, soil disturbances, and similar impacts.

Stream migration and flooding are principal sources of structural and compositional variation within and among plant communities in most undisturbed floodplains (Brinson et al. 1981). Although streams exert a complex influence on plant communities, vegetation directly affects the integrity and characteristics of stream systems. For example, root systems bind bank sediments and moderate erosion processes, and floodplain vegetation slows overbank flows, inducing sediment deposition. Trees and smaller woody debris that fall into the channel deflect flows, inducing erosion at some points and deposition at others, alter pool distribution, the transport of organic material, as well as a number of other processes. The stabilization of streams that are highly interactive with their floodplains can disrupt the fundamental processes controlling the structure and function of stream corridor ecosystems, thereby indirectly affecting the characteristics of the surrounding landscape.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishment of corridors that are structurally different from native systems or inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages (Knopf et al. 1988).

Some riparian dependent species are linked to streamside riparian areas with fairly contiguous dense tree canopies. Without new trees coming into the population, older trees creating this linked canopy eventually drop out, creating ever smaller patches of habitat. Restoration that influences tree stands so that sufficient recruitment and patch size can be attained will benefit these species. For similar reasons, many riparian-related raptors such as the common black-hawk (*Buteogallus anthracinus*), gray hawk (*Buteo nitidus*), bald eagle (*Haliaeetus leucocephalus*), Cactus ferruginous pygmy-owl (*Glaucidium brasilianum cactorum*), and Cooper's hawk (*Accipiter cooperii*), depend upon various sizes and shapes of woody riparian trees for nesting substrate and roosts. Restoration practices that attain sufficient tree recruitment will greatly benefit these species in the long term, and other species in the short term.

Some aspects related to this subject have been discussed as ecosystem components and functions under other sections. Findings from the earliest studies of the impacts of fragmentation of riparian habitats on breeding birds were published for the Southwest (Carothers and Johnson 1971, Johnson 1971, Carothers et al. 1974). Subsequent studies by other investigators found similar results. Basically, cottonwood-willow gallery forests of the North American Southwest supported the highest concentrations of noncolonial nesting birds for North America. Destruction and fragmentation of these riparian forests reduced species richness and resulted in a nearly straight-line relationship between numbers of nesting pairs/acre and number of mature trees/acre. Later studies demonstrated that riparian areas are equally important as conduits for migrating birds (Johnson and Simpson 1971, Stevens et al. 1977).

When considering restoration of riparian habitats, the condition of adjacent habitats must be considered. Carothers (1979) found that riparian ecosystems, especially the edges, are widely used by nonriparian birds. In addition he found that some riparian birds utilized adjacent nonriparian ecosystems. Carothers et al. (1974) found that smaller breeding species [e.g., warblers and the Western wood pewee (*Contopus sordidulus*)] tended to carry on all activities within the riparian ecosystem during the breeding season. However, larger species (e.g., kingbirds and doves) commonly foraged outside the riparian ecosystem in adjacent habitats. Larger species (e.g., raptors) may forage miles from riparian ecosystems, but still depend on them in critical ways (Lee et al. 1989).

Because of more mesic conditions created by the canyon effect, canyons and their attendant riparian vegetation serve as corridors for short-range movements of animals along elevational gradients (e.g., between summer and winter ranges). Long-range movements that occur along riparian zones throughout North America include migration of birds and bats. Riparian zones also serve as stopover habitat for migrating birds (Stevens et al. 1977). Woody vegetation is generally important, not only to most riparian ecosystems, but also to adjacent aquatic and even upland ecosystems. However, it is important to establish clear management objectives before attempting habitat modification.

Restoring all of a given ecosystem to its "pristine condition" may be impossible, especially if upstream conditions have been heavily modified, such as by a dam or other water diversion project. Even if complete restoration is a possibility, it may not accomplish or complement the restoration goals.

For example, encroachment of woody vegetation in the channel below several dams in the Platte River Valley in Nebraska has greatly decreased the amount of important wet meadow habitat. This area has been declared critical habitat for the whooping crane (*Grus americana*) (Aronson and Ellis 1979), for piping plover, and for the interior least tern. It is also an important staging area for up to 500,000 sandhill cranes (*Grus canadensis*) from late February to late April and supports 150 to 250 bald eagles (*Haliaeetus leucocephalus*). Numerous other important species using the area include the peregrine falcon (*Falco peregrinus*), Canada goose (*Branta canadensis*), mallard (*Anas platyrhynchos*), numerous other waterfowl, and raptors (USFWS 1981). Thus, managers here are confronted with means of reducing riparian groves in favor of wet meadows.

2.E Functions and Dynamic Equilibrium

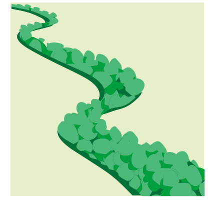
Throughout the past two chapters, this document has covered stream corridor structure and the physical, chemical, and biological processes occurring in stream corridors. This information shows how stream corridors function as ecosystems, and consequently, how these characteristic structural features and processes must be understood in order to enable stream corridor functions to be effectively restored. In fact, reestablishing structure or restoring a particular physical or biological process is not the only thing that restoration seeks to achieve. Restoration aims to reestablish valued functions. Focusing on ecological functions gives the restoration effort its best chance to recreate a self-sustaining system. This property of sustainability is what separates a functionally sound stream, that freely provides its many benefits to people and the natural environment, from an impaired watercourse that cannot sustain its valued functions and may remain a costly, long-term maintenance burden.

Section 1.A of Chapter 1 emphasized matrix, patch, corridor and mosaic as the most basic building blocks of physical structure at local to regional scales. Ecological functions, too, can be summarized as a set of basic, common themes that recur in an infinite variety of settings. These six critical functions are *habitat*, *conduit*, *filter*, *barrier*, *source*, and *sink* (**Figure 2.37**).

In this section, the processes and structural descriptions of the past two chapters are revisited in terms of these critical ecological functions.

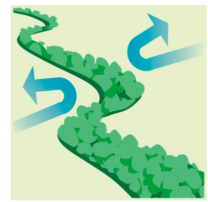
Two attributes are particularly important to the operation of stream corridor functions:

Habitat—***the spatial structure of the environment which allows species to live, reproduce, feed, and move.***



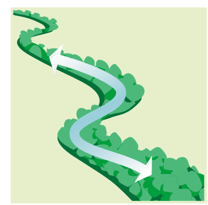
Habitat

Barrier—***the stoppage of materials, energy, and organisms.***



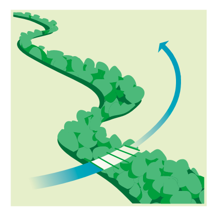
Barrier

Conduit—***the ability of the system to transport materials, energy, and organisms.***



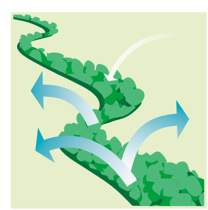
Conduit

Filter—***the selective penetration of materials, energy, and organisms.***



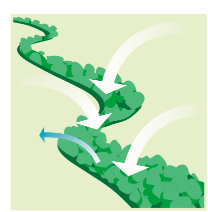
Filter

Source—***a setting where the output of materials, energy, and organisms exceeds input.***



Source

Sink—***a setting where the input of water, energy, organisms and materials exceeds output.***



Sink

Figure 2.37: Critical ecosystem functions. *Six functions can be summarized as a set of basic, common themes recurring in a variety of settings.*

- *Connectivity*—This is a measure of how spatially continuous a corridor or a matrix is (Forman and Godron 1986). This attribute is affected by gaps or breaks in the corridor and between the corridor and adjacent land uses (**Figure 2.38**). A stream corridor with a high degree of connectivity among its natural communities promotes valuable functions including transport of materials and energy and movement of flora and fauna.
- *Width*—In stream corridors, this refers to the distance across the stream and its zone of adjacent vegetation cover. Factors affecting width are edges, community composition, environmental gradients, and disturbance effects of adjacent ecosystems, including those with human activity. Example measures of width include average dimension and variance, number of narrows, and varying habitat requirements (Dramstad et al. 1996).

Width and connectivity interact throughout the length of a stream corridor. Corridor width varies along the length of the stream and may have gaps. Gaps across the corridor interrupt and reduce connectivity. Evaluating connectivity and width can provide some of the most valuable insight for designing restoration actions that mitigate disturbances.

The following subsections discuss each of the functions and general relationship to connectivity and width. The final subsection discusses dynamic equilibrium and its relevance to stream corridor restoration.

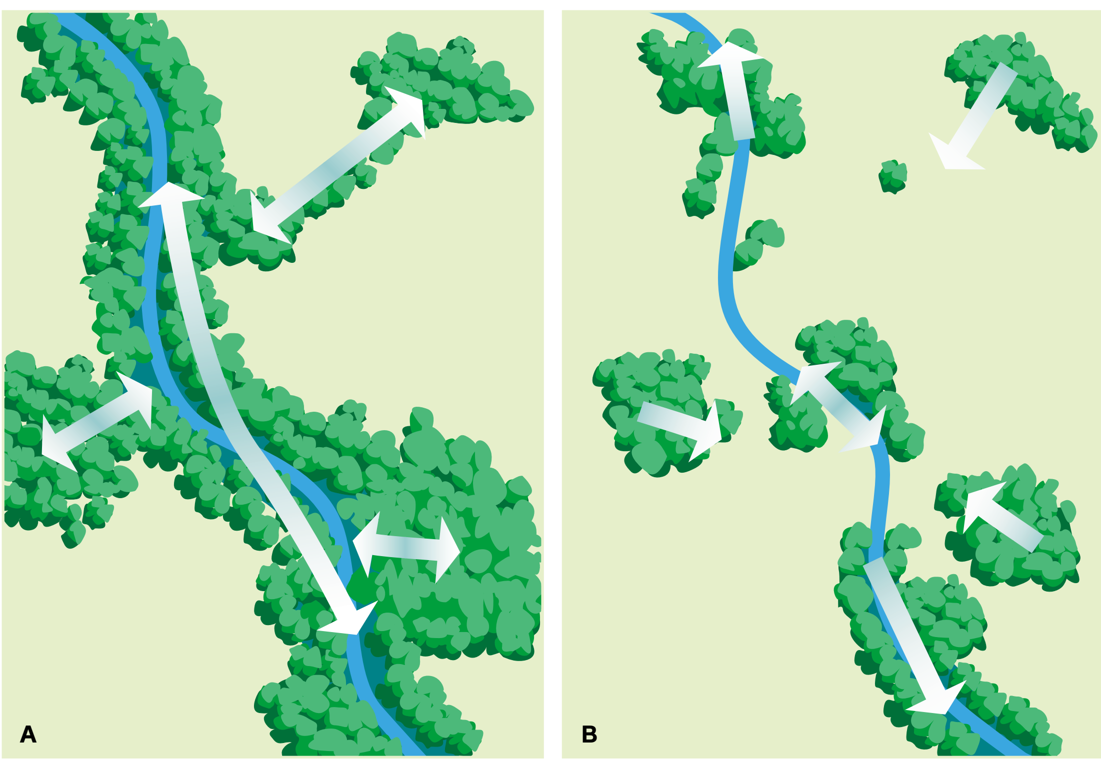
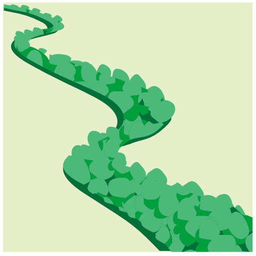


Figure 2.38: Landscapes with (A) high and (B) low degrees of connectivity. *A connected landscape structure generally has higher levels of functions than a fragmented landscape.*

Habitat Functions



Habitat is a term used to describe an area where plants or animals (including people) normally live, grow, feed, reproduce, and otherwise exist for any portion of their life cycle. Habitats provide organisms or communities of organisms with the necessary elements of life, such as space, food, water, and shelter.

Under suitable conditions often provided by stream corridors, many species can use the corridor to live, find food and water, reproduce, and establish viable populations. Some measures of a stable biological community are population size, number of species, and genetic variation, which fluctuate within expected limits over time. To varying degrees, stream corridors constructively influence these measures. The corridor's value as habitat is increased by the fact that corridors often connect many small habitat patches and thereby create larger, more complex habitats with larger wildlife populations and higher biodiversity.

Habitat functions differ at various scales, and an appreciation of the scales at which different habitat functions occur will help a restoration initiative succeed. The evaluation of habitat at larger scales, for example, may make note of a biotic community's size, composition, connectivity, and shape.

At the landscape scale, the concepts of matrix, patches, mosaics and corridors are often involved in describing habitat over large areas. Stream corridors and major river valleys together can provide substantial habitat. North American flyways include examples of stream and river corridor habitat exploited by migratory birds at landscape to regional scales.

Stream corridors, and other types of naturally vegetated corridors as well, can provide migrating forest and riparian species with their preferred resting and feeding habitats during migration stopovers. Large mammals such as black bear are known to require large, contiguous wild terrain as home range, and in many parts of the country broad stream corridors are crucial to linking smaller patches into sufficiently large territories.

Habitat functions within watersheds may be examined from a somewhat different perspective. Habitat types and patterns within the watershed are significant, as are patterns of connectivity to adjoining watersheds. The vegetation of the stream corridor in upper reaches of watersheds sometimes has become disconnected from that of adjacent watersheds and corridors beyond the divide. When terrestrial or semiaquatic stream corridor communities are connected at their headwaters, these connections will usually help provide suitable alternative habitats beyond the watershed.

Assessing habitat function at the stream corridor and smaller scales can also be viewed in terms of patches and corridors, but in finer detail than in landscapes and watersheds. It is also at local scales that transitions among the various habitats within the corridor can become more important. Stream corridors often include two general types of habitat structure: interior and edge habitat. Habitat diversity is increased by a corridor that includes both edge and interior conditions, although for most streams, corridor width is insufficient to provide

Edge and Interior Habitat

*Two important habitat characteristics are edges and interior (**Figure 2.39**) Edges are critical lines of interaction between different ecosystems. Interior habitats are generally more stable, sheltered environments where the ecosystem may remain relatively the same for prolonged periods. Edge habitat is exposed to highly variable environmental gradients. The result is a different species composition and abundance than observed interior habitat. Edges are important as filters of disturbance to interior habitat. Edges can also be diverse areas with a large variety of flora and fauna.*

Edges and interiors are scale-independent concepts. Larger mammals known as interior forest species may need to be miles from the forest edge to find desired habitat, while an insect or amphibian may be sensitive to the edges and interiors of the microhabitat under a rotted log. The edges and interiors of a stream corridor, therefore, depend upon the species being considered. As elongated, narrow ecosystems that include land/water interfaces and often include natural/human-made boundaries as well at the upland fringe, stream corridors have an abundance of edges and these have a pronounced effect on their biota.

Edges and interiors are each preferred by different sets of plant and animal species, and it is inappropriate to consider edges or interiors as consistently "bad" or "good" habitat characteristics. It may be desirable to maintain or increase edge in some circumstances, or favor interior habitats in others. Generally speaking, however, human activity tends to increase edge and decrease interior, so more often it is restoring or protecting interior that merits specific management action.

Edge habitat at the stream corridor boundary typically has higher inputs of solar energy, precipitation, wind energy, and other influences from the adjacent ecosystems. The difference in environmental gradients at the stream corridor's edge results in a diversified plant and animal community interacting with adjacent ecosystems. The effect of edge is more pronounced when the amount of interior habitat is minimal.

Interior habitat occurs further from the perimeter of the element. Interior is typified by more stable environmental inputs than those found at the edge of an ecosystem. Sunlight, rainfall, and wind effects are less intense in the interior. Many sensitive or rare species depend upon a less-disturbed environment for their survival. They are therefore tolerant of only "interior" habitat conditions. The distance from the perimeter required to create these interior conditions is dependent upon the species' requirements.

Interior plants and animals differ considerably from those that prefer or tolerate the edge's variability. With an abundance of edge, stream corridors often have mostly edge species. Because large ecosystems and wide corridors are becoming increasingly fragmented in modern landscapes, however, interior species are often rare and hence are targets for restoration. The habitat requirements of interior species (with respect to distance from edge are a useful guide in restoring larger stream corridors to provide a diversity of habitat types and sustainable communities.

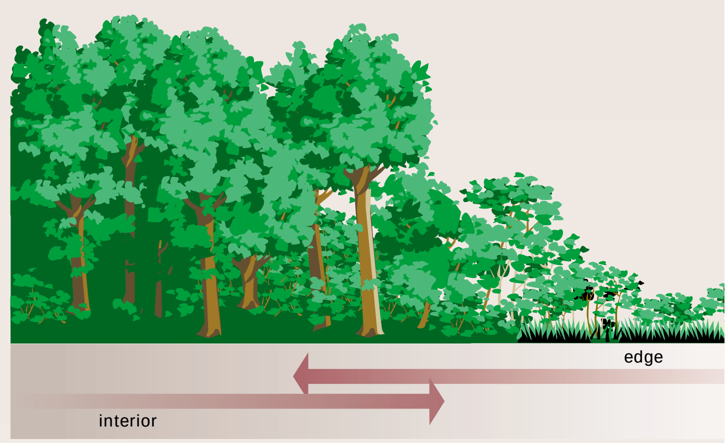


Figure 2.39: Edge and interior habitat of a woodlot. *Interior plants and animals differ considerably from those that prefer or tolerate the edge's variability.*

much interior habitat for larger vertebrates such as forest interior bird species. For this reason, increasing interior habitat is sometimes a watershed scale restoration objective.

Habitat functions at the corridor scale are strongly influenced by connectivity and width. Greater connectivity and increased width along and across a stream corridor generally increases its value as habitat. Stream valley morphology and environmental gradients (such as gradual changes in soil wetness, solar radiation, and precipitation) can cause changes in plant and animal communities. More species generally find suitable habitat conditions in a wide, contiguous, and diverse assortment of native plant communities within the stream corridor than in a narrow, homogeneous or highly fragmented corridor.

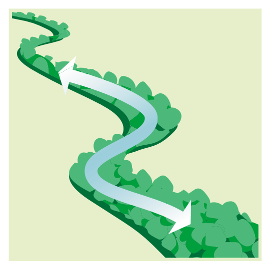
When applied strictly to stream channels, however, this might not be true. Some narrow and deeply incised streams, for example, provide thermal conditions that are critical for endangered salmonids.

Habitat conditions within a corridor vary according to factors such as climate and microclimate, elevation, topography, soils, hydrology, vegetation, and human uses. In terms of planning restoration measures, corridor width is especially important for wildlife. When planning for maintenance of a given wildlife species, for example, the dimension and shape of the corridor must be wide enough to include enough suitable habitat that this species can populate the stream corridor. Corridors that are too narrow may provide as much of a barrier to some species' movement as would a complete gap in the corridor.

On local scales, large woody debris that becomes lodged in the stream channel can create morphological changes to the stream and adjacent streambanks. Pools may be formed downstream from a log that has fallen across a stream and both upstream and downstream flow characteristics are altered. The structure formed by large woody debris in a stream improves aquatic habitat for most fish and invertebrate species.

Riparian forests, in addition to their edge and interior habitats, may offer vertical habitat diversity in their canopy, subcanopy, shrub and herb layers. And within the channel itself, riffles, pools, glides, rapids and backwaters all provide different habitat conditions in both the water column and the streambed. These examples, all described in terms of physical structure, illustrate once again the strong linkage between structure and habitat function.

Conduit Function



The conduit function is the ability to serve as a flow pathway for energy, materials, and organisms. A stream corridor is above all a conduit that was formed by and for collecting and transporting water and sediment. In addition, many other types of materials and biota move throughout the system.

The stream corridor can function as a conduit laterally, as well as longitudinally, with movement by organisms and materials in any number of directions. Materials or animals may further move across the stream corridor, from one side to another. Birds or small mammals, for example, may cross a stream with a closed canopy by moving through its vegetation. Organic debris and nutrients may fall from higher to lower floodplains and into the stream within corridors, affecting the food supply for stream invertebrates and fishes.

Moving material is important because it impacts the hydrology, habitat, and structure of the stream as well as the terrestrial habitat and connections in the floodplain and uplands. The structural attributes of connectivity and width also influence the conduit function.

For migratory or highly mobile wildlife, corridors serve as habitat and conduit simultaneously. Corridors in combination with other suitable habitats, for example, make it possible for songbirds to move from wintering habitat in the neo-tropics to northern, summer habitats. Many species of birds can only fly for limited distances before they must rest and refuel. For stream corridors to function effectively as conduits for these birds, they must be sufficiently connected and be wide enough to provide required migratory habitat.

Stream corridors are also conduits for the movement of energy, which occurs in many forms. The gravity-driven energy of stream flow continually sculpts and modifies the landscape. The corridor modifies heat and energy from sunlight as it remains cooler in spring and summer and warmer in the fall. Stream valleys are effective airsheds, moving cool air from higher to lower elevations in the evening. The highly productive plant communities of a corridor accumulate energy as living plant material, and export large amounts in the form of leaf fall or detritus. The high levels of primary productivity, nutrient flow, and leaf litter fall also fuel increased decomposition in the corridor, allowing new transformations of energy and materials. At its outlet, a stream's outputs to the next larger water body (e.g., increased water volume, higher temperature, sediments, nutrients, and organisms) are in part the excesses of energy from its own system.

One of the best known and studied examples of aquatic species movement and interaction with the watershed is the migration of salmon upstream for spawning. After maturing in the ocean, the fish are dependent on access to their upstream spawning grounds. In the case of Pacific salmon species, the stream corridor is dependent upon the resultant biomass and nutrient input of abundant spawning and dying adults into the upper reaches of stream systems during spawning. Thus, connectivity is often critical for aquatic species transport, and in turn, nutrient transport upstream from ocean waters to stream headwaters.

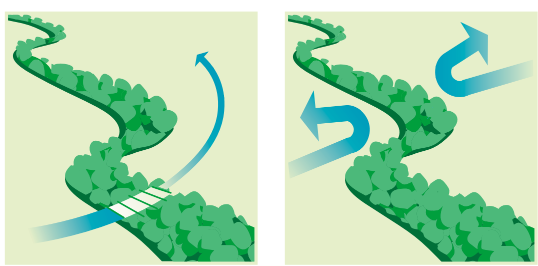
Streams are also conduits for distribution of plants and their establishment in new areas (Malanson 1993). Flowing water may transport and deposit seeds over considerable distances. In flood stage, mature plants may be uprooted, relocated, and redeposited alive in new locations. Wildlife also help redistribute plants by ingesting and transporting seeds throughout different parts of the corridor.

Sediment (bed load or suspended load) is also transported through the stream. Alluvial streams are dependent on the continual supply and transport of sediment, but many of their fish and invertebrates can also be harmed by too much fine sediment. When conditions are altered, a stream may become either starved of sediment or choked with sediment down-gradient. Streams lacking appropriate amounts of sediment attempt to reestablish equilibrium through downcutting, bank erosion, and channel erosion. An appropriately structured stream corridor will optimize timing and supply of sediment to the stream to improve sediment transport functions.

Local areas in the corridor are dependent on the flow of materials from one point to another. In the salmonid example, the local upland area adjacent to spawning grounds is dependent upon the nutrient transfer from the biomass of the fish into other terrestrial wildlife and off into the uplands. The local structure of the streambed and aquatic ecosystem are dependent upon the sediment and woody material from upstream and upslope to create a self-regulating and stable channel.

Stream corridor width is important where the upland is frequently a supplier of much of the natural load of sediment and biomass into the stream. A wide, contiguous corridor acts as a large conduit, allowing flow laterally and longitudinally along the corridor. Conduit functions are often more limited in narrow or fragmented corridors.

Filter and Barrier Functions



Stream corridors may serve as barriers that prevent movement or filters that allow selective penetration of energy, materials and organisms. In many ways, the entire stream corridor serves beneficially as a filter or barrier that reduces water pollution, minimizes sediment transport, and often provides a natural boundary to land uses, plant communities, and some less mobile wildlife species.

Materials, energy, and organisms which moved into and through the stream corridor may be filtered by structural attributes of the corridor. Attributes affecting barrier and filter functions include connectivity (gap frequency) and corridor width (**Figure 2.40**). Elements which are moving along a stream corridor edge may also be selectively filtered as they enter the stream corridor. In these circumstances it is the shape of the edge, whether it is straight or convoluted, which has the greatest effect on filtering functions. Still, it is most often movement perpendicular to the stream corridor which is most effectively filtered or halted.

Materials may be transported, filtered, or stopped altogether depending upon the width and connectedness of a stream corridor. Material movement across landscapes toward large river valleys may be intercepted and filtered by stream corridors. Attributes such as the structure of native plant communities can physically affect the amount of runoff entering a stream system through uptake, absorption, and interruption. Vegetation in the corridor can filter out much of the overland flow of nutrients, sediment, and water.

Siltation in larger streams can be reduced through a network of stream corridors functioning to filter excessive sediment. Stream corridors filter many of the upland materials from moving unimpeded across the landscape. Ground water and surface water flows are filtered by plant parts below and above ground. Chemical elements are intercepted by flora and fauna within stream corridors. A wider corridor provides more effective filtering, and a contiguous corridor functions as a filter along its entire length.

Breaks in a stream corridor can sometimes have the effect of funneling damaging processes into that area. For example, a gap in contiguous vegetation along a stream corridor can reduce the filtering function by focusing increased runoff into the area, leading to erosion,

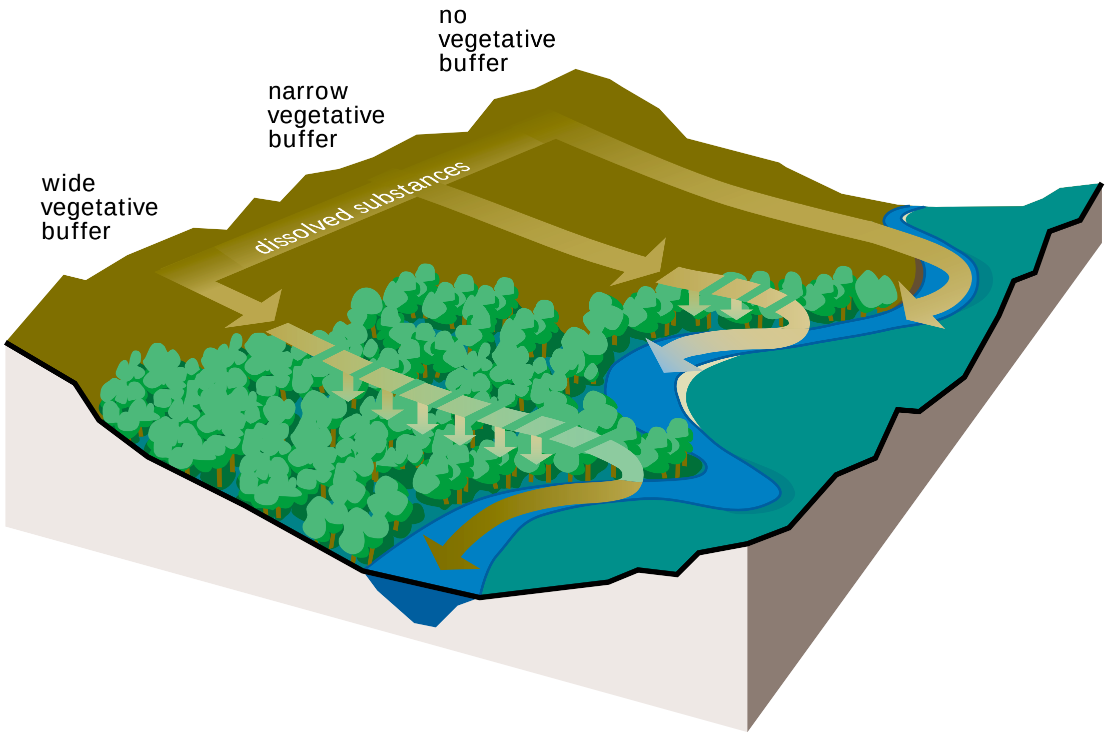
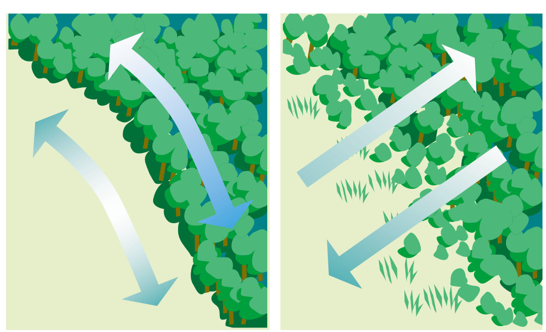


***Figure 2.40**: The width of the vegetation buffer influences filter and barrier functions.* *Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter.*
Adapted from* Ecology of Greenways: Design and Function of Linear Conservation Areas. *Edited by Smith and Hellmund. © University of Minnesota Press 1993.

gullying, and the free flow of sediments and nutrients into the stream.

Edges at the boundaries of stream corridors begin the process of filtering. Abrupt edges concentrate initial filtering functions into a narrow area. A gradual edge increases filtering and spreads it across a wider ecological gradient (**Figure 2.41**).

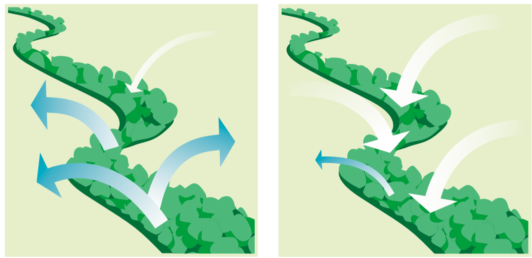
Movement parallel to the corridor is affected by coves and lobes of an uneven corridor's edge. These act as barriers or filters for materials flowing into the corridor. Individual plants may selectively capture materials such as wind-borne sediment, carbon, or propagules as they pass through a convoluted edge. Herbivores traveling along a boundary edge, for example, may stop to rest and selectively feed in a sheltered nook. The wind blows a few seeds into the corridor, and those suited to the conditions of the corridor may germinate and establish a population. The lobes have acted as a selective filter collecting some seeds at the edge and allowing other species to interact at the boundary (Forman 1995).



(a) (b)

Figure 2.41: Edges can be (a) abrupt or (b) gradual. *Abrupt edges, usually caused by disturbances, tend to discourage movement between ecosystems and promote movement along the boundary. Gradual edges usually occur in natural settings, are more diverse, and encourage movement between ecosystems.*

Source and Sink Functions



Sources provide organisms, energy or materials to the surrounding landscape. Areas that function as sinks absorb organisms, energy, or materials from the surrounding landscape. Influent and effluent reaches, discussed in Section 1.B of Chapter 1, are classic examples of sources and sinks. The influent or "losing" reach is a source of water to the aquifer, and the effluent or "gaining" reach is a sink for ground water.

Stream corridors or features within them can act as a source or a sink of environmental materials. Some stream corridors act as both, depending on the time of year or location in the corridor. Streambanks most often act as a source, for example, of sediment to the stream. At times, however, they can function as sinks while flooding deposits new sediments there. At the landscape scale, corridors are connectors to various other patches of habitats in the landscape and as such they are sources and conduits of genetic material throughout the landscape.

Stream corridors can also act as a sink for storage of surface water, ground water, nutrients, energy, and sediment allowing for materials to be temporarily fixed in the corridor. Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter. Although these functions of source and sink are conceptually understood, they lack a suitable body of research and practical application guidelines.

Forman (1995) offers three source and sink functions resulting from floodplain vegetation:

- Decreased downstream flooding through floodwater moderation and/or uptake
- Containment of sediments and other materials during flood stage
- Source of soil organic matter and water-borne organic matter

Biotic and genetic source/sink relationships can be complex. Interior forest birds are vulnerable to nest parasitism by cowbirds when they try to nest in too small a forest patch. For these species, small forest patches can be considered sinks that reduce their population numbers and genetic diversity by causing failed reproduction. Large forest patches with sufficient interior habitat, in comparison, support successful reproduction and serve as sources of more individuals and new genetic combinations.

Dynamic Equilibrium

The first two chapters of this document have emphasized that, although stream corridors display consistent patterns in their structure, processes, and functions, these patterns change naturally and constantly, even in the absence of human disturbance. Despite frequent change, streams and their corridors exhibit a dynamic form of stability. In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

The maintenance of dynamic equilibrium requires that a series of self-correcting mechanisms be active in the stream corridor ecosystem. These mech-

In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

anisms allow the ecosystem to control external stresses or disturbances within a certain range of responses thereby maintaining a self-sustaining condition. The threshold levels associated with these ranges are difficult to identify and quantify. If they are exceeded, the system can become unstable. Corridors may then undergo a series of adjustments to achieve a new steady state condition, but usually after a long period of time has elapsed.

Many stream systems can accommodate fairly significant disturbances and still return to functional condition in a reasonable time frame, once the source of the disturbance is controlled or removed. Passive restoration is based on this tendency of ecosystems to heal themselves when external stresses are removed. Often the removal of stress and the time to recover naturally are an economical and effective restoration strategy. When significant disturbance and alteration has occurred, however, a stream corridor may require several decades to restore itself. Even then, the recovered system may be a very different type of stream that, although at equilibrium again, is of severely diminished ecological value in comparison with its previous potential. When restoration practitioners' analysis indicates lengthy recovery time or dubious recovery potential for a stream, they may decide to use active restoration techniques to reestablish a more functional channel form, corridor structure, and biological community in a much shorter time frame. The main benefit of an active restoration approach is regaining functionality more quickly, but the biggest challenge is to plan, design, and implement correctly to reestablish the desired state of dynamic equilibrium.

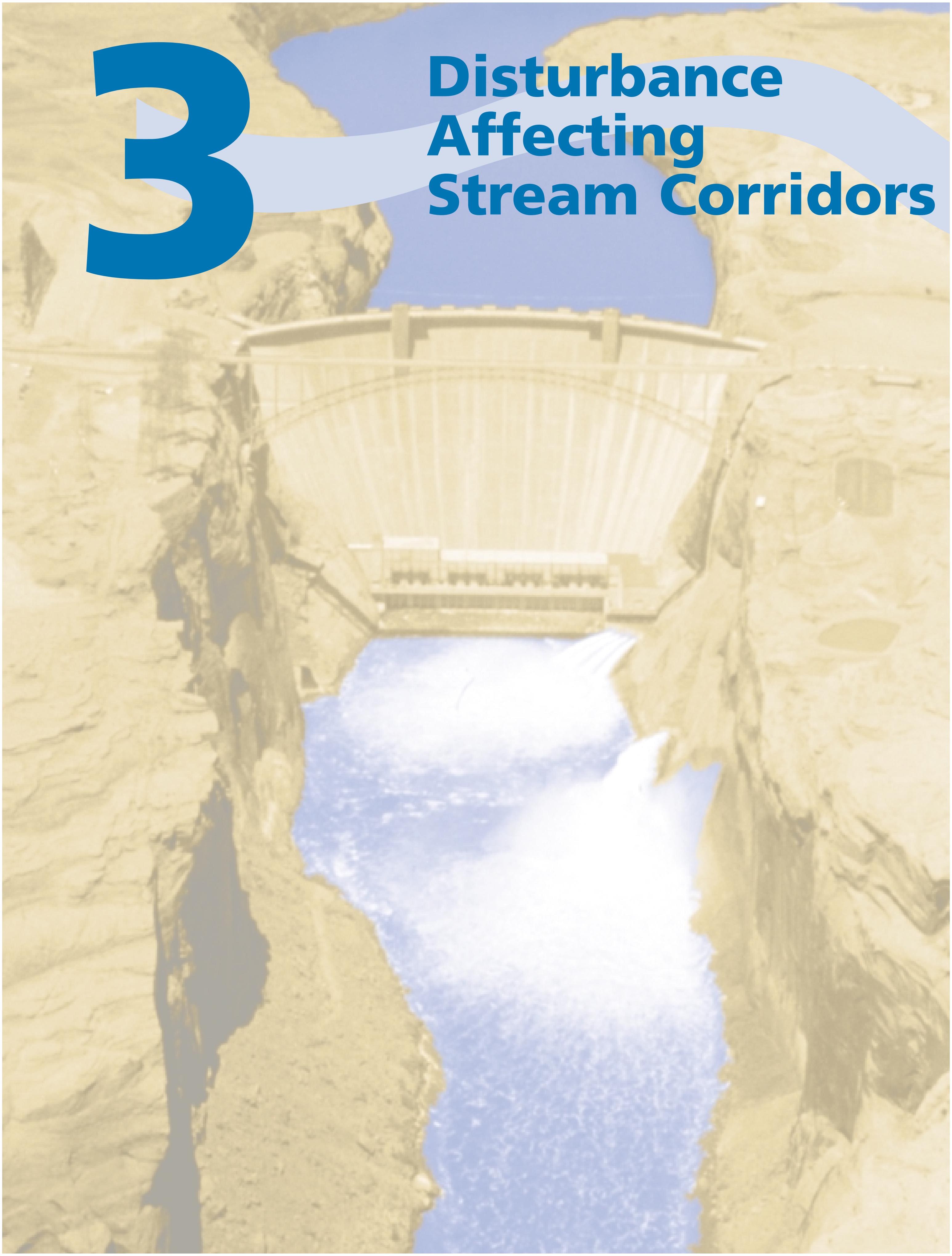
This new equilibrium condition, however, may not be the same that existed prior to the initial occurrence of the disturbance. In addition, disturbances can often stress the system beyond its natural ability to recover. In these instances restoration is needed to remove the cause of the disturbance or stress (passive) or to repair damages to the structure and functions of the stream corridor ecosystem (active).

Stability, Disturbance, and Recovery

Stability, as a characteristic of ecosystems, combines the concepts of resistance, resilience, and recovery. Resistance is the ability to maintain original form and functions. Resilience is the rate at which a system returns to a stable condition after a disturbance. Recovery is the degree to which a system returns to its original condition after a disturbance. Natural systems have developed ways of coping with disturbance, in order to produce recovery and stability. Human activities often superimpose additional disturbances which may exceed the recovery capability of a natural system. The fact that change occurs, however, does not always mean a system is unstable or in poor condition.

The term mosaic stability is used to denote the stability of a larger system within which local changes still take place. Mosaic stability, or the lack thereof, illustrates the importance of the landscape perspective in making site-specific decisions. For example, in a rapidly urbanizing landscape, a riparian system denuded by a 100-year flood may represent a harmful break in already diminished habitat that splits and isolates populations of a rare amphibian species. In contrast, the same riparian system undergoing flooding in a less-developed landscape may not be a geographic barrier to the amphibian, but merely the mosaic of constantly shifting suitable and unsuitable habitats in an unconfined, naturally functioning stream. The latter landscape with mosaic stability is not likely to need restoration while the former landscape without mosaic stability is likely to need it urgently. Successful restoration of any stream corridor requires an understanding of these key underlying concepts.

3 Disturbance Affecting Stream Corridors



3.A Natural Disturbances

- *How does natural disturbance contribute to shaping a local ecology?*
- *Are natural disturbances bad?*
- *How do you describe or define the frequency and magnitude of natural disturbance?*
- *How does an ecosystem respond to natural disturbances?*
- *What are some types of natural disturbances you should anticipate in a stream corridor restoration?*

3.B Human-Induced Disturbances

- *What are some examples of human-induced disturbances at several landscape scales?*
- *What are the effects of some common human-induced disturbances such as dams, channelization, and the introduction of exotic species?*
- *What are some of the effects of land use activities such as agriculture, forestry, mining, grazing, recreation, and urbanization?*

3 Disturbance Affecting Stream Corridors

*Disturbances that bring changes to stream corridors and associated ecosystems are natural events or human-induced activities that occur separately or simultaneously (**Figure 3.1**). Either individually or in combination, disturbances place stresses on the stream corridor that have the potential to alter its structure and impair its ability to perform key ecological functions. The true impact of these disturbances can best be understood by how they affect the ecosystem structure, processes, and functions introduced in Chapters 1 and 2.*

A disturbance occurring within or adjacent to a corridor typically produces a causal chain of effects, which may permanently alter one or more characteristics of a stable system. A view of this chain is illustrated in Figure 3.2 (Wesche 1985). This view can be applied in many stream corridor restoration initiatives with the ideal goal of moving back as far as feasible on the cause-effect chain to plan and select restoration alternatives

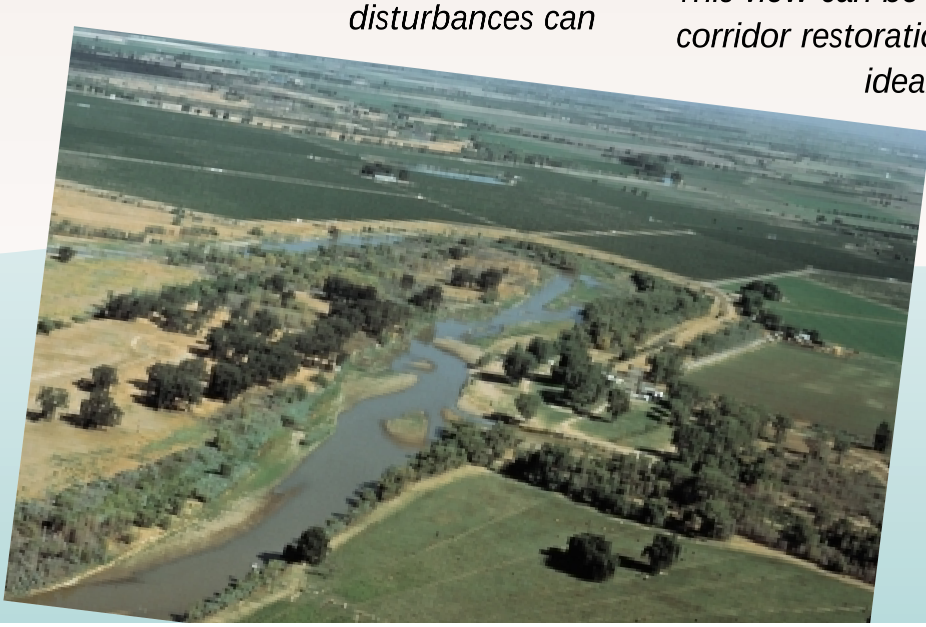


***Figure 3.1: Disturbance in the stream corridor.** Both natural and human-induced disturbances result in changes to stream corridors.*

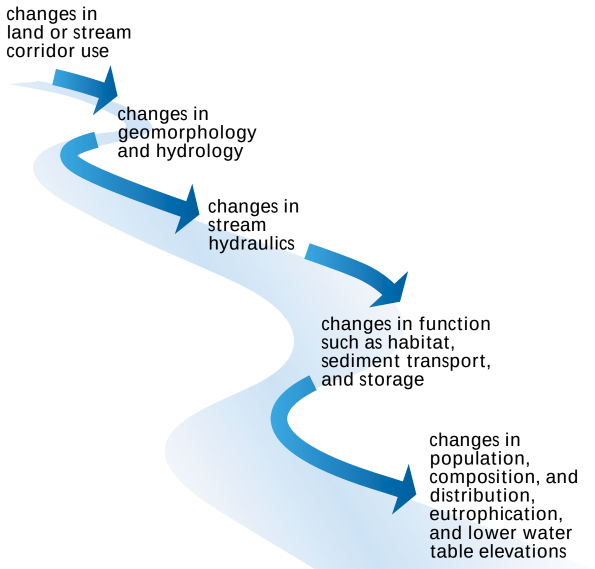


Figure 3.2: Chain of events due to disturbance. *Disturbance to a stream corridor system typically results in a causal chain of alterations to stream corridor structure and functions.*

(Armour and Williamson 1988). Otherwise, chosen alternatives may merely treat symptoms rather than the source of the problem.

Using this broad goal along with the thoughtful use of a responsive evaluation and design process will greatly reduce the need for trial-and-error experiences and enhance the opportunities for successful restoration. Passive restoration, as the critical first option to pursue, will result.

Disturbances can occur anywhere within the stream corridor and associated ecosystems and can vary in terms of frequency, duration, and intensity. A single disturbance event may trigger a variety of disturbances that differ in frequency, duration, intensity, and location. Each of these subsequent forms of direct or indirect disturbance should be addressed in restoration planning and design for successful results.

This chapter focuses on understanding how various disturbances affect the stream corridor and associated ecosystems. We can better determine what actions are needed to restore stream corridor structure and functions by understanding the evolution of what disturbances are stressing the system, and how the system responds to those stresses.

Section 3.A: Natural Disturbances

This section introduces natural disturbances as a multitude of potential events that cover a broad range of temporal and spatial scales. Often the agents of natural regeneration and restoration, natural disturbances are presented briefly as part of the dynamic system and evolutionary process at work in stream corridors.

Section 3.B: Human-Induced Disturbances

Traditionally the use and management of stream corridors have focused on the health and safety or material wealth of society. Human-induced forms of disturbances and resulting effects on the ecological structure and functions of stream corridors are, therefore, common. This section briefly describes some of these major disturbance activities and their potential effects.

Changes on Broad Temporal and Spatial Scales

Disturbance occurs within variations of scale and time. Changes brought about by land use, for example, may occur within a single year at the stream or reach scale (crop rotation), a decade within the corridor or stream scale (urbanization), and even over decades within the landscape or corridor scale (long-term forest management). Wildlife populations, such as monarch butterfly populations, may fluctuate wildly from year to year in a given locality while remaining nationally stable over several decades. Geomorphic or climatic changes may occur over hundreds to thousands of years, while weather changes daily.

Tectonics alter landscapes over periods of hundreds to millions of years, typically beyond the limits of human observance. Tectonics involves mountain-building forces like folding and faulting or earthquakes that modify the elevation of the earth's surface and change the slope of the land. In response to such changes, a stream typically will modify its cross section or its planform. Climatic changes, in contrast, have been historically and even geologically recorded. The quantity, timing, and distribution of precipitation often causes major changes in the patterns of vegetation, soils, and runoff in a landscape. Stream corridors subsequently change as runoff and sediment loads vary.

3.A Natural Disturbances

Floods, hurricanes, tornadoes, fire, lightning, volcanic eruptions, earthquakes, insects and disease, landslides, temperature extremes, and drought are among the many natural events that disturb structure and functions in the stream corridor (**Figure 3.3**). How ecosystems respond to these disturbances varies according to their relative stability, resistance, and resilience. In many instances they recover with little or no need for supplemental restoration work.

Natural disturbances are sometimes agents of regeneration and restoration. Certain species of riparian plants, for example, have adapted their life cycles to include the occurrence of destructive, high-energy disturbances, such as alternating floods and drought.

In general, riparian vegetation is resilient. A flood that destroys a mature cottonwood gallery forest also commonly creates nursery conditions necessary for the establishment of a new forest (Brady et al. 1985), thereby increasing the resilience and degree of recovery of the riparian system.

Figure 3.3: Drought—one of many types of natural disturbance. *How a stream corridor responds to disturbances depends on its relative stability, resistance, and resilience.*

Ecosystem Resilience in Eastern Upland Forests

*Eastern upland forest systems, dominated by stands of beech/maple, have adapted to many types of natural disturbances by evolving attributes such as high biomass and deep, established root systems (**Figure 3.4**). Consequently, they are relatively unperturbed by drought or other natural disturbances that occur at regular intervals. Even when unexpected severe stress such as fire or insect damage occurs, the impact is usually only on a local scale and therefore insignificant in the persistence of the community as a whole.*

Resilience of the Eastern Upland Forest can be disrupted, however, by widespread effects such as acid rain and indiscriminate logging and associated road building. These and other disturbances have the potential to severely alter lighting conditions, soil moisture, soil nutrients, soil temperature, and other factors critical for persistence of the beech/maple forest. Recovery of an eastern "climax" system after a widespread disturbance might take more than 150 years.

***Figure 3.4**: **Eastern upland forest system.** The beech/maple-dominated system is resistent to many natural forms of stress due to high biomass; deep, established root systems; and other adaptations.*

CASE STUDY

Before the Next Flood

Recently the process of recovery from major flood events has taken on a new dimension. Environmental easements, land acquisition, and relocation of vulnerable structures have become more prominent tools to assist recovery and reduce long-term flood vulnerability. In addition to meeting the needs of disaster victims, these actions can also be effective in achieving stream corridor restoration. Local interest in and support for stream corridor restoration may be high after a large flood event, when the floodwaters recede and the extent of property damage can be fully assessed. At this point, public recognition of the costly and repetitive nature of flooding can provide the impetus needed for communities and individuals to seek better solutions. Advanced planning on a systemwide basis facilitates identification of areas most suited to levee setback, land acquisition, and relocation.

*The city of Arnold, Missouri, is located about 20 miles southwest of St. Louis at the confluence of the Meramec and Mississippi Rivers. When the Mississippi River overflows its banks, the city of Arnold experiences backwater conditions—river water is forced back into the Meramec River, causing flooding along the Meramec and smaller tributaries to the Meramec. The floodplains of the Mississippi, Meramec, and local tributaries have been extensively developed. This development has decreased the natural function of the floodplain. In 1991 Arnold adopted a floodplain management plan that included, but was not limited to, a greenway to supplement the floodplain of the Mississippi River, an acquisition and relocation program to facilitate creation of the greenway, regulations to guide future development and ensure its consistency with the floodplain management objectives, and a watershed management plan. The 1993 floods devastated Arnold (***Figure 3.5***). More than $2 million was spent on federal disaster assistance to individuals, and the city's acquisition program spent $7.3 million in property buyouts. Although not as severe as the 1993 floods, the 1995 floods were the fourth largest in Arnold's history. Because of the relocation and other floodplain management efforts, federal assistance to individuals totaled less than $40,000. As the city of Arnold demonstrated, having a local floodplain management plan in place before a flood makes it easier to take advantage of the mitigation opportunities after a severe flood.*

Across the Midwest, the 1993 floods resulted in record losses with over 55,000 homes flooded. Total damage estimates ranged between $12 billion and $16 billion. About half of the damage was to residences, businesses, public facilities, and transportation infrastructure. The Federal Emergency Management Agency and the U.S. Department of Housing and Urban Development were able to make considerably more funding available for acquisition, relocation, and raising the elevation of properties than had been available in the past. The U.S. Fish and Wildlife Service and state agencies were also able to acquire property easements along the rivers. As a result, losses from the 1995 floods in the same areas were reduced and the avoided losses will continue into the future. In addition to reducing the potential for future flood damages, the acquisition of property in floodplains and the subsequent conversion of that property into open space provides an opportunity for the return of the natural functions of stream corridors.

Figure 3.5: Flooding in Arnold, Missouri (1983).

3.B Human-Induced Disturbances

Human-induced disturbances brought about by land use activities undoubtedly have the greatest potential for introducing enduring changes to the ecological structure and functions of stream corridors (**Figure 3.6**). Chemically defined disturbance effects, for example, can be introduced through many activities including agriculture (pesticides and nutrients), urban activities (municipal and industrial waste contaminants), and mining (acid mine drainage and heavy metals).

Human-induced disturbances brought about by land use activities undoubtedly have the greatest potential for introducing enduring changes to the ecological structure and functions of stream corridors.

They have the potential to disturb natural chemical cycles in streams, and thus to degrade water quality. Chemical disturbances from agriculture are usually widespread, nonpoint sources. Municipal and industrial waste contaminants are typically point sources and often chronic in duration. Secondary effects, such as agricultural chemicals attached to sediments and increased soil salinity, frequently occur as a result of physical activities (irrigation or heavy application of herbicide). In these cases, it is better to control the physical activity at its source than to treat the symptoms within a stream corridor.

Biologically defined disturbance effects occur within species (competition, cannibalism, etc.) and among species (competition, predation, etc.). These are natural interactions that are important determinants of population size and community organization in many ecosystems. Biological disturbances due to improper grazing management or recreational activities are frequently encountered. The introduction of exotic flora and fauna species can introduce widespread, intense, and continuous stress on native biological communities.

Physical disturbance effects occur at any scale from landscape and stream corridor to stream and reach, where they can cause impacts locally or at locations far removed from the site of origin. Activities such as flood control, forest management, road building and maintenance, agricultural tillage, and irrigation, as well as urban encroachment, can have dramatic effects on the geomorphology and hydrology of a watershed and the stream corridor morphology within it. By altering the structure of plant communities and soils, these and other activities can affect the infiltration and movement of water, thereby altering the timing and magnitude of runoff events. These disturbances also occur at the reach scale and cause changes that can be addressed in stream corridor restoration. The modification of stream hydraulics, for example, directly affects the system,

Figure 3.6: Agricultural activity. *Land use activities can cause extensive physical, biological, or chemical disturbances in a watershed and stream corridor.*

causing an increase in the intensity of disturbances caused by floods.

This section is divided into two subsections. Common disturbances are discussed first, followed by land use activities.

Common Disturbances

Dams, channelization, and the introduction of exotic species represent forms of disturbance found in many if not all of the land uses discussed later in this chapter. Therefore, they are presented as separate discussions in advance of more specific land use activities that potentially introduce disturbance. Many societal benefits are derived from these land use changes. This document, however, focuses on their potential for disturbance and subsequent restoration of stream corridors.

Figure 3.7: An impoundment dam. *Dams range widely in size and purpose, and in their effects on stream corridors.*

Dams

Ranging from small temporary structures constructed of stream sediment to huge multipurpose structures, dams can have profound and varying impacts on stream corridors (**Figure 3.7**). The extent and impact largely depend on the purposes of the dam and its size in relation to stream flow.

Changes in discharges from dams can cause downstream effects. Hydropower dam discharges may vary widely on a hourly and daily basis in response to peaking power needs and affect the downstream morphology. The rate of change in the discharge can be a significant factor increasing streambank erosion and subsequent loss of riparian habitat. Dams release water that differs from that received. Flowing streams can slow and change into slack water pools, sometimes becoming lacustrine environments. A water supply dam can decrease instream flows, which alters the stream corridor morphology, plant communities, and habitat or can augment flows, which also results in alterations to the stream corridor.

Dams affect resident and migratory organisms in stream channels. The disruption of flow blocks or slows the passage and migration of aquatic organisms, which in turn affects food chains associated with stream corridor functions (**Figure 3.8**). Without high flows, silt is not washed from the gravel beds on which many aquatic species rely for spawning. Upstream fish movement may be blocked by relatively small structures. Downstream movement may be slowed or stopped by the dam or its reservoir. As a stream current dissipates in a reservoir, smolts of anadromous fish may lose a sense of downstream direction or might be subject to more predation, altered water chemistry, and other effects.

Dams also affect species by altering water quality. Relatively constant flows can create constant temperatures, which affect those species dependent on temperature variations for reproduction or maturation. In places where irrigation water is stored, unnaturally low flows can occur and warm more easily and hold less oxygen, which can cause stress or death in aquatic organisms. Likewise, large storage pools keep water cool, and released water can result in significantly cooler temperatures downstream to which native fish might not be adapted.

Dams also disrupt the flow of sediment and organic materials (Ward and Standford 1979). This is particularly evident with the largest dams, whereas dams which are typically low in elevation and have small pools modify natural flood and transport cycles only slightly. As stream flow slackens, the load of suspended sediment decreases and sediment drops out of the stream to the reservoir bottom. Organic material suspended in the sediment, which provides vital nutrients for downstream food webs, also drops out and is lost to the stream ecosystem.

When suspended sediment load is decreased, scouring of the downstream streambed and banks may occur until the equilibrium bed load is reestablished. Scouring lowers the streambed and erodes streambanks and riparian zones, vital habitat for many species. Without new sources of sediment, sandbars alongside and within streams are eventually lost, along with the habitats and species they support. Additionally, as the stream channel becomes incised, the water table underlying the riparian zone also lowers. Thus, channel incision can lead to adverse changes in the composition of vegetative communities within the stream corridor.

Figure 3.8: Biological effects of dams. *Dams can prevent the migration of anadromous fish and other aquatic organisms.*

Conversely, when dams are constructed and operated to reduce flood damages, the lack of large flood events can result in channel aggradation and the narrowing and infilling of secondary channels (Collier et al. 1996).

Channelization and Diversions

Like dams, channelization and diversions cause changes to stream corridors. Stream channelization and diversions can disrupt riffle and pool complexes needed at different times in the life cycle of certain aquatic organisms. The flood conveyance benefits of channelization and diversions are often offset by ecological losses resulting from increased stream velocities and reduced habitat diversity. Instream modifications such as uniform cross section and armoring result in less habitat for organisms living in or on stream sediments (**Figure 3.10**). Habitat is also lost when large woody debris, which frequently supports a high density of aquatic macroinvertebrates, is removed (Bisson et al. 1987, Sweeney 1992).

The impacts of diversions on the stream corridor depend on the timing and amount of water diverted, as well as the location, design, and operation

CASE STUDY

The Glen Canyon Dam Spiked Flow Experiment

The Colorado River watershed is a 242,000-square-mile mosaic of mountains, deserts, and canyons. The watershed begins at over 14,000 feet in the Rocky Mountains and ends at the Sea of Cortez. Many native species require very specific environments and ecosystem processes to survive. Before settlement of the Colorado River watershed, the basin's rivers and streams were characterized by a large stochastic variability in the annual and seasonal flow levels. This was representative of the highly variable levels of moisture and runoff. This hydrologic variability was a key factor in the evolution of the basin's ecosystems.

Settlement and subsequent development and management of the waters of the Colorado River system detrimentally affected the ecological processes. Today over 40 dams and diversion structures control the river system and result in extensive fragmentation of the watershed and riverine ecosystem. Watershed development, in addition to the dams, has also resulted in modifications to the hydrology and the sediment input.

*Historically, flood flows moved nutrients into the ecosystem, carved the canyons, and redistributed sand from the river bottom creating sandbars and backwaters where fish could breed and grow. In 1963, the closure of Glen Canyon Dam, about 15 miles upstream of the Grand Canyon, permanently altered these processes (**Figure 3.9**). In the spring of 1996 the Bureau of Reclamation ran the first controlled release of water from Glen Canyon Dam to test and study the ability to use "spike flows" for redistribution of sediment (sand) from the river bottom to the river's margins in eddy zones. The primary objective of the controlled release of large flows was to restore portions of the ecological equation by mimicking the annual floods which used to occur in the Grand Canyon.*

Flow releases of 45,000 cfs were maintained for one week. The results were mixed. The flood heightened and slightly widened existing sandbars. It built scores of new camping beaches and provided additional protection for archeological sites threatened with loss from erosion. The spike flow also liberated large quantities of vital nutrients. It created 20 percent more backwater areas for spawning native fish. No endangered species were significantly harmed, nor was the trout fishery immediately below Glen Canyon Dam harmed. The flow was not, however, strong enough to flush some nonnative species (e.g., tamarisk) from the system as had been hoped. One important finding was that most of the ecological effects were realized during the first 48 hours of the week-long high-flow conditions.

The Bureau of Reclamation is continuing to monitor the effects of the spike flow. The effects of the restorative flood are not permanent. New beaches and sandbars will continue to erode. An adaptive management approach will help guide future decisions about spike flows and management of flows to better balance the competing needs for hydropower, flood protection, and preservation of the Grand Canyon ecosystem. It might be that short spike flows are ecologically more acceptable. Changing flow releases provides another tool that, if properly used, can help restore ecological processes that are essential for maintaining ecosystem health and biodiversity.

Figure 3.9: Glen Canyon Dam. *The Glen Canyon Dam permanently altered downstream functions and ecology.*

of the diversion structure or its pumps (**Figure 3.11**). The effects of diversions on stream flows are similar to those addressed for dams. The effects of levees depend on siting considerations, design, and maintenance practices.

Earthen diversion channels leak, and the water lost for irrigation may create wetlands. Leakage may support a vegetative corridor approaching that of a simple riparian community, or it can facilitate spread of exotic species, such as tamarisk (*Tamarisk chinensis*). Diversions can also trap fish, resulting in diminished spawning, lowered health of species, and death of fish.

Flood damage reduction measures encompass a wide variety of strategies, some of which might not be compatible with goals of stream corridor restoration.

Flood damage reduction measures encompass a wide variety of strategies, some of which might not be compatible with goals of stream corridor restoration. Floodwalls and levees can increase the velocity of the stream and elevate flood heights by constraining high flows of the river to a narrow band. When floodwalls are set farther back from streams, they can define the stream corridor and for some or all of the natural functions of the floodplain, including temporary flood storage.

Figure 3.10*: *Stream channelization. *Instream modifications, such as uniform cross section and armoring, result in ecological decline.*

Levees juxtaposed to streams tend to replace riparian vegetation. The loss or diminishment of the tree overstory and other riparian vegetation results in the changes in shading, temperature, and nutrients discussed earlier.

Introduction of Exotic Species

Stream corridors naturally evolve in an environment of fluctuating flows and seasonal rhythms. Native species adapted to such conditions might not survive without them. For stream corridors that have naturally evolved in an environment of spring floods and low winter and summer flows, the diminution of such patterns can result in the creation of a new succession of plants and animals and the decline of native species. In the West, nonnative species like tamarisk can invade altered stream corridors and result in creation of a habitat with lower stability. The native fauna might not secure the same survival benefits from this altered condition because they did not evolve with tamarisk and are not adapted to using it.

The introduction of exotic species, whether intentional or not, can cause disruptions such as predation, hybridization, and the introduction of diseases. Nonnative species compete with native species for moisture, nutrients, sunlight, and space and can adversely influence establishment rates for new plantings, foods, and habitat. In some cases, exotic plant species can even detract from the recreational value of streams by creating a dense, impenetrable thicket along the streambank. Well-known examples of the effects of exotic species introduction include the planned introduction of kudzu and the inadvertent introduction of the zebra mussel. Both species have imposed widespread, intense, and continuous stress on native biological communities. Tamarisk (also known as salt cedar) is perhaps the most renowned exotic in North America. It is an aggressive, exotic colonizer in the West due to its high rate of seed production and ability to withstand long periods of inundation.

Figure 3.11: Stream diversion. *Diversions are built to provide water for numerous purposes, including agriculture, industry, and drinking water supplies.*

Exotic Species in the West

*Exotic animals are a common problem in many areas of the West. "Wild" burros wander up and down many desert washes and stream corridors. Their destructive foraging is often evident in sensitive riparian areas. Additionally, species such as bullfrogs, not native to most of the West, have been introduced in many waters (***Figure 3.12***). Without the normal checks and balances found in their native habitat in the eastern United States, bullfrogs reproduce prodigiously and prey on numerous native amphibians, reptiles, fish, and small mammals.*

Figure 3.12: Bullfrog. *Without the normal checks and balances found in the eastern United States, bullfrogs in the West have reproduced prodigiously.*
Source: C. Zabawa.

CASE STUDY

Salt Cedar Control at Bosque del Apache National Wildlife Refuge, New Mexico

The exotic salt cedar (Tamarix chinensis) *has become the predominant woody species along many of the stream corridors in the Southwest. The wide distribution of this species can be attributed to its ability to tolerate a wide range of environmental factors and its adaptability to new stream conditions accelerated by human activities (e.g., summer flooding or no flooding, reduced or altered water tables, high salinity from agricultural tail water, and high levels of sediment downstream from grazed watersheds). Salt cedar is particularly abundant on regulated rivers. Its ability to rapidly dominate riparian habitat results in exclusion of cottonwood, willow, and many other native riparian species.*

Salt cedar control is an integral part of riparian restoration and enhancement at Bosque del Apache National Wildlife Refuge on the Rio Grande in central New Mexico. Diverse mosaics of native cottonwood/black willow (Populus fremontii/Salix nigra) *forests, screw bean mesquite* (Prosobis pubescens) *brushlands, and saltgrass* (Distichlis *sp.*) *meadows have been affected by this invasive exotic. The degree of infestation varies widely throughout the refuge, ranging from isolated plants to extensive monocultures totaling thousands of acres. For the past 10 years, the refuge has experimented with mechanical and herbicide programs for feasible control of salt cedar.*

*The refuge has experimented with several techniques in controlling large salt cedar monocultures prior to native plant establishment. Herbicide/broadcast burn and mechanical techniques have been employed on three 150-acre units on the refuge (**Figure 3.13**). Initially, the strategy for control was aerial application of a low-toxicity herbicide, at 2 quarts/acre in the late summer, followed by a broadcast prescribed burn a year later. This control method appeared effective; however, extensive resprouting following the burn indicated the herbicide might not have had time to kill the plant prior to the burning.*

Mechanical control using heavy equipment was another option. Root plowing and raking have long been used as a technique for salt cedar control. A plow is pulled by a bulldozer, severing salt cedar root crowns from the remaining root mass about 12 to 18 inches below the ground surface, followed by root raking, which pulls the root crowns from the ground for later stacking.

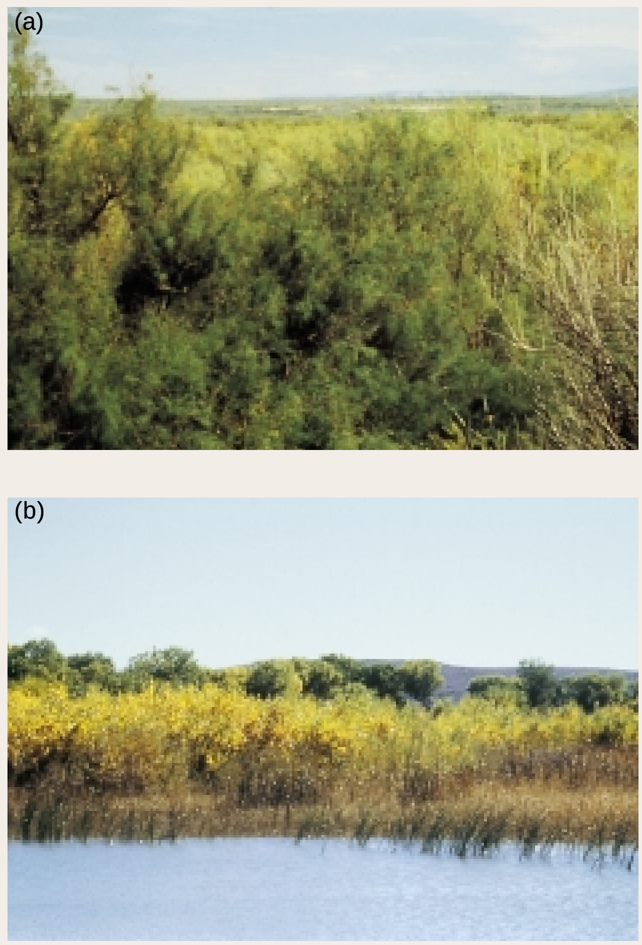
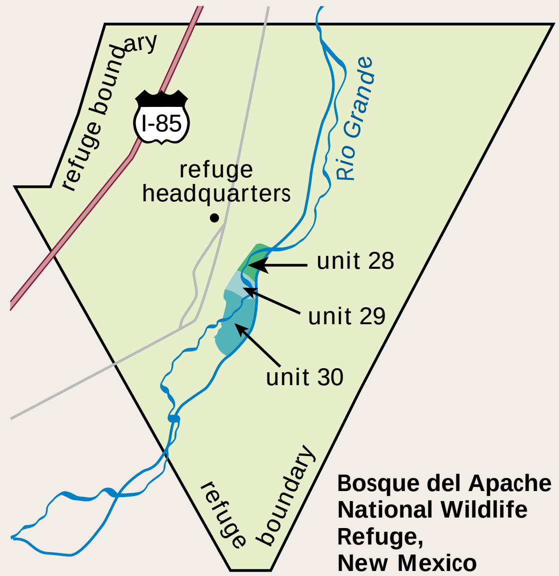


Figure 3.13: Salt cedar site (a) before and (b) after treatment. *Combinations of burning, chemical treatment, and mechanical control techniques can be used to control salt cedar, giving native vegetation an opportunity to colonize and establish.*

There are advantages and disadvantages with each technique (**Table 3.1**). Cost-effectiveness is the distinct advantage of an herbicide/burn control program. Costs can be low if resprouting is minor and burning removes much of the aerial vegetation. Because an herbicide/burn program is potentially cost-effective, this technique is again being experimented with at the refuge. Costs are being further reduced by combining the original herbicide with a less expensive herbicide. A delay of 2 years prior to broadcast burning is expected to dramatically reduce resprouting, allowing time for the herbicide to effectively move throughout the entire plant. Disadvantages of herbicide application include restrictions regarding application near water bodies and impacts on native vegetation remnants within salt cedar monocultures.

Advantages of mechanical control include proven effectiveness and more thorough site preparation for revegetation. Disadvantages include significant site disturbance, equipment breakdowns/delays, and lower effectiveness in tighter clay soils. Both methods require skill in equipment operation, whether applying herbicide aerially or operating heavy equipment.

Other salt cedar infestations on the refuge are relatively minor, consisting of small groups of plants or scattered individual plants. Nonetheless, these patches are aggressively controlled to prevent spread. Heavy equipment requires working space and is generally restricted to sites of 1 acre and larger. For these smaller areas, front end loaders have been filled with "stinger bars," which remove individual plant root crowns much like a root plow. For areas of less than 1 acre, spot herbicide applications are made using a 1 percent solution from a small sprayer. To date, approximately 1,000 acres of salt cedar have been controlled, with over 500 acres effectively restored to native riparian vegetative communities. A combination of techniques in the control of salt cedar has proven effective and will continue to be used in the future.



Bosque del Apache National Wildlife Refuge, New Mexico

Table 3.1: Salt cedar control techniques at Bosque del Apache.

Unit	Herbicide	Broadcast Burn	Root Plow	Root Rake	Pile Burn	% Control
28	x	x	x			88%
29	x	x	x	x	x	90%
30			x	x	x	99%

Land Use Activities

Agriculture

According to the 1992 Natural Resources Inventory (USDA-NRCS 1992), cultivated and noncultivated cropland make up approximately 382 million acres of the roughly 1.9 billion acres existing in the contiguous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands (excludes Alaska). The conversion of undisturbed land to agricultural production has often disrupted the previously existing state of dynamic equilibrium. Introduced at the landscape, watershed, stream corridor, stream, and reach scales, agricultural activities have generally resulted in encroachment on stream corridors with significant changes to the structure and mix of functions usually found in stable systems (**Figure 3.14**).

Figure 3.14: Agriculture fragments natural ecosystems. *Cultivated and noncultivated cropland make up approximately 382 million acres of the roughly 1.9 billion acres existing in the contiguous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands (excludes Alaska).*

Vegetative Clearing

One of the most obvious disturbances from agriculture involves the removal of native, riparian, and upland vegetation. Producers often crop as much productive land as possible to enhance economic returns; therefore, vegetation is sacrificed to increase arable acres.

As the composition and distribution of vegetation are altered, the interactions between structure and function become fragmented. Vegetative removal from streambanks, floodplains, and uplands often conflicts with the hydrologic and geomorphic functions of stream corridors. These disturbances can result in sheet and rill as well as gully erosion, reduced infiltration, increased upland surface runoff and transport of contaminants, increased streambank erosion, unstable stream channels, and impaired habitat.

Instream Modifications

Flood-control structures and channel modifications implemented to protect agricultural systems further disrupt the geomorphic and hydrologic characteristics of stream corridors and associated uplands. For agricultural purposes, streams are often straightened or moved to “square-up” fields for more efficient production and reconstructed to a new profile and geometric cross section to accommodate increased runoff. Stream corridors are also often modified to enhance conditions for single purposes such as fish habitat, or to manage conditions such as localized streambank erosion. Some of the potential effects caused by these changes are impaired upland or floodplain surface and subsurface flow; increased water temperature, turbidity, and pH; incised channels; lower ground water elevations; streambank failure; and loss of habitat for aquatic and terrestrial species.

Soil Exposure and Compaction

Tillage and soil compaction interfere with soil's capacity to partition and regulate the flow of water in the landscape, increase surface runoff, and decrease the water-holding capacity of soils. Increases in the rate and volume of throughflow in the upper soil layers are frequent. Tillage also often aids in the development of a *hard pan*, a layer of increased soil density and decreased permeability that restricts the movement of water into the subsurface.

The resulting changes in surface and ground water flow often initiate incised channels and effects similar to those discussed previously for instream modifications.

Irrigation and Drainage

Diverting surface water for irrigation and depleting aquifers have brought about major changes in stream corridors. Aquifers have been a desired source of water for agriculture because ground water is usually high-quality and historically abundant and is a more reliable source than rivers, lakes, and reservoirs (**Figure 3.15**). Underground water supplies have diminished at an alarming rate in the United States, with ground water levels reported to be dropping an estimated foot or more a year under 45 percent of the ground water-irrigated cropland (Dickason 1988).

Agricultural drainage, which allows the conversion of wetland soils to agricultural production, lowers the water table. Tile drainage systems concentrate ground water discharge to a point source, in contrast to a diffuse source of seeps and springs in more natural discharges. Subsurface tile drainage systems, constructed waterways, and drainage ditches constitute a landscape scale network of disturbances. These practices have eliminated or fragmented habitat and natural filtration systems needed to slow and purify runoff. The results are often a compressed and exaggerated hydrograph.

Figure 3.15: Central pivot irrigation systems use ground water sources. *Reliance on aquifers for irrigation has brought about major changes in ground water supply, as well as the landscape.*

Sediment and Contaminants

Disturbance of soil associated with agriculture generates runoff polluted with sediment, a major nonpoint source pollutant in the nation. Pesticides and nutrients (mainly nitrogen, phosphorous, and potassium) applied during the growing season can leach into ground water or flow in surface water to stream corridors, either dissolved or adsorbed to soil particles. Applied aerially, these same chemicals can drift into the stream corridor. Improper storage and application of animal waste from concentrated animal production facilities are potential sources of chemical and bacterial contaminants to stream corridors.

Soil salinity is a naturally occurring phenomenon found most often in floodplains and other low-lying areas of wet soils, lakes, or shallow water tables. Dissolved salts in surface and ground water entering these areas become concentrated in the shallow ground water and the soils as evapotranspiration removes water. Agricultural activities in such landscapes can increase the rate of soil salinization by changing vegetation patterns or by applying irrigation water without adequate drainage. In the arid and semiarid areas of the West, irrigation can import salts into a drainage basin. Since crops do not use up the salts, they accumulate in the soil. Salinity levels greater than 4 millimhos/cm can alter soil structure, promote waterlogging, cause salt toxicity in plants, and decrease the ability of plants to take up water.

Drainage and Streambank Erosion

Many wetlands have been drained to increase the acres of arable land. The drainage area of the Blue Earth River in the glaciated areas of west-central Minnesota, for example, has almost doubled due to extensive tile drainage of depressional areas that formerly stored surface runoff. Studies to identify sources of sediment in this watershed have been made, and as a result, farmers have complied with reduced tillage and increased crop residue recommendations to help decrease the suspended sediment load in the river. Testing, however, indicates the sediment problem has not been solved. Some individuals have suggested that streambank erosion, not erosion on agricultural lands, might be the source of the sediment. Streambank erosion is more likely to be the result of drainage and subsequent changes to runoff patterns in the watershed.

Forestry

Three general activities associated with forestry operations can affect stream corridors—tree removal, activities necessary to transport the harvested timber, and preparation of the harvest site for regeneration.

Removal of Trees

Forest thinning includes the removal of either mature trees or immature trees to provide more growth capability for the remaining trees. Final harvest removes mature trees, either singularly or in groups. Both activities reduce vegetative cover.

Tree removal decreases the quantity of nutrients in the watershed since approximately one-half of the nutrients in trees are in the trunks. Instream nutrient levels can increase if large limbs fall into streams during harvesting and decompose. Conversely, when tree cover is removed, there is a short-term increase in nutrient release followed by long-term reduction in nutrient levels.

Removal of trees can affect the quality, quantity, and timing of stream flows for the same reasons that vegetative clearing for agriculture does. If trees are removed from a large portion of a watershed, flow quantity can increase accordingly. The overall effect depends on the quantity of trees removed and their proximity to the stream corridor (**Figure 3.16**). Increases in flood peaks can occur if vegetation in the area closest to the stream is removed. Long-term loss of riparian vegetation can result in bank erosion and channel widening, increasing the width/depth ratio (Hartman et al. 1987, Oliver and Hinckley 1987, Shields et al. 1994). Water temperature can increase during summer and decrease in winter by removal of shade trees in riparian areas. Allowing large limbs to fall into a stream and divert stream flow may alter flow patterns and cause bank or bed erosion.

Removal of trees can reduce availability of cavities for wildlife use and otherwise alter biological systems, particularly if a large percentage of the tree cover is removed. Loss of habitat for fish, invertebrates, aquatic mammals, amphibians, birds, and reptiles can occur.

Transportation of Products

Forest roads are constructed to move loaded logs from the landing to higher-quality roads and then to a manufacturing facility. Mechanical means to move logs to a loading area (landing) produce “skid trails.” Stream crossings are necessary along some skid trails and most forest road systems and are especially sensitive areas.

Removal of topsoil, soil compaction, and disturbance by equipment and log skidding can result in long-term loss of productivity, decreased porosity, decreased soil infiltration, and increased runoff and erosion. Spills of petroleum products can contaminate soils. Trails, roads, and landings can intercept ground water flow and cause it to become surface runoff.

Soil disturbance by logging equipment can have direct physical impact on habitat for a wide variety of amphibians, mammals, fish, birds, and reptiles, as well as physically harm wildlife. Loss of cover, food, and other needs can be critical. Sediment can clog fish habitat, widen streams, and accelerate streambank erosion.

Site Preparation

Preparing the harvested area for the next generation of desired trees typically includes some use of prescribed fire or other methods to prepare a seed bed and reduce competition from unwanted species.

Figure 3.16: Riparian forest. *Streamside forest cover serves many important functions such as stabilizing streambanks and moderating diurnal stream temperatures.*

Mechanical methods that completely remove competing species can cause severe compaction, particularly in wet soils. This compaction reduces infiltration and increases runoff and erosion. Moving logging debris into piles or windrows can remove important nutrients from the soil. Depending on the methods used, significant soil can be removed from the site and stacked with piled debris, further reducing site productivity.

Intense prescribed fire can volatilize important nutrients, while less intense fire can mobilize nutrients for rapid plant uptake and growth. Use of fire can also release nutrients to the stream in unacceptable quantities.

Mechanical methods that cause significant compaction or decrease infiltration can increase runoff and therefore the amount of water entering the stream system. Severe mechanical disturbance can result in significant erosion and sedimentation. Conversely, less disruptive mechanical means can increase organic matter in the soil surface and increase infiltration. Each method has advantages and disadvantages.

Direct harm can occur to wildlife by mechanical means or fire. Loss of habitat can occur if site preparation physically removes most competing vegetation. Loss of diversity can result from efforts to strongly limit competition with desired timber species. Careless use of mechanical equipment can directly damage streambanks and cause erosion.

Domestic Livestock Grazing

Grazing of domestic livestock, primarily cattle and sheep, is commonplace across the nation. Stream corridors are particularly attractive to livestock for many reasons. They are generally highly productive, providing ample forage. Water is close at hand, shade is available to cool the area, and slopes are gentle, generally less than 35 percent in most areas. Unless carefully managed, livestock can overuse these areas and cause significant disturbance (**Figure 3.17**). For purposes of the following discussion, cattle grazing provides the focus, although sheep, goats, and other less common species also can have particular effects that might be different from those discussed. It is important to note that the effects discussed result from poorly managed grazing systems.

Figure 3.17: Livestock in stream. *Use of stream corridors by domestic livestock can result in extensive physical disturbance and bacteriological contamination.*

The primary impacts that result from grazing of domestic livestock are the loss of vegetative cover due to its consumption or trampling and streambank erosion from the presence of livestock (**Table 3.2**).

Loss of Vegetative Cover

Reduced vegetative cover can increase soil compaction and decrease the depth of and productivity of topsoil. Reduced cover of mid-story and overstory plants decreases shade and increases water temperatures, although this effect diminishes as stream width increases. Sediment from upland or streambank erosion can reduce water quality through increases in turbidity and attached chemicals. Where animal concentrations are large, fecal material can increase nutrient loads above standards and introduce bacteria and pathogens, although this is uncommon. Dissolved oxygen reductions can result from high temperature and nutrient-rich waters.

Extensive loss of ground cover in the watershed and stream corridor can decrease infiltration and increase runoff, leading to higher flood peaks and additional runoff volume. Where reduced cover increases overland flow and prevents infiltration, additional water may flow more rapidly into stream channels so that flow peaks come earlier rather than later in the runoff cycle, producing a more "flashy" stream system. Reductions in baseflow and increases in stormflow can result in a formerly perennial stream becoming intermittent or ephemeral.

Table 3.2: Livestock impacts on stream corridors.

Impact
Decreased plant vigor
Decreased biomass
Alteration of species composition and diversity
Reduction or elimination of woody species
Elevated surface runoff
Erosion and sediment delivery to streams
Streambank erosion and failure
Channel instability
Increased width to depth ratios
Degradation of aquatic species
Water quality degradation

References: Ames (1977); Knopf and Cannon (1982); Hansen et al. (1995); Kauffman and Kreuger (1984); Brooks et al. (1991); Platts (1979); MacDonald et al. (1991).

Increased sedimentation of channels can reduce channel capacity, increasing width/depth ratios, forcing water into streambanks, and inducing bank erosion. This leads to channel instability, causing other adjustments in the system. Similarly, excessive water reaching the system without additional sediment may cause channel degradation as increased stream energy erodes channel bottoms, incising the channel.

Physical Impacts from Livestock Presence

Trampling, trailing, and similar activities of livestock physically impact stream corridors. Impacts on soils are particularly dependent on soil moisture content, with compaction presenting a major concern. Effects vary markedly by soil type and moisture content. Very dry soils are seldom affected, while very wet soils may also be resistant to compaction. Moist soils are typically more subject to compaction damage. Very wet soils may be easily displaced, however. Adjusting grazing use to periods where soil moisture will minimize impacts will prevent many problems.

Compaction of soils by grazing animals can cause increased soil bulk density, reduced infiltration, and increased runoff. Loss of capillarity reduces the ability of water to move vertically and laterally in the soil profile. Reduced soil moisture content can reduce site capacity for riparian-dependent plant species and favor drier upland species.

Trailing can break down streambanks, causing bank failure and increasing sedimentation. Excessive trailing can result in gully formation and eventual channel extension and migration.

Unmanaged grazing can significantly change stream geomorphology. Bank instability and increased sedimentation can cause channel widening and increases in the width/depth ratio. Increased meandering may result, causing further instability. Erosion of fine materials into the system can change channel bottom composition and alter sediment transport relationships.

Excessive livestock use can cause breakage or other physical damage to streamside vegetation. Loss of bank-holding species and undercut banks can reduce habitat for fish and other aquatic species. Excessive sedimentation can result in filling of stream gravels with fine sediments, reducing the survival of some fish eggs and newly hatched fish due to lack of oxygen. Excessive stream temperatures can be detrimental to many critical fish species, as well as amphibians. Loss of preferred cover reduces habitat for riparian-dependent species, particularly birds.

Mining

Exploration, extraction, processing, and transportation of coal, minerals, sand and gravel, and other materials has had and continues to have a profound effect on stream corridors across the nation (**Figure 3.18**). Both surface mining and subsurface mining damage stream corridors. Surface mining methods include strip mining, open-pit operations, dredging, placer mining, and hydraulic mining. Although several of these methods are no longer commonly practiced today, many streams throughout the United States remain in a degraded condition as a result of mining activities that, in some cases, occurred more than a century ago. Such mining activity frequently resulted in total destruction of the stream corridor. In some cases today, mining operations still disturb most or all of entire watersheds.

Figure 3.18: Results of surface mining. *Many streams remain in a degraded condition as a result of mining activities.*

Vegetative Clearing

Mining can often remove large areas of vegetation at the mine site, transportation facilities, processing plant, tailings piles, and related activities. Reduced shade can increase water temperatures enough to harm aquatic species.

Loss of cover vegetation, poor-quality water, changes in food availability, disruption of migration patterns, and similar difficulties can have serious effects on terrestrial wildlife. Species composition may change significantly with a shift to more tolerant species. Numbers will likely drop as well. Mining holds few positive benefits for most wildlife species.

Soil Disturbance

Transportation, staging, loading, processing, and similar activities cause extensive changes to soils including loss of topsoils and soil compaction. Direct displacement for construction of facilities reduces the number of productive soil acres in the watershed. Covering of soil by materials such as tailings piles further reduces the acreage of productive soils. These activities decrease infiltration, increase runoff, accelerate erosion, and increase sedimentation.

Altered Hydrology

Changes to hydrologic conditions due to mining activity are extensive. Surface mining is, perhaps, the only land use with a greater capacity to change the hydrologic regime of a stream than urbanization. Increased runoff and decreased surface roughness will cause peaks earlier in the hydrograph with steeper rising and falling limbs. Once-perennial streams may become intermittent or ephemeral as baseflow decreases.

Changes in the quantity of water leaving a watershed are directly proportional to the amount of impervious surface or reduced infiltration in a watershed. Loss of topsoils, soil compaction, loss of vegetation, and related actions will decrease infiltration, increase runoff, increase stormflow, and decrease baseflows. Total water leaving the watershed may increase due to reduced in-soil storage.

Stream geomorphology can change dramatically, depending on the mining method used. Floating dredges and hydraulic mining with high-pressure hoses earlier in the century completely altered streamcourses. In many places virtually no trace of the original stream character exists today. Flow may run completely out of view into piles of mine tailings. Once-meandering streams may now be straight, gullied channels. Less extreme mining methods can also significantly alter stream form and function through steepening or lowering the gradient, adding high sediment loads, adding excessive water to the system, or removing water from the system.

Contaminants

Water and soils are contaminated by *acid mine drainage* (AMD) and the materials used in mining. AMD, formed from the oxidation of sulfide minerals like pyrite, is widespread. Many hard rock mines are located in iron sulfide deposits. Upon exposure to water and air, such deposits undergo sulfide oxidation with attendant release of iron, toxic metals (lead, copper, zinc), and excessive acidity. Mercury was often used to separate gold from the ore; therefore, mercury was also lost into streams. Present-day miners using suction dredges often find considerable quantities of mercury still resident in streambeds. Current heap-leaching methods use cyanide to extract gold from low-quality ores. This poses a special risk if operations are not carefully managed.

Toxic runoff or precipitates can kill streamside vegetation or can cause a shift to species more tolerant of mining conditions. This affects habitat required by many species for cover, food, and reproduction.

Aquatic habitat suffers from several factors. Acid mine drainage can coat stream bottoms with iron precipitates, thereby affecting the habitat for bottom-dwelling and feeding organisms. AMD also adds sulfuric acid to the water, killing aquatic life. The low pH alone can be toxic, and most metals exhibit higher solubility and more bioavailability under acidic conditions. Precipitates coating the stream bottom can eliminate places for egg survival. Fish that do hatch may face hostile stream conditions due to poor water quality, loss of cover, and limited food base.

Floating dredges and hydraulic mining with high-pressure hoses earlier in the century completely altered streamcourses.

Recreation

The amount of impact caused by recreation depends on soil type, vegetation cover, topography, and intensity of use. Various forms of foot and vehicular traffic associated with recreational activities can damage riparian vegetation and soil structure. All-terrain vehicles, for example, can cause increased erosion and habitat reduction. At locations heavily used by hikers and tourists, reduced infiltration due to soil compaction and subsequent surface runoff can result in increased sediment loading to the stream (Cole and Marion 1988). Widening of the stream channel can occur where hiking trails cross the stream or where intensive use destroys bank vegetation (**Figure 3.19**).

In areas where the stream can support recreational boating, the system is vulnerable to additional impacts (**Figure**

Figure 3.19: Trail sign. *Recreational hiking can cause soil compaction and increased surface runoff.*

3.20). Propeller wash and water displacement can disrupt and resuspend bottom sediments, increase bank erosion, and disorient or injure sensitive aquatic species. In addition, waste discharges or accidental spills from boats or loading facilities can contribute pollutants to the system (NRC 1992).

Both concentrated and dispersed recreational use of stream corridors can cause disturbance and ecological change. Camping, hunting, fishing, boating, and other forms of recreation can cause serious disturbances to bird colonies. Ecological damage primarily results from the need for access for the recreational user. A pool in the stream might be the attraction for a swimmer or fisherman, whereas a low streambank might provide an access point for boaters. In either case, a trail often develops along the shortest or easiest route to the point of access on the stream. Additional impact may be a function of the mode of access to the stream: motorcycles and horses cause far more damage to vegetation and trails than do pedestrians.

Urbanization

Urbanization in watersheds poses special challenges to the stream restoration practitioner. Recent research has shown that streams in urban watersheds have a character fundamentally different from that of streams in forested, rural, or even agricultural watersheds. The amount of impervious cover in the watershed can be used as an indicator to predict how severe these differences can be. In many regions of the country, as little as 10 percent watershed impervious cover has been linked to stream degradation, with the degradation becoming more severe as impervious cover increases (Schueler 1995).

Impervious cover directly influences urban streams by dramatically increasing surface runoff during storm events (**Figure 3.21**). Depending on the degree of watershed impervious cover, the

Figure 3.20: Recreational boating. *Propeller wash and accidental spills can degrade stream conditions.*

annual volume of storm water runoff can increase by 2 to 16 times its predevelopment rate, with proportional reductions in ground water recharge (Schueler 1995).

The unique character of urban streams often requires unique restoration strategies for the stream corridor. For example, the practitioner must seriously consider the degree of upland development that has occurred or is projected to occur. In most projects, it is advisable or even necessary to investigate whether upstream detention or retention can be provided within the watershed to at least partially restore the predevelopment hydrologic regime.

Some of the key changes in urban streams that merit special attention from the stream restoration practitioner are discussed in the following subsections.

Altered Hydrology

The peak discharge associated with the bankfull flow (i.e., the 1.5- to 2-year return storm) increases sharply in magnitude in urban streams. In addition, channels experience more bankfull flood events each year and are exposed to critical erosive velocities for longer

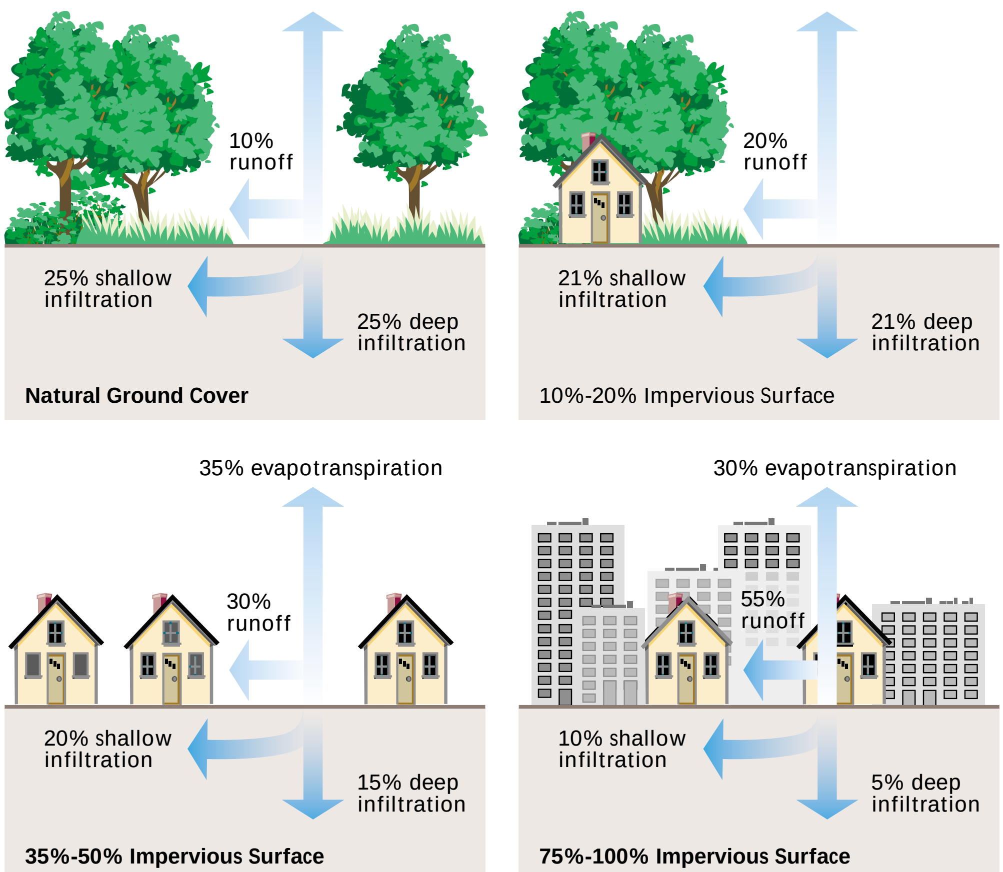


Figure 3.21: Relationship between impervious cover and surface runoff. *Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious cover in a watershed can result in stream degradation.*

intervals (Hollis 1975, Macrae 1996, Booth and Jackson 1997).

Since impervious cover prevents rainfall from infiltrating into the soil, less flow is available to recharge ground water. Consequently, during extended periods without rainfall, baseflow levels are often reduced in urban streams (Simmons and Reynolds 1982).

Altered Channels

The hydrologic regime that had defined the geometry of the predevelopment stream channel irreversibly changes toward higher flow rates on a more frequent basis. The higher flow events of urban streams are capable of performing more "effective work" in moving sediment than they had done before (Wolman 1964).

The customary response of urban streams is to increase their cross-sectional area to accommodate the higher flows. This is done by streambed downcutting or streambank widening, or a combination of both. Urban stream channels often enlarge their cross-sectional areas by a factor of 2 to 5, depending on the degree of impervious cover in the upland watershed and the age of development (Arnold et al. 1982, Gregory et al. 1992, and Macrae 1996).

Stream channels react to urbanization not only by adjusting their widths and depths, but also by changing their gradients and meanders (Riley 1998).

Urban stream channels are also extensively modified in an effort to protect adjacent property from streambank erosion or flooding (**Figure 3.22**). Headwater streams are frequently enclosed within storm drains, while others are channelized, lined, or armored by heavy stone. Another modification unique to urban streams is the installation of sanitary sewers underneath or parallel to the stream channel.

The wetted perimeter of a stream is the proportion of the total cross-sectional area of the channel that is covered by flowing water during dry-weather periods. It is an important indicator of habitat degradation in urban streams. Given that urban streams develop a larger channel cross section at the same time that their baseflow rates decline, it necessarily follows that the wetted perimeter will become smaller. Thus, for many urban streams, this results in a very shallow, low-flow channel that wanders across a very wide streambed, often changing its lateral position in response to storms.

Sedimentation and Contaminants

The prodigious rate of channel erosion in urban streams, coupled with sediment erosion from active construction sites, increases sediment discharge to urban streams. Researchers have documented that channel erosion constitutes as much as 75 percent the total sediment budget of urban streams (Crawford and Lenat 1989, Trimble 1997). Urban streams also tend to have a higher sediment discharge than

Figure 3.22: Urban stream channel modifications. *Channel armoring often prevents streams from accommodating hydrologic changes that result from urbanization.*

nonurban streams, at least during the initial period of active channel enlargement.

The water quality of urban streams during storm events is consistently poor. Urban storm water runoff contains moderate to high concentrations of sediment, carbon, nutrients, trace metals, hydrocarbons, chlorides, and bacteria (Schueler 1987) (**Figure 3.23**). Although considerable debate exists as to whether storm water pollutant concentrations are actually toxic to aquatic organisms, researchers agree that pollutants deposited in streambeds exert undesirable impacts on stream communities.

Figure 3.23: Water quality in urban streams. *Surface runoff carries numerous pollutants to urban streams, resulting in consistently poor water quality.*
Source: C. Zabawa.

Habitat and Aquatic Life

Urban streams are routinely scored as having poor instream habitat quality, regardless of the specific metric or method employed. Habitat degradation is often exemplified by loss of pool and riffle structure, embedding of streambed sediments, shallow depths of flow, eroding and unstable banks, and frequent streambed turnover.

Large woody debris (LWD) is an important structural component of many low-order streams systems, creating complex habitat structure and generally making the stream more retentive. In urban streams, the quantity of LWD found in stream channels is reduced due to the loss of riparian forest cover, storm washout, and channel maintenance practices (Booth et al. 1996, May et al. 1997).

Many forms of urban development are linear in nature (e.g., roads, sewers, and pipelines) and cross stream channels. The number of stream crossings increases directly in proportion to impervious cover (May et al. 1997), and many crossings can become partial or total barriers to upstream fish migration, particularly if the streambed erodes below the fixed elevation of a culvert or a pipeline.

The important role that riparian forests play in stream ecology is often diminished in urban watersheds since tree cover is often partially or totally removed along the stream as a consequence of development (May et al. 1997) (**Figure 3.24**). Even when stream buffers are reserved, encroachment often reduces their effective width and native species are supplanted by exotic trees, vines, and ground covers.

The impervious surfaces, ponds, and poor riparian cover in urban watersheds can increase mean summer stream temperatures by 2 to 10 degrees Fahrenheit (Galli 1991). Since temperature plays a central role in the rate and timing of biotic and abiotic reactions in stream, such increases have an adverse impact on streams. In some regions, summer stream warming can irreversibly shift a cold-water stream to

Figure 3.24: Stream corridor encroachment. *Stream ecology is disturbed when riparian forests are removed for development.*

a cool-water or even warm-water stream, with deleterious effects on salmonoids and other temperature-sensitive organisms.

Urban streams are typified by fair to poor fish and macroinvertebrate diversity, even at relatively low levels of watershed impervious cover or population density (Schueler 1995, Shaver et al. 1995, Couch 1997, May et al. 1997). The ability to restore predevelopment fish assemblages or aquatic diversity is constrained by a host of factors—irreversible changes in carbon supply, temperature, hydrology, lack of instream habitat structure, and barriers that limit natural recolonization.

Summary of Potential Effects of Land Use Activities

Table 3.3 presents a summary of the disturbance activities associated with major land uses and their potential for changing stream corridor functions. Many of the potential effects of disturbance are cumulative or synergistic. Restoration might not remove all disturbance factors; however, addressing one or two disturbance activities can dramatically reduce the impact of those remaining. Simple changes in management, such as the use of conservation buffer strips in cropland or managed livestock access to riparian areas, can substantially overcome undesired cumulative effects or synergistic interactions.

Table 3.3: Potential effects of major land use activities.

	Disturbance Activities																					
Potential Effects	Vegetative Clearing	Channelization	Streambank Armoring	Streambed Disturbance	Withdrawal of Water	Dams	Levees	Soil Exposure or Compaction	Irrigation and Drainage	Contaminants	Hard Surfacing	Overgrazing	Roads and Railroads	Trails	Exotic Species	Utility Crossings	Reduction of Floodplain	Dredging for Mineral Extract.	Land Grading	Bridges	Woody Debris Removal	Piped Discharge/Cont.Outlets
Homogenization of landscape elements	■	■	□	□	□	□	□	□	■	□	□	■	□	□	■	□	■	■	■	□	□	□
Point source pollution	□	□	□	□	□	■	□	□	□	■	■	■	■	□	□	■	□	■	□	□	□	■
Nonpoint source pollution	■	■	□	■	□	□	■	□	■	■	■	■	■	■	□	■	□	■	■	□	■	■
Dense compacted soil	■	□	■	□	□	■	■	■	□	□	■	■	■	■	□	■	■	■	■	□	□	□
Increased upland surface runoff	■	□	□	□	□	□	□	■	■	□	■	■	■	■	□	□	□	□	■	□	□	□
Increased sheetflow w/surface erosion rill and gully flow	■	□	□	□	□	□	□	■	■	□	■	■	■	■	□	□	□	□	■	□	□	□
Increased levels of fine sediment and contaminants in stream corridor	■	■	□	■	□	■	■	■	■	■	■	■	■	■	□	■	■	■	■	■	■	■
Increased soil salinity	□	□	□	□	■	□	□	□	■	■	■	□	■	□	□	□	□	□	□	□	□	□
Increased peak flood elevation	■	■	□	□	□	■	■	■	■	□	■	■	■	□	□	□	■	□	□	□	□	■
Increased flood energy	■	■	■	■	□	□	■	■	■	□	■	■	■	□	□	□	■	□	□	□	■	■
Decreased infiltration of surface runoff	■	□	■	□	□	□	□	■	■	□	■	■	■	■	□	□	□	□	■	□	□	■
Decreased interflow and subsurface flow	■	■	■	□	□	□	□	■	□	■	□	□	□	□	□	□	□	□	■	□	□	■
Reduced ground water recharge and aquifer volumes	■	□	□	□	■	■	■	■	■	□	■	■	■	□	□	□	■	■	□	□	■	■
Increased depth to ground water	■	■	□	□	■	■	■	■	■	□	■	■	■	□	□	□	■	■	■	□	□	□
Decreased ground water inflow to stream	■	■	■	□	■	□	■	■	■	□	■	■	■	□	□	□	■	■	■	□	□	■
Increased flow velocities	■	■	■	■	□	■	■	■	■	□	■	■	■	□	□	□	■	■	■	□	■	■
Reduced stream meander	□	■	■	■	□	■	■	□	□	□	■	□	□	□	□	□	■	□	■	□	■	■
Increased or decreased stream stability	■	■	■	■	■	■	■	■	□	□	■	■	■	□	□	□	■	■	■	■	■	■
Increased stream migration	■	□	□	■	□	□	□	■	□	□	■	■	■	□	□	□	■	■	□	□	■	■
Channel widening and downcutting	■	■	■	■	■	■	■	□	□	□	■	■	■	□	□	□	■	■	□	■	■	■
Increased stream gradient and reduced energy dissipation	□	■	■	■	■	■	■	□	□	□	□	□	□	□	□	□	■	■	□	□	■	■
Increased or decreased flow frequency	■	□	□	□	■	■	■	■	■	□	■	■	■	□	□	□	■	□	■	□	□	■
Reduced flow duration	■	■	■	■	■	□	■	■	■	□	■	■	■	□	□	□	■	□	□	□	■	■
Decreased capacity of floodplain and upland to accumulate, store, and filter materials and energy	■	□	□	□	□	□	■	■	■	■	■	■	■	■	□	□	■	■	■	□	■	■
Increased levels of sediment and contaminants reaching stream	■	■	■	■	□	□	□	□	■	■	■	■	■	□	□	■	□	■	■	■	■	■
Decreased capacity of stream to accumulate and store or filter materials and energy	□	■	■	■	□	□	■	□	□	■	□	□	□	□	□	□	□	■	□	□	■	■
Reduced stream capacity to assimilate nutrients/pesticides	■	■	■	■	■	■	■	■	■	■	■	■	□	□	□	□	■	■	□	□	■	■
Confined stream channel w/little opportunity for habitat development	□	■	■	■	□	□	■	□	□	□	□	□	□	□	□	□	■	□	□	□	□	□

■ Activity has potential for direct impact.

□ Activity has potential for indirect impact.

Table 3.3: Potential effects of major land use activities (continued)

Potential Effects	Vegetative Clearing	Channelization	Streambank Armoring	Streambed Disturbance	Withdrawal of Water	Dams	Levees	Soil Exposure or Compaction	Irrigation and Drainage	Contaminants	Hard Surfacing	Overgrazing	Roads and Railroads	Trails	Exotic Species	Utility Crossings	Reduction of Floodplain	Dredging for Mineral Extract.	Land Grading	Bridges	Woody Debris Removal	Piped Discharge/Cont.Outlets
Increased streambank erosion and channel scour	■	■	□	■	□	■	■	■	□	□	□	■	□	□	□	□	□	■	□	□	■	■
Increased bank failure	■	■	□	■	■	■	■	■	□	□	□	■	□	□	□	□	□	■	□	□	■	■
Loss of instream organic matter and related decomposition	■	■	■	■	□	■	■	□	□	□	□	■	□	□	□	□	■	■	□	□	■	□
Increased instream sediment, salinity, and turbidity	■	■	□	■	□	■	■	□	■	■	■	■	■	■	□	■	■	■	■	□	■	■
Increased instream nutrient enrichment, siltation, and contaminants leading to eutrophication	■	□	□	■	□	■	■	■	■	■	■	■	■	□	□	■	■	■	□	□	■	■
Highly fragmented stream corridor with reduced linear distribution of habitat and edge effect	■	■	■	□	■	■	□	□	□	□	■	■	□	□	□	□	■	■	■	■	■	□
Loss of edge and interior habitat	■	■	■	■	□	□	■	□	□	□	■	■	■	□	■	□	■	■	■	□	■	□
Decreased connectivity and width within the corridor and to associated ecosystems	■	■	■	■	□	■	■	□	□	□	■	■	■	■	■	■	■	■	■	■	□	□
Decreased movement of flora and fauna species for seasonal migration, dispersal, and population	■	■	■	■	■	■	■	□	□	□	■	■	■	■	■	■	■	■	■	■	□	□
Increase of opportunistic species, predators, and parasites	■	■	■	□	□	■	■	□	□	■	□	■	□	■	■	■	□	□	□	□	■	■
Increased exposure to solar radiation, weather, and temperature extremes	■	■	■	■	■	□	■	■	□	□	■	■	■	■	□	■	■	■	■	□	■	□
Magnified temperature and moisture extremes throughout the corridor	■	□	□	□	□	□	■	■	□	□	■	■	□	□	□	□	□	□	□	□	□	□
Loss of riparian vegetation	■	■	■	■	■	■	■	■	□	□	□	■	■	■	■	■	■	■	□	■	■	□
Decreased source of instream shade, detritus, food, and cover	■	■	■	■	■	□	■	□	□	□	□	□	□	□	□	□	□	■	□	□	■	□
Loss of vegetative composition, structure, and height diversity	■	■	■	□	■	□	■	□	■	□	■	■	■	□	■	□	■	■	□	□	□	□
Increased water temperature	■	■	■	■	■	■	■	□	□	□	■	■	□	□	□	□	■	■	□	□	■	□
Impaired aquatic habitat diversity	■	■	■	■	■	■	■	□	■	■	■	■	□	□	■	□	■	■	□	□	■	■
Reduced invertebrate population in stream	■	■	■	■	■	■	■	□	■	■	■	■	□	□	■	□	■	■	□	□	■	■
Loss of associated wetland function including water storage, sediment trapping, recharge, and habitat	□	■	□	■	■	■	■	□	■	□	■	■	■	□	■	□	■	■	■	□	□	□
Reduced instream oxygen concentration	■	■	■	■	■	■	■	□	□	□	■	■	□	□	□	□	■	■	□	□	■	■
Invasion of exotic species	■	■	■	■	■	□	■	□	□	□	□	■	□	□	■	□	■	□	□	□	□	■
Reduced gene pool of native species for dispersal and colonization	■	■	■	■	■	□	■	□	□	□	□	■	□	□	■	□	■	□	□	□	■	□
Reduced species diversity and biomass	■	■	■	■	■	□	■	■	■	□	■	■	□	□	■	□	■	□	□	□	■	□

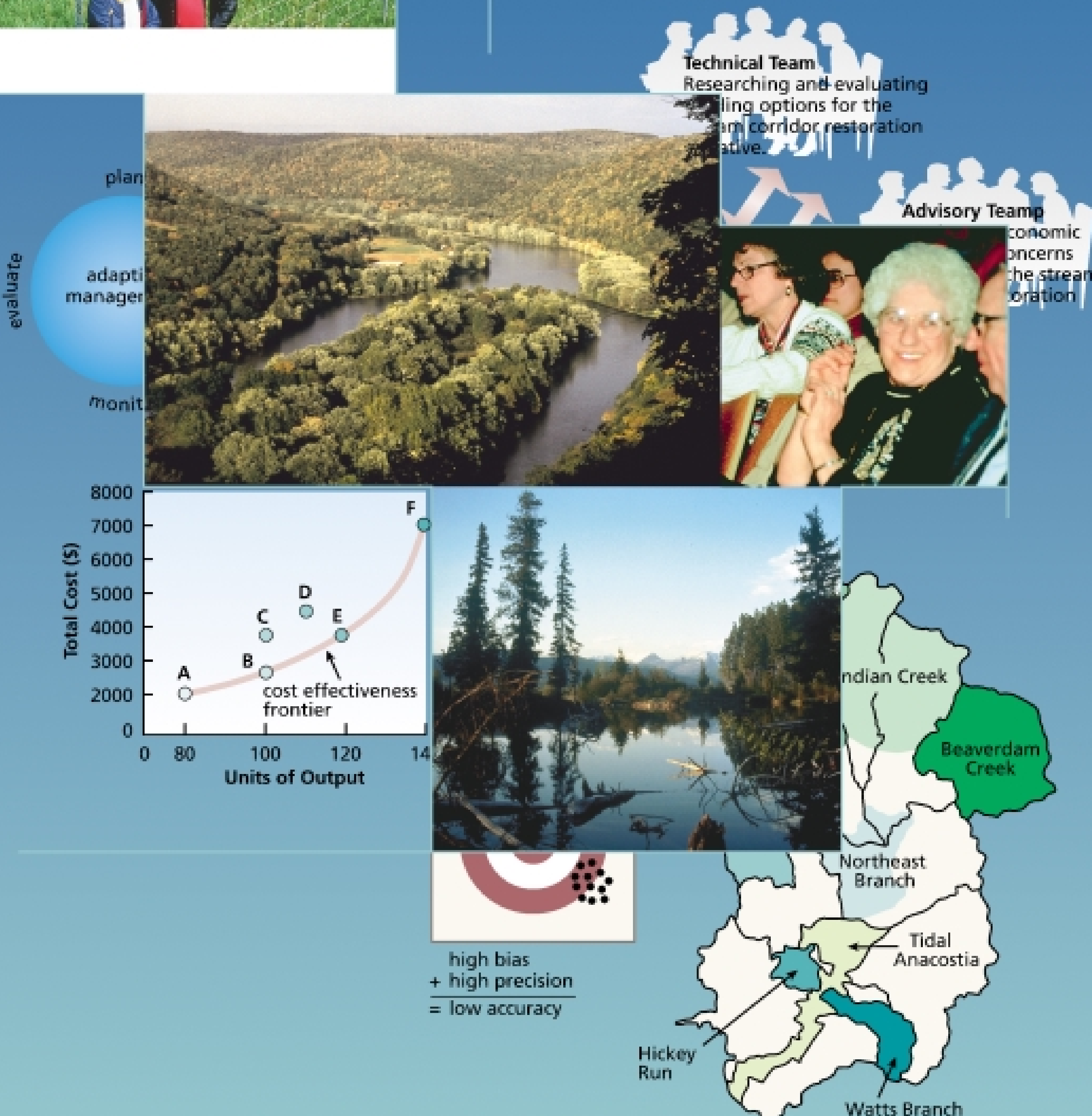
(Column group heading: Disturbance Activities)

■ Activity has potential for direct impact.

□ Activity has potential for indirect impact.

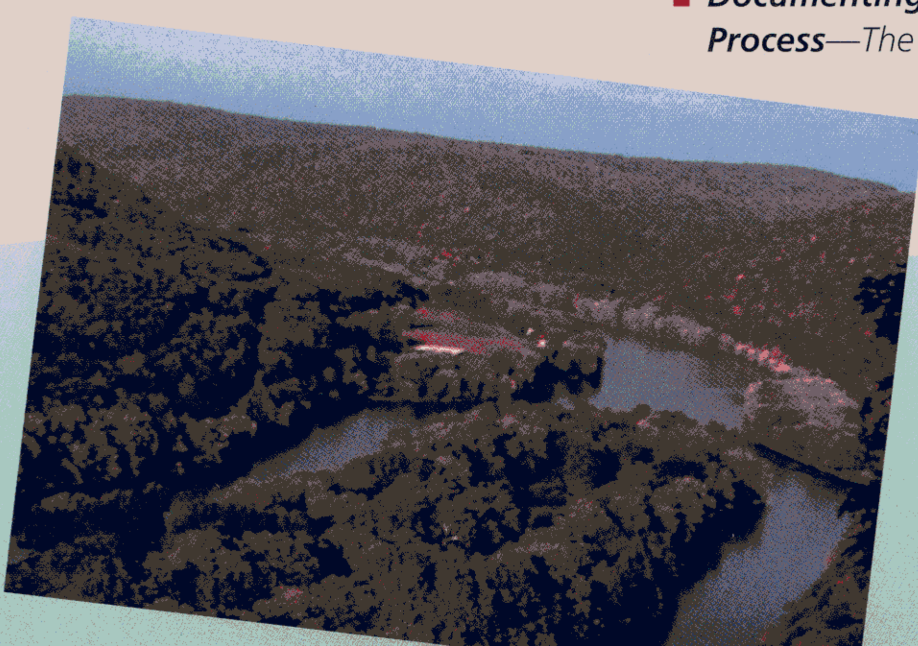
Part II

Developing A Restoration Plan



II Developing a Stream Corridor Restoration Plan

A well conceived and developed stream corridor restoration plan is critical to any restoration effort. The restoration plan establishes a framework for documenting the processes, forms, and functions operating within the corridor, identifying disturbances that disrupt or eliminate those functions, and planning and implementing restoration activities. The restoration plan essentially serves as the cornerstone of the restoration effort by achieving several key functions.



- ***Problem Solving Framework**—The restoration plan establishes a framework for addressing critical stream corridor restoration issues, problems, and needs. As such, it prevents disjointed decision-making and facilitates the organization of restoration activities.*
- ***Documenting the Results of the Process**—The restoration plan serves as a record of all subsequent activities by outlining the restoration process. As a result, the plan enables*

the transfer of "lessons learned" to other groups undertaking restoration efforts and helps legitimize the restoration process.

- ***Communication and Outreach***—*The restoration plan serves to communicate the elements of the corridor restoration process to the public and other interested parties. It also serves an important symbolic function in that it represents the common vision of multiple partners.*

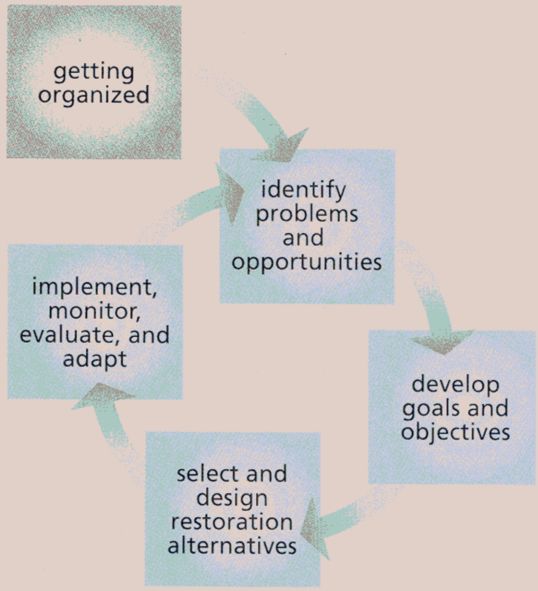
The overall objective of the restoration plan will differ depending on local needs and objectives. Each corridor restoration initiative has unique ecological, social, and economic conditions that dictate activities to meet specific needs and changing circumstances. Despite these differences, the restoration plan should emphasize the ecological integrity of the stream corridor.

A Note About Scope

Although the concepts presented in these chapters are appropriate for all restoration initiatives, the organizational structure can be simplified for smaller restorations.

Not all restorations are complex or costly. Some may be as simple as a slight change in the way that resources are managed in and along the stream corridor involving only minor costs. Other restoration initiatives, however, may require substantial funds because of the complexity and extent of the measures needed to achieve the planned restoration goals.

The restoration plan should emphasize the maintenance and restoration of the ecological integrity and the dynamic stability of the stream corridor by focusing on multiple scales, functions, and values.



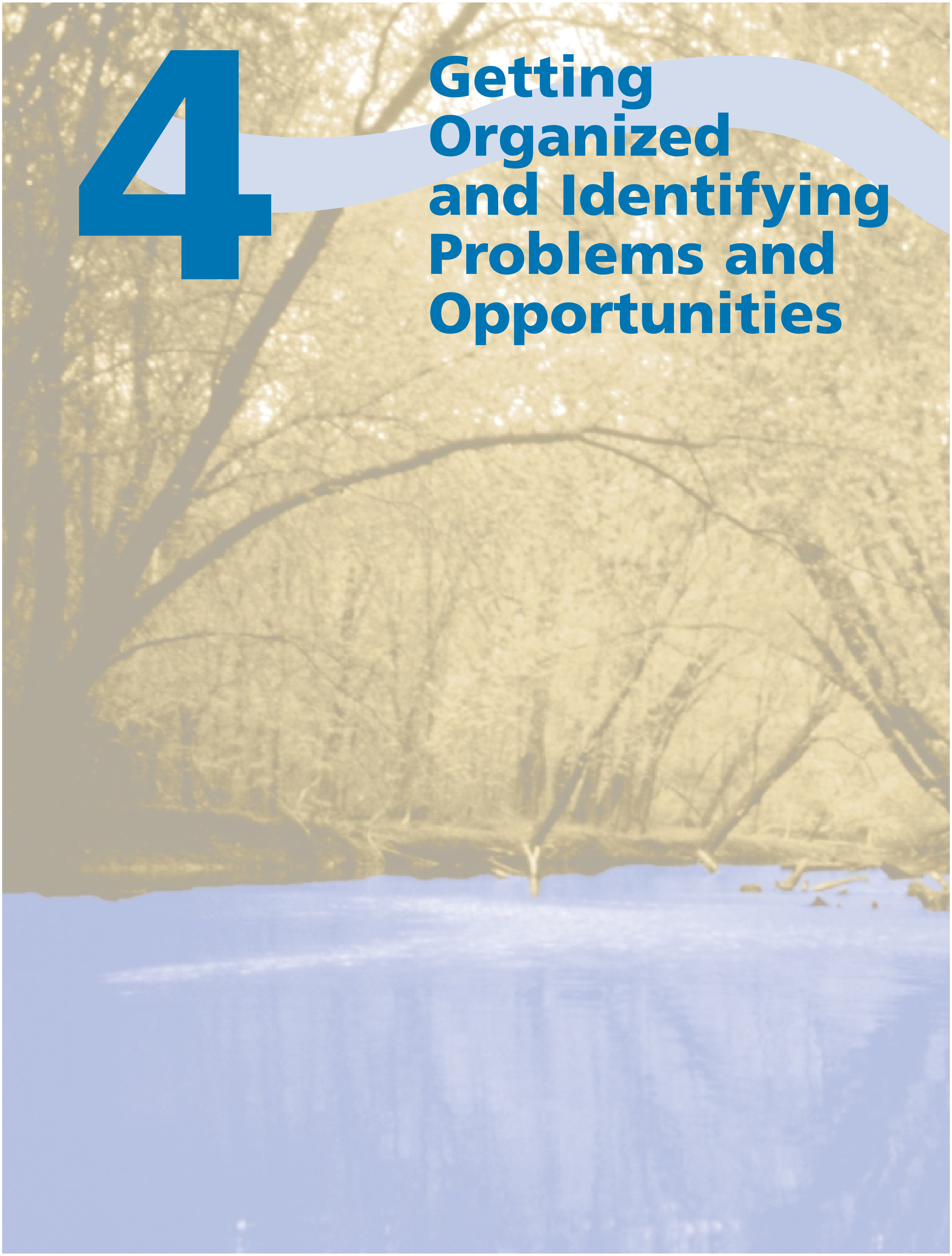
The Stream Corridor Restoration Plan Development Process

In recognition of the diversity of restoration plan objectives, Part II of the document focuses on identifying and explaining a general restoration plan development process that each initiative should follow. This process is characterized as a decision-making process composed of several steps (see illustration). These fundamental steps include: getting organized; identifying problems and opportunities; developing goals and objectives; selecting and designing restoration alternatives; and implementation, monitoring, evaluation, and adaptation.

Each of these steps can be integrated into any program- or agency-specific restoration planning process. In addition, these steps *should not be viewed as sequential, but iterative in nature. Many of the fundamental steps may be repeated or may occur simultaneously. In addition, the process, which is based on the philosophy of adaptive management, should be flexible enough to adjust management actions and directions in light of new information about the corridor and about progress toward restoration objectives.*

Part II consists of three chapters and is organized in accordance with the fundamental steps of the restoration plan development process.

- ***Chapter 4*** *introduces the first two steps of plan development. The first portion of the chapter focuses on the basics of getting organized and presents key steps that should be undertaken to initiate the restoration process. The remainder of the chapter centers on problem/opportunity identification and introduces the basics of stream corridor condition analysis and problem assessment.*
- ***Chapter 5*** *presents information concerning how restoration goals and objectives are identified and how alternatives are designed and selected.*
- ***Chapter 6*** *concludes with a discussion of implementation of restoration as well as monitoring and evaluation.*



4 Getting Organized and Identifying Problems and Opportunities

4.A Getting Organized

- *Why is planning important?*
- *Is an Advisory Group needed?*
- *How is an Advisory Group formed?*
- *Who should be on an Advisory Group?*
- *How can funding be identified and acquired?*
- *How are technical teams established and what are their roles?*
- *What procedures should an Advisory Group follow?*
- *How is communication facilitated among affected stakeholders?*

4.B Problem and Opportunity Identification

- *Why is it important to spend resources on the problem ("When everyone already knows what the problem is")?*
- *How can the anthropogenic changes that caused the need for the restoration initiative be altered or removed?*
- *How are data collection and analysis procedures organized?*
- *How are problems affecting the stream corridor identified?*
- *How are reference conditions for the stream corridor determined?*
- *Why are reference conditions needed?*
- *How are existing management activities influencing the stream corridor?*
- *How are problems affecting the stream corridor described?*

4 Getting Organized and Identifying Problems and Opportunities

The impetus for a restoration initiative may come from several sources. The realization that a problem or opportunity exists in a stream corridor may warrant community action and any number of interested groups, and individuals may be actively involved in recognizing the situation and initiating the restoration effort. Federal or state agencies may be designated to undertake a corridor restoration effort as a result of a legislative mandate or an internal agency directive. Citizen groups or groups with special cultural or economic interests in the corridor (e.g., native tribes, sport fishermen) may also initiate a restoration effort. Still others might undertake stream corridor restoration as part of a broad-based cooperative initiative that draws from various funding sources and addresses a diversity of interests and objectives.

Accompanying the recognition of the situation and initiation of the restoration effort is the initial proposal of "the solution." This almost instantaneous leap from problem/opportunity recognition to the identification of the initial "solution" occurs during the formative stage of nearly every initiative involving water and multiple landowners. This instantaneous leap might not always address the true causes of the problem or identified opportunity and therefore might not result in a *successful restoration initiative. Projects that come through a logical process of plan development tend to be more successful.*

Regardless of the origins of the restoration initiative or the introduction of the proposed "solution," it is essential that the focus of the leadership for the restoration planning process be at the local level; i.e., the people who are pushing for action, who own the land, who are affected, who might benefit, who can make decisions, or who can lead. With this local leadership in place, a logical, iterative restoration plan development process can be undertaken. Often, this approach will involve going back to the identification of the problem or opportunity and realizing that the situation is not as simple as initially perceived and needs further definition and refinement.

This chapter concentrates on the two initial steps of stream corridor restoration plan development—getting organized and problem/opportunity identification. The chapter is divided into two sections and includes a discussion of the core components of each of these initial steps.

Section 4.A: Getting Organized

This section outlines some of the organizational considerations that should be taken into account when conducting stream corridor restoration.

Section 4.B: Problem and Opportunity Identification

Once some of the organizational logistics have been settled, the disturbances affecting the stream corridor ecosystem and the resulting problems/opportunities need to be identified. Section B outlines the core components of the problem/opportunity identification process. One of the most common mistakes made in planning restorations is the failure to characterize the nature of the problems to be solved and when, where, and exactly how they affect the stream corridor.

4.A Getting Organized

This section presents the key components of organizing and initiating the development of a stream corridor restoration plan and establishing a planning and management framework to facilitate communication among all involved and interested parties. Ensuring the involvement of all partners and beginning to secure their commitment to the project is a central aspect of "getting organized" and undertaking a restoration initiative. (See Chapter 6 for detailed information on securing commitments.) It is often helpful to identify a common motivation for taking action and also to develop a rough outline of restoration goals. In addition, defining the scale of the corridor restoration initiative is important. Often the issues to be addressed require that restoration be considered on a watershed or whole-reach basis, rather than by an individual jurisdiction or one or two landholders.

Setting Boundaries

Geographical boundaries provide a spatial context for technical assessment and a sense of place for organizing community-based involvement. An established set of project boundaries streamlines the process of gathering, organizing, and depicting information for decision making.

When boundaries are selected, the area should reflect relevant ecological processes. The boundaries may also reflect the various scales at which ecological processes influence stream corridors (see Chapter 5, *Identifying Scale Considerations*). For example, matters affecting the conservation of biodiversity tend to play out at broader, more regional scales. On the other hand, the quality of drinking water is usually more of a basin-specific or local-scale issue.

In setting boundaries, two other factors are equally as important. One is the nature of human-induced disturbance, including the magnitude of its impact on stream corridors. The other factor is the social organization of people, including where opportunities for action are distributed across the landscape.

The challenge of establishing useful boundaries is met by conceptually superimposing the three selection factors. One effective way of starting this process is through the identification, by public forum or other free and open means, of a stream reach or aquatic resource area that is particularly valued by the community. The scoping process would continue by having resource managers or landowners define the geographical area that contributes to both the function and condition of the valued site or sites. Those boundaries

FAST FORWARD

REVERSE

Review Chapter 1. Preview Chapter 5's Identifying Scale Considerations.

Core Components of Getting Organized

- *Setting boundaries*
- *Forming an advisory group*
- *Establishing technical teams*
- *Identifying funding sources*
- *Establishing points of contact and a decision structure*
- *Facilitating involvement and information sharing among participants*
- *Documenting the process*

would then be further adjusted to reflect community interests and goals.

Forming an Advisory Group

Central to the development of a stream corridor restoration plan is the formation of an *advisory group* (**Figure 4.1**). An advisory group is defined as a collection of key participants, including private citizens, public interest groups, economic interests, public officials, and any other groups or individuals who are interested in or might be affected by the restoration initiative. Grassroots citizen groups comprise multiple interests that hopefully share a stated common concern for environmental conservation. Such broad-based participation helps ensure that self-interest or agency agendas do not drive the process from the top down. Local citizens should be enlisted and informed to the extent that their values and preferences drive decision making with technical guidance from agency participants.

Forming an advisory group is an effective and efficient way to plan and manage the restoration effort, although not all restoration decision makers will choose to establish one.

Figure 4.1: Advisory group meeting. *The advisory group, composed of a variety of community interests, plays an active role in advising the decision maker(s) throughout the restoration process.*
Source: S. Ratcliffe. Reprinted by permission.

The advisory group generally meets for the following purposes:

- Carrying out restoration planning activities.
- Coordinating plan implementation.
- Identifying the public's interest in the restoration effort.
- Making diverse viewpoints and objectives known to decision makers.
- Ensuring that local values are taken into account during the restoration process.

The point to remember is that the true role of the advisory group is to advise the *decision maker* or *sponsor*—the agency(s), organization(s), or individual(s) leading and initiating the restoration effort—on the development of the restoration plan and execution of restoration activities. Although the advisory group will play an active planning and coordinating role, it will not make the final decisions. As a result, it is important that all members of the advisory group understand the issues, develop practical and well thought-out recommendations, and achieve consensus in support of their recommendations.

Typically, it is the responsibility of the decision maker(s) to identify and organize the members of the advisory group. Critical to this process is the identification of the key participants. Participants can be identified by making announcements to the news media, writing to interested organizations, making public appearances, or directly contacting potential partners.

The exact number of groups or individuals that will compose the advisory group is difficult to determine and is usually situation-specific. In general, it is important that the group not be so small that it is not representative of all interests. Exclusion of certain community interests can undermine the legitimacy of or even halt the restoration initiative. Conversely, a large group might include so many interests that organization and consensus building become unmanageable. Include a balance of representative interests such as the following:

- Private citizens
- Public interest groups
- Public officials
- Economic interests

It is important to note that while forming an advisory group is an effective and efficient way to plan and manage the restoration effort, not all restoration decision makers will choose to establish one. There might be cases where a landowner or small group of landowners elect to take on all of the responsibilities of the advisory group in addition to playing a leadership or decision-making role.

Regardless of the number of individuals involved, it is important for all project participants (and funders) to note at this early stage that the usual duration of projects is 2 to 3 years. There are no guarantees that every project will be a success, and in some cases a project may fail simply due to lack of time to allow nature to "heal itself" and restoration methods to take effect. All participants must be reminded up front to set realistic expectations for the project and for themselves.

Establishing Technical Teams

Planning and implementing restoration work requires a high level of knowledge, skill, and ability, as well as professional judgment. Often, the advisory group will find it necessary to establish special technical teams, or subcommittees, to provide more information on a particular issue or subject.

In general, interdisciplinary technical teams should be organized to draw upon the knowledge and skills of different agencies, organizations, and individuals. These teams can provide continuity as well as important information and insight from varied disciplines, experiences, and backgrounds.

The expertise of an experienced multidisciplinary team is essential. No single text, manual, or training course can provide the technical background and judgment needed to plan, design, and implement stream corridor restoration. A team with a broad technical background is needed and should include expertise in both engineering and biological disciplines, particularly in aquatic and terrestrial ecology, hydrology, hydraulics, geomorphology, and sediment transport.

Team members should represent interagency, public, and private interests and include major partners, especially if they are sharing costs or work on the restoration initiative. Team makeup is based on the type of task the team is assembled to undertake. Members of the technical teams can also be members of the advisory committee or even the decision-making body.

Some of the technical teams that could be formed to assist in the restoration initiative will have responsibilities such as these:

- Soliciting financial support for the restoration work.
- Coordinating public outreach.
- Providing scientific support for the restoration work. This support may encompass anything from conducting the baseline condition analysis to designing and implementing restoration measures and monitoring.

CASE STUDY

Lower Missouri River Coordinated Resource Management Efforts in Northeast Montana

The Lower Missouri River Coordinated Resource Management (CRM) Council is an outgrowth of the Lower Fort Peck Missouri River Development Group, which was formed in September 1990 as a result of an irrigation and rural development meeting held in Poplar, Montana. The meeting was held to determine the degree of interest in economic and irrigation development along the Missouri River below Fort Peck Dam.

A major blockade to development seemed to be the erosion problems along the river. The Roosevelt County Conservation District and other local leaders decided that before developing irrigation along the river, streambank erosion needed to be addressed.

*The large fluctuation of the water being released from Missouri River dams is causing changes in the downstream river dynamics, channel, and streambanks. Before the dams, the river carried a sediment load based on the time of the year and flow event. Under natural conditions, a river system matures and tries to be in equilibrium by transporting and depositing sediment. Today, below the dams, the water is much cleaner because the sediment has settled behind the dams (**Figure 4.2**). The clean water releases have changed the river system from what it was prior to the dams. The clean water now picks up sediment in the river and attacks the streambanks, while trying to reach equilibrium. These probable causes and a river system out of equilibrium could be part of the cause of the river erosion.*

Figure 4.2: Lower Missouri River. *Water released from dams is causing downstream erosion.*

Leaders in the group are politically active, traveling to Washington, D.C., and meeting with congressional delegates and the US Army Corps of Engineers (USACE) to secure funding to address streambank erosion. As a result of the trips to Washington, $3 million was appropriated and transferred to the USACE for streambank erosion abatement. However, efforts to agree on a mutually beneficial solution continued to delay the progress. The USACE had completed an economic analysis of the area, and the only viable alternative it could offer was sloughing easements. This would do little to save the valuable soils along the Missouri River.

The group seemed to be at a stalemate. In July 1994, then Chief of the Natural Resources Conservation Service (NRCS), Paul Johnson, met with the members of the Lower Fort Peck Missouri River Development Group, local landowners, surrounding Conservation District members, NRCS field office staff, and Bill Miller, Project Manager for the Omaha District of the USACE, at an erosion site along the Missouri River. After sharing of ideas and information, Chief Johnson suggested that a Coordinated Resource Management (CRM) group be formed to resolve the sensitive issues surrounding the erosion and other problems of the river. He instructed local and state NRCS staff to provide technical assistance to the CRM group. The group followed Chief Johnson's idea, and the Lower Missouri River CRM Council was formed. This has helped those involved in solving the problems to overcome many of the stumbling blocks with which they were being confronted. Some of these successes include:

- *Through the CRM Council the $3 million transferred to the USACE was used to try some new innovative erosion solutions on a site in Montana and one in North Dakota. The group helped the USACE to select the site. NRCS assisted in the design and implementation. For the first time in this area, materials such as hay bales, willow cuttings, and log revetments were used.*
- *An interagency meeting and tour of erosion sites was sponsored by the CRM Council in September of 1996. In addition to local producers, CRM Council members, NRCS state and national staff, USACE staff, researchers from the USDA Agricultural Research Service (ARS) National Sedimentation Laboratory of Oxford, Mississippi, attended the session. The group agreed that the erosion problem needed to be studied further. The NRCS, USACE, and ARS have been doing studies on the River System below Fort Peck Dam since the 1996 meeting. A final report on the research is planned for summer of 1998.*
- *The CRM Council has been surveying producers along the river to determine what they perceive to be their major problems. This helps the group to stay in tune with current problems.*
- *The CRM Council contracted with a group of Montana State University senior students from the Film and TV Curriculum to develop an informational video about the Missouri River and its resources. This project has been completed, and the video will be used to show legislators and others what the problems and resources along the river are.*

The group has been successful because of the CRM process. The process takes much effort by all involved, but it does work.

CASE STUDY

Watershed Planning Through a Coordinated Resource Management Planning Process

The American River watershed, located in the Sierra Nevada Mountains of California, comprises 963 square miles. It is an important source of water for the region. The watershed also supports a diversity of habitats from grassland at lower elevations, transitioning to chaparral and to hardwood forest, and eventually to coniferous forest at upper elevations. In addition, the watershed is a recreational and tourist destination for the adjacent foothill communities like the greater Sacramento metropolitan area and the San Francisco Bay area.

Urban development is rapidly expanding in the watershed, particularly at lower elevations. This additional development is challenging environmental managers in the watershed and stressing the natural resources of the area. In 1996, the Placer County Resource Conservation District (PCRCD) spearheaded a multi-interest effort to address watershed concerns within the American River watershed. Due to the range of issues to be addressed, they sought to involve representatives from various municipalities, environmental and recreational groups, fire districts, ranchers, and state and federal agencies. The group established a broad goal "to enhance forest health and the overall condition of the watershed," as well as a set of specific goals that include the following:

- *Actively involve the community and be responsive to its needs.*
- *Optimize citizen initiative to manage fuels on private property to enhance forest and watershed.*
- *Restore hydrologic and vegetative characteristics of altered meadows and riparian areas.*
- *Create and sustain diverse habitats supporting diverse species.*
- *Ensure adequate ground cover to prevent siltation of waterways.*
- *Reduce erosion from roads and improvements.*
- *Prevent and correct pollution discharges before they adversely affect water quality.*
- *Reduce excessive growths of fire-dependent brush species.*
- *Increase water retention and water yield of the watershed.*
- *Optimize and sustain native freshwater species.*

Because of past conflicts and competing interests among members of the group, a Memorandum of Understanding (MOU) was prepared to develop a cooperative framework within which the various experts and interest groups could participate in natural resource management of the watershed. The signatories jointly committed to find common ground from which to work. The first step was to establish "future desired conditions" that will meet the needs of all the signatories as well as the local landowners and the public.

By including all of the signatories in the prioritization of implementation actions, PCRCD continues to keep the watershed planning process moving forward. In addition, PCRCD has encouraged the development of a small core group of landowners, agency representatives, and environmental organizations to determine how specific actions will be implemented. Several projects that incorporate holistic ecosystem management and land stewardship principles to achieve measurable improvements within the watershed are already under way.

- Investigating sensitive legal, economic, or cultural issues that might influence the restoration effort.
- Facilitating the restoration planning, design, and implementation process outlined in this document.

It is important to note that technical expertise often plays an important role in the success of restoration work. For example, a restoration initiative might involve resource management or land use considerations that are controversial or involve complex cultural and social issues. An initiative might address issues like western grazing practices or water rights and require the restriction of certain activities, such as timber or mineral extraction, certain farming and grazing practices, or recreation (**Figure 4.3**). In these cases, involving persons who have the appropriate expertise on regulatory programs, as well as social, political, and legal issues, can prevent derailment of the restoration effort.

Perhaps the most important benefit of establishing technical teams, however, is that the advisory group and decision makers will have the necessary information to develop restoration objectives. The advisory group will be able to integrate the knowledge gained from the analysis of what is affecting stream corridor structure and functions with the information on the social, political, and economic factors operative within the stream corridor. Essentially, the advisory group will be able to help define a thorough set of restoration objectives.

Identifying Funding Sources

Identifying funding sources is often an early and vital step toward an effective stream restoration initiative. The funding needed may be minimal or substantial, and it may come from a variety of sources. Funding may come from state or federal sources that have recognized the need for restoration due to the efforts of local citizens' groups. Funding may come from counties or any entity that has taxing authority. Philanthropic organizations, nongovernmental organizations, landowners' associations, and voluntary contributions are other funding sources. Regardless of the source of funds, the funding agent (sponsor) will almost certainly influence restoration decisions or act as the leader and decision maker in the restoration effort.

Interdisciplinary Nature of Stream Corridor Restoration

The complex nature of stream corridor restoration requires that any restoration initiative be approached from an interdisciplinary perspective. Specialists from a variety of disciplines are needed to provide both the advisory group and sponsor with valuable insight on scientific, social, political, and economic issues that might affect the restoration effort. The following is a list of some of the professionals who can provide important input for this interdisciplinary effort:

- *Foresters*
- *Legal consultants*
- *Botanists*
- *Microbiologists*
- *Engineers*
- *Hydrologists*
- *Economists*
- *Geomorphologists*
- *Archaeologists*
- *Sociologists*
- *Soil scientists*
- *Rangeland specialists*
- *Landscape architects*
- *Fish and wildlife biologists*
- *Public involvement specialists*
- *Real estate experts*
- *Ecologists*
- *Native Americans and Tribal Leaders*

Figure 4.3: Livestock grazing. *Technical teams can be helpful in addressing controversial and complex issues that have the potential to influence the acceptance and success of a restoration initiative.*

Establishing a Decision Structure and Points of Contact

Once the advisory group and relevant technical teams have been formed, it is important to develop a decision-making structure (**Figure 4.4**) and to establish clear points of contact.

As noted earlier, the advisory group will play an active planning and coordinating role, but it will not make the final decisions. The primary decision-making authority should reside in the hands of the stakeholders. The advisory group, however, will play a strong role by providing recommendations and informing the decision maker(s) of various restoration options and the opinions of the various participants.

It is important to note that the decision maker, as well as the advisory group, may be composed of a collection of interests and organizations. Consequently, both entities should establish some basic protocols to facilitate decision making and communication. Within each group some of the following rules of thumb might be helpful:

- Select officers
- Establish ground rules
- Establish a planning budget
- Appoint technical teams

In conjunction with establishing a decision structure, the sponsor, advisory group, and relevant subcommittees need to establish points of contact. These points of contact should be people who are accessible and possess strong outreach and communication skills. Points of contact play an important role in the restoration process by facilitating communication among the various groups and partners.

Facilitating Involvement and Information Sharing Among Participants

It is important that every effort be made to include all interested parties throughout the duration of the restoration process. Solicit input from participants and keep all interested parties informed of the plan development, including uncertainties associated with a particular solution, approach, or management prescription and what must be involved in modifying and adapting them as the need arises. In other words, it is important to operate under the principles of both information giving and information receiving.

Receiving Input from Restoration Participants

In terms of information receiving, a special effort should be made to directly contact landowners, resource users, and other interested parties to ask them to participate in the planning process. Typically, these groups or indi-

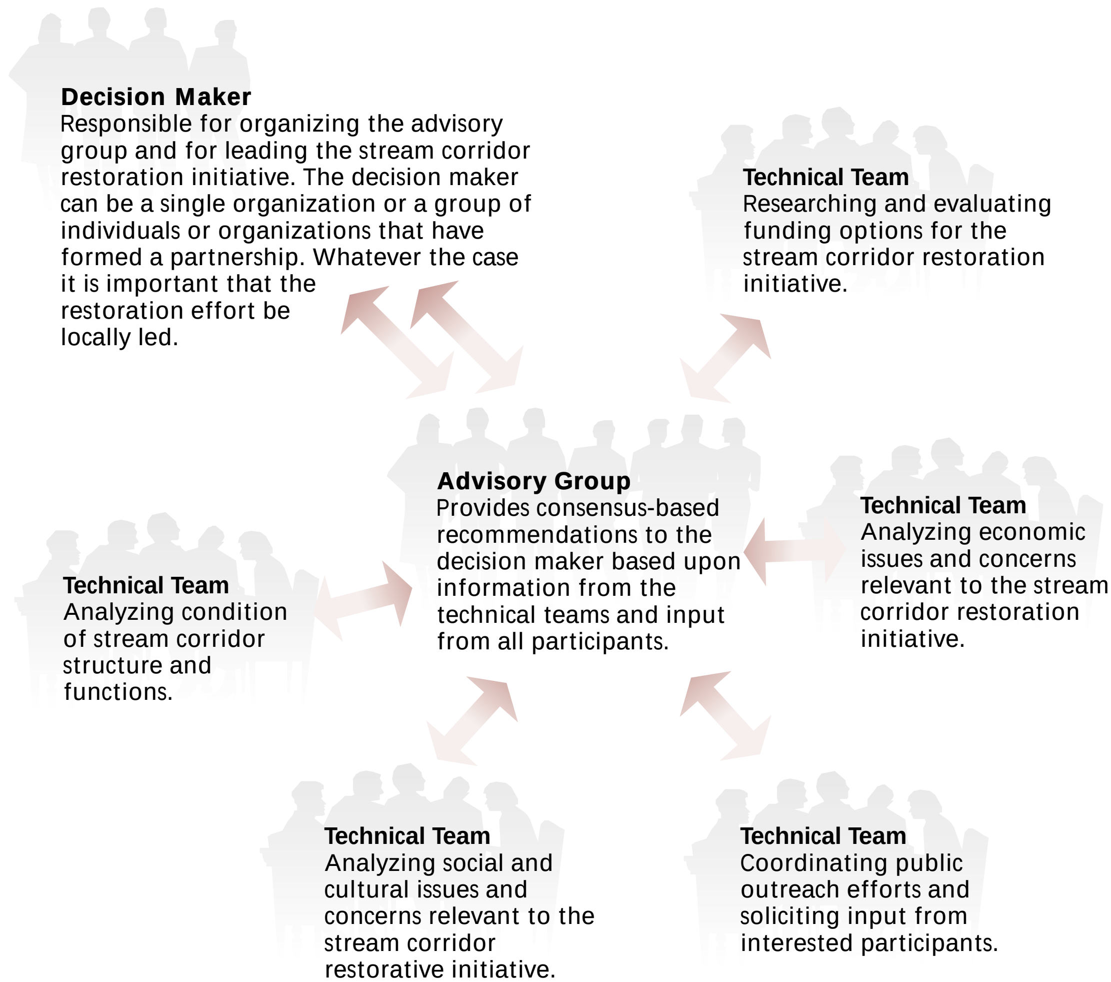


Figure 4.4: Flow of communication. *Restoration plan development requires a decision structure that streamlines communication between the decision maker, the advisory group, and the various technical teams.*

viduals will have some personal interest in the condition of the stream corridor and associated ecosystems in their region. A failure to provide them the opportunity to review and comment on stream corridor restoration plans will often result in objections later in the process.

Private landowners, in particular, often have the greatest personal stake in the restoration work. As part of the restoration effort it might be necessary for private landowners to place some of their assets at increased risk, make them more available for public use, or reduce the economic return they provide (e.g., restricting grazing in riparian areas or increasing buffer widths between agricultural fields and drainage channels). Thus, it is in the best interest of the restoration initiative to include these persons as decision makers.

A variety of public outreach tools can be useful in soliciting input from participants. Some of the most common mechanisms include public meetings, workshops, and surveys. *Tools for Facilitating Participant Involvement and Information Sharing During the Restoration Process*, provides a more complete list of potential outreach options.

Informing Participants Throughout the Restoration Process

In addition to actively seeking input from participants, it is important that the sponsor(s) and the advisory group regularly inform the public of the status of the restoration effort. The restoration initiative can also be viewed as a strong educational resource for the entire community. Some effective ways to communicate this information and to provide educational opportunities include newsletters, fact sheets, seminars, and brochures. A more complete list of potential outreach tools is provided in the box *Tools for Facilitating Participant Involvement and Information Sharing During the Restoration Process*.

It is important to note that the educational opportunities associated with information giving can help support restoration initiatives. For example, in cases that require the implementation of costly management prescriptions, outreach tools can be effective in improving landowner awareness of ways in which risks and losses can be offset, such as incentive programs (e.g., Conservation Reserve Program) or cost-sharing projects (e.g., Section 319 of the Clean Water Act). In these cases, the most effective approach might be for the representative landowners serving on the decision-making team to be responsible for conducting this outreach to their constituents.

In addition, educational outreach can also be viewed as an opportunity to demonstrate the anticipated benefits of restoration work, on both regional and local levels. One of the most effective ways to accomplish this is with periodic public field days involving visits to the restoration corridor, as well as pilot demonstration sites, model farms, and similar examples of restoration actions planned.

Finally, wherever possible, information on the effectiveness and lessons learned from restoration work should be made available to persons interested in carrying out restoration work elsewhere. Most large restoration initiatives will require relatively detailed documentation of design and performance, but this information is usually not widely distributed. Summaries of restoration experiences can be published in any of a variety of technical journals, newsletters, bulletins, Internet Web sites, or other media and can be valuable to the success of future restoration initiatives.

Tools for Facilitating Participant Involvement and Information Sharing During the Restoration Process

Tools for Receiving Input

- *Public Hearings*
- *Task Forces*
- *Training Seminars*
- *Surveys*
- *Focus Groups*
- *Workshops*
- *Interviews*
- *Review Groups*
- *Referendums*
- *Phone-in Radio Programs*
- *Internet Web Sites*

Tools for Informing Participants

- *Public Meetings*
- *Internet Web Sites*
- *Fact Sheets*
- *News Releases*
- *Newsletters*
- *Brochures*
- *Radio or TV Programs or Announcements*
- *Telephone Hotlines*
- *Report Summaries*
- Federal Register

Selecting Tools for Facilitating Information Sharing and Participant Involvement

Although a variety of outreach tools can be used to inform participants and solicit input, attention should be paid to selecting the best tool at the most appropriate time. In making this selection, it is helpful to consider the stage of the restoration process as well as the outreach objectives.

For example, if a restoration initiative is in the early planning stages, providing community members with background information through a newsletter or news release might be effective in bringing interested parties to the table and in generating support for the initiative (**Figures 4.5 and 4.6**). Conversely, once the planning process is well under way and restoration alternatives are being selected, a public hearing may be a useful mechanism for receiving input on the desirability of the various options under consideration (**Figure 4.7**).


CBF NEWS

The Newsletter of the Chesapeake Bay Foundation

Oyster Plan Falls Short on Conservation

Rockfish Rebound Affirms Management Controls

Figure 4.5: Chesapeake Bay Foundation newsletter. *Newsletters can be an effective way to communicate the status of restoration efforts to the community.*

Some additional factors that should be taken into account in selecting outreach tools include the following:

- Strengths and weaknesses of individual techniques.
- Cost, time, and personnel required for implementation.
- Receptivity of the community.

Again, no matter what tools are selected, it is important to make an effort to solicit input from participants as well as to keep all interested parties informed of plan developments. The Interagency Ecosystem Management Task Force (1995) provides the following suggestion for a combination of techniques that can be used to facilitate participant involvement and information sharing:

- Regular newsletters or information sheets apprising people of plans and progress.
- Regularly scheduled meetings of landowner and citizen groups.
- Public hearings.
- Field trips and workdays on project sites for volunteers and interested parties.

In addition, the innovative communication possibilities afforded by the Internet and the World Wide Web cannot be ignored.

Documenting the Process

The final element of getting organized involves the documentation of the various activities being undertaken as part of the stream corridor restoration effort. Although the restoration plan, when completed, will ultimately document the results of the restoration process, it

FAST FORWARD

Preview Chapter 6's Developing a Monitoring Plan.

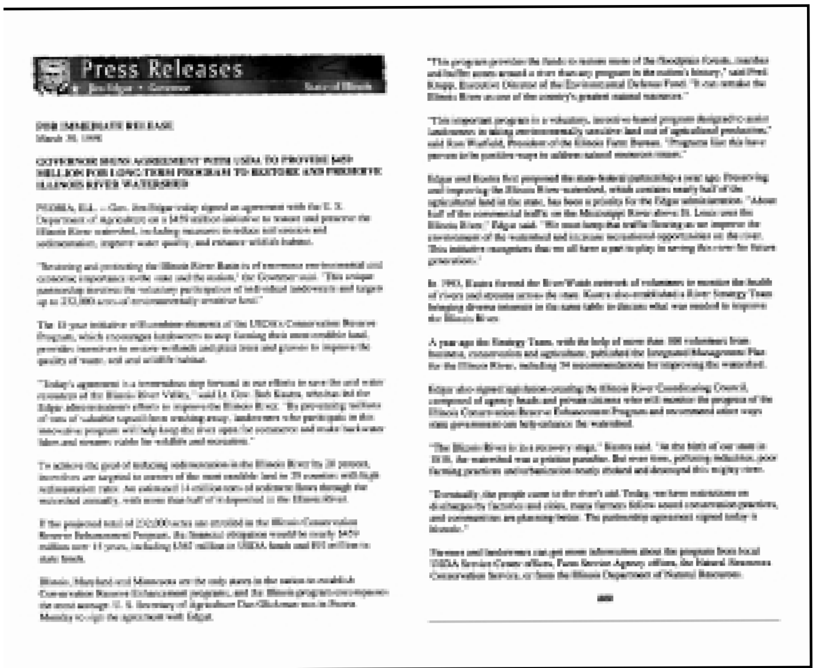

Press Releases

Figure 4.6: Regional restoration news releases. *A news release is an effective tool for informing the community of the planning of the restoration initiative.*
Source: State of Illinois.

Figure 4.7: Local public hearing. *Public hearings are a good way to solicit public input on restoration options.*
Source: S. Ratcliffe. Reprinted by permission.

is also important to keep track of activities as they occur.

An effective way to identify important restoration issues and activities as well as keep track of those activities is through the use of a "restoration checklist" (National Research Council, 1992). The checklist can be maintained by the advisory group or sponsor and used to engage project stakeholders and to inform them of the progress of restoration efforts. The checklist can serve as an effective guide through the remaining components of restoration plan development and project implementation. In addition, a draft version of *Developing a Monitoring Plan* (see Chapter 6) should be prepared as part of planning data collection.

Restoration Checklist (Adapted from National Research Council 1992)

During Planning...

- ❑ Have all potential participants been informed of the restoration initiative?
- ❑ Has an advisory committee been established?
- ❑ Have funding sources been identified?
- ❑ Has a decision structure been developed and points of contact identified?
- ❑ Have steps been taken to ensure that participants are included in the restoration processes?
- ❑ Has the problem that requires treatment been investigated and defined?
- ❑ Has consensus been reached on the mission of the restoration initiative?
- ❑ Have restoration goals and objectives been identified by all participants in the restoration effort?
- ❑ Has the restoration been planned with adequate scope and expertise?
- ❑ Has the restoration plan had an annual or mid-course correction point in line with adaptive management procedures?
- ❑ Have the indicators of stream corridor structure and function been directly and appropriately linked to the restoration objectives?
- ❑ Have adequate monitoring, surveillance, management, and maintenance programs been specified as an integral part of the restoration plan? Have monitoring costs and operational details been integrated so that results will be available to serve as input in improving techniques used in the restoration work?
- ❑ Has an appropriate reference system (or systems) been selected from which to extract target values of performance indicators for comparison in conducting the evaluation of the restoration initiative?
- ❑ Have sufficient baseline data been collected over a suitable period of time on the stream corridor and associated ecosystems to facilitate before-and-after treatment comparisons?
- ❑ Have critical restoration procedures been tested on a small experimental scale to minimize the risks of failure?
- ❑ Has the length of a monitoring program been established that is sufficiently long to determine whether the restoration work is effective?
- ❑ Have risk and uncertainty been adequately considered in planning?
- ❑ Have alternative designs been formulated?
- ❑ Have cost-effectiveness and incremental cost of alternatives been evaluated?

During Project Implementation and Management...

- ❑ Based on the monitoring result, are the anticipated intermediate objectives being achieved? If not, are appropriate steps being taken to correct the problem(s)?
- ❑ Do the objectives or performance indicators need to be modified? If so, what changes might be required in the monitoring program?
- ❑ Is the monitoring program adequate?

During Postrestoration...

- ❑ To what extent were restoration plan objectives achieved?
- ❑ How similar in structure and function is the restored corridor ecosystem to the reference ecosystem?
- ❑ To what extent is the restored corridor self-sustaining (or will be), and what are the maintenance requirements?
- ❑ If all stream corridor structure and functions were not restored, have the critical structure and functions been restored?
- ❑ How long did the restoration initiative take?
- ❑ What lessons have been learned from this effort?
- ❑ Have those lessons been shared with interested parties to maximize the potential for technology transfer?
- ❑ What was the final cost, in net present value terms, of the restoration work?
- ❑ What were the ecological, economic, and social benefits realized by the restoration initiative?
- ❑ How cost-effective was the restoration initiative?
- ❑ Would another approach to restoration have produced desirable results at lower cost?

4.B Problem and Opportunity Identification

FAST FORWARD

Preview Chapter 7's Data Collection and Analysis Methods sections.

Development of stream corridor restoration objectives is preceded by an analysis of resource conditions in the corridor. It is also preceded by the formulation of a problem/opportunity statement that identifies conditions to be improved through and benefit from restoration activities. Although problem/opportunity identification can be very difficult, in terms of measurable stream corridor conditions, it is the single most important step in the development of the restoration plan and in the restoration process. This section focuses on the six steps of the problem/opportunity identification process that are critical to any stream corridor restoration initiative.

The Six Steps of the Problem/ Opportunity Identification Process

1. *Data collection and analysis*
2. *Definition of existing stream corridor conditions (structure and function) and causes of disturbance*
3. *Comparison of existing conditions to desired conditions or a reference condition*
4. *Analysis of the causes (disturbances) of altered or impaired stream corridor conditions*
5. *Determination of how management practices might be affecting stream corridor structure and functions*
6. *Development of problem and opportunity statements*

Data Collection and Analysis

Data collection and analysis are important to all aspects of decision making and are conducted throughout the duration of the restoration process. The same data and analytic techniques are often applied to, and are important components of, problem/opportunity identification; goal formulation; alternative selection; and design, implementation, and monitoring. Data collection and analysis, however, begin with problem/opportunity identification. They are integral to defining existing stream corridor and reference conditions, identifying causes of impairment, and developing problem/opportunity statements. Data collection and analysis should be viewed as the first step in this process.

Data Collection

Data collection should begin with a technical team, in consultation with the advisory group and the decision maker, identifying potential data needs based on technical and institutional requirements. The perspective of the public should then be solicited from participants or through public input forums. Data targeted for collection should generally provide information on both the historical and baseline conditions of stream corridor structure and functions, as well as the social, cultural, and economic conditions of the corridor and the larger watershed.

Data are collected with the help of a variety of techniques, including remote sensing, historical maps and photographs, and actual resource inventory using standardized on-site field techniques, evaluation models, and other recognized and widely accepted methodologies. Community mapping (drawing areas of importance to the community or individuals) is becoming a popular method of involving the public and children in restoration initiatives. This technique can solicit information not accessible to traditional survey or data collection techniques and it also makes the data collection process accessible to the public. Additional data collection and analysis methods are discussed in Part III, Chapter 7.

Collecting Baseline Data

Restoration work should not be attempted without having knowledge of existing stream corridor conditions. In fact, it is impossible to determine goals and objectives without this basic information. As a result, it is important to collect and analyze information that provides an accurate account of existing conditions. Due to the dynamic nature of hydrologic systems, a range of conditions need to be monitored. Ultimately, these *baseline data* will provide a point from which to compare and measure future changes.

Baseline data consist of the existing structure and functions of the stream corridor and surrounding ecosystems across scales, as well as the associated disturbance factors. These data, when compared to a desired reference condition (derived from either existing conditions elsewhere in the corridor or historical conditions), are important in determining cumulative effects on the stream corridor's structure and functions (i.e., hydrologic, geomorphic, habitat, etc.). Baseline data collection efforts should include information needed to determine associated problems and opportunities to be addressed in later design and implementation stages of the restoration process.

Collecting Historical Data

As described in earlier chapters, stream corridors change over time in response to ongoing natural or human-induced processes and disturbances. It is important to identify historical conditions and activities to understand the present stream corridor condition (**Figure 4.8**).

(a)

(b)

Figure 4.8: The Winooski River (a) in the 1930s and (b) at the same location in the 1990s.
Using photographs is one way to identify the historical condition of the corridor.

Part of collecting *historical data* is collecting background information on the requirements of the species and ecosystems of concern. Historical data should also include processes that occurred at the site. The historic description may also be used to establish target conditions, or the reference condition, for restoration. Often the goal of restoration will not be to return a corridor to a pristine, or pre-European settlement, condition. However, by understanding this condition, valuable knowledge is gained for making decisions on restoring and sustaining a state of dynamic equilibrium.

In terms of gathering historical data, emphasis should be placed on understanding changes in land use, channel planform, cover type, and other physical conditions. Historical data, such as maps and photographs, should be reviewed and long-time residents interviewed to determine changes to the stream corridor and associated ecosystems. Major human-induced or natural disturbances, such as land clearing, floods, fires, and channelization, should also be considered. These data will be critical in understanding present conditions, identifying a reference condition, and determining future trends.

Collecting Social, Cultural, and Economic Data

In addition to physical, chemical, and biological data, it is also important to gather data on the social, cultural, and economic conditions in the area. These data more often than not will drive the overall restoration effort, delimit its scale, determine its citizen and landowner acceptance, determine ability to coordinate and communicate, and generally decide overall stability and capability to maintain and manage. In addition, these data are likely to be of most interest to participants and should be collected with their assistance to avoid derailment or alteration of the restoration effort due to misconceptions and misinformation.

Properly designed surveys of social attitudes, values, and perceptions can also be valuable tools both to assess the changes needed to accomplish the restoration goals and to determine changes in these intangible values over time, throughout the planning process, and after implementation.

Prioritizing Data Collection

Although data on both the historical and baseline conditions related to ecosystem structure and functions and social, cultural, and economic values are important, it is not always practical to collect all of the available information. Budgets and technical limitations often place constraints on the amount and types of data that can be collected. It is therefore important for the technical team, advisory group, and decision maker to prioritize the data needed.

At a minimum, the data necessary to explain the mechanisms or processes that affect stream corridor conditions need to be collected. To illustrate the challenges of data prioritization, consider the example of identifying data for assessing habitat functions. Potential habitat data could include items such as the extent of impacted fish, wildlife, and other biota; ecological aspects; biological characteristics of soils and water; vegetation (both native and nonnative); and relationships among ecological considerations (**Figure 4.9**). Depending on the scope of the restoration plan, however, data for all of these elements might not be necessary to successfully accomplish restoration. This holds especially true for smaller restoration efforts in limited stream reaches.

An effective way to prioritize data collection is through a scoping process designed to determine those data which are critical to decision making. The scoping process identifies significant concerns by institutional recognition (laws, policies, rules, and regulations), public recognition (public concern and local perceptions), or technical recognition (standards, criteria, and procedures).

Data Analysis

Data analysis, like data collection, plays an important role in all elements of problem identification as well as other aspects of the restoration process. Data analysis techniques range from qualitative evaluations using professional judgment to elaborate computer models.

The scope and complexity of the restoration effort, along with the budget, will influence the type of analytical techniques selected. A wealth of techniques are discussed in the literature and various manuals and will not be listed in this document. Part I, however, provides examples of the types of processes and functions that need to be analyzed. In addition, Part III discusses some analytical techniques used for condition analysis and restoration design, offers some analytic methodologies, and provides additional references.

Existing Stream Corridor Structure, Functions, and Disturbances

The second step in problem identification and analysis is determining which stream corridor conditions best characterize the existing situation. Corridor structure, functions, and associated disturbances used to describe the existing condition of the stream corridor will be determined on a case-by-case basis. Just as human health is indexed by such parameters as blood pressure and body

Figure 4.9: Characterizing stream corridor conditions. *Data collection and analysis are important components of problem identification.*

temperature, the condition of a stream corridor must be indexed by an appropriate suite of measurable attributes.

There are no hard-and-fast rules about which attributes are most useful in characterizing the condition of stream corridor structure and functions. However, as a starting point, consideration should be given to describing present conditions associated with the following eight components of the corridor:

- Hydrology
- Erosion and sediment yield
- Floodplain/riparian vegetation
- Channel processes
- Connectivity
- Water quality
- Aquatic and riparian species and critical habitats
- Corridor dimension

Since the ultimate goal is to establish restoration objectives in terms of the structure and functions of the stream corridor, it is useful to characterize those attributes which either measure or index the eventual attainment of the desired ecological condition. Some measurable attributes that might be useful for describing the above components of a stream corridor are listed in the box *Measurable Attributes for Describing Conditions in the Stream Corridor*. Detailed guidance for quantifying many of the following attributes is either described or referenced elsewhere in this document.

Existing vs. Desired Structure and Functions: The Reference Condition

The third step in problem identification and analysis is to define the conditions within which the stream corridor problems and opportunities will be defined and restoration objectives established. It is helpful to describe how the present baseline conditions of the stream corridor compare to a *reference condition* that represents, as closely as possible, the desired outcome of restoration (**Figure 4.10**). The reference condition might be similar to what the stream corridor would have been like had it remained relatively stable. It might represent a condition less ideal than the pristine, but substantially improved from the present condition. Developing a set of reference conditions might not be an easy task, but it is essential to conducting a good problem/opportunity analysis.

Figure 4.10: Example reference condition in the western United States. *A reference condition may be similar to what the corridor would have been like in a state of relative "dynamic equilibrium."*

Several information sources can be very helpful in defining the reference condition. Published literature might provide information for developing reference conditions. Hydrologic data can often be used to describe natural flow and sediment regimes, and regional hydraulic geometry relations may define reference conditions for channel dimensions, pattern, and profile. Published soil surveys contain soil map-unit descriptions and interpretations reflecting long-term ecological conditions that may be suitable for reference. Species lists of plants and animals (both historical and present) and literature on species habitat needs provide information on distribution of organisms, both by habitat characteristics and by geographic range.

In most cases, however, reference conditions are developed by comparison with *reference reaches* or sites believed to be indicative of the natural potential of the stream corridor. The *reference site* might be the predisturbance condition of the stream to be restored, where such conditions are established by examining relic areas (enclosures, preserves), historical photos, survey notes, and/or other descriptive accounts. Similarly, reference conditions may be developed from nearby stream corridors in similar physiographic settings if those streams are minimally impacted by natural and human-caused disturbances.

Measurable Attributes for Describing Conditions in the Stream Corridor

Hydrology

- *total (annual) discharge*
- *seasonal (monthly) discharge*
- *peak flows*
- *minimum flows*
- *annual flow durations*
- *rainfall records*
- *size and shape of the watershed*

Erosion and Sediment Yield

- *watershed cover and soil health*
- *dominant erosion processes*
- *rates of surface erosion and mass wasting*
- *sediment delivery ratios*
- *channel erosion processes and rates*
- *sediment transport functions*

Floodplain/Riparian Vegetation

- *community type*
- *type distribution*
- *surface cover*
- *canopy*
- *community dynamics and succession*
- *recruitment/reproduction*
- *connectivity*

Channel Processes

- *flow characteristics*
- *channel dimensions, shape, profile, and pattern*
- *substrate composition*
- *floodplain connectivity*
- *evidence of entrenchment and/or deposition*
- *lateral (bank) erosion*
- *floodplain scour*
- *channel avulsions/realignments*
- *meander and braiding processes*
- *depositional features*
- *scour-fill processes*
- *sediment transport class (suspended, bedload)*

Water Quality

- *color*
- *temperature, dissolved oxygen (BOD, COD, and TOC)*
- *suspended sediment*
- *present chemical condition*
- *present macroinvertebrate condition*

Aquatic and Riparian Species and Critical Habitats

- *aquatic species of concern and associated habitats*
- *riparian species of concern and associated habitats*
- *native vs. introduced species*
- *threatened or endangered species*
- *benthic, macroinvertebrate, or vertebrate indicator species*

Corridor Dimension

- *plan view maps*
- *topographic maps*
- *width*
- *linearity, etc.*

FAST FORWARD

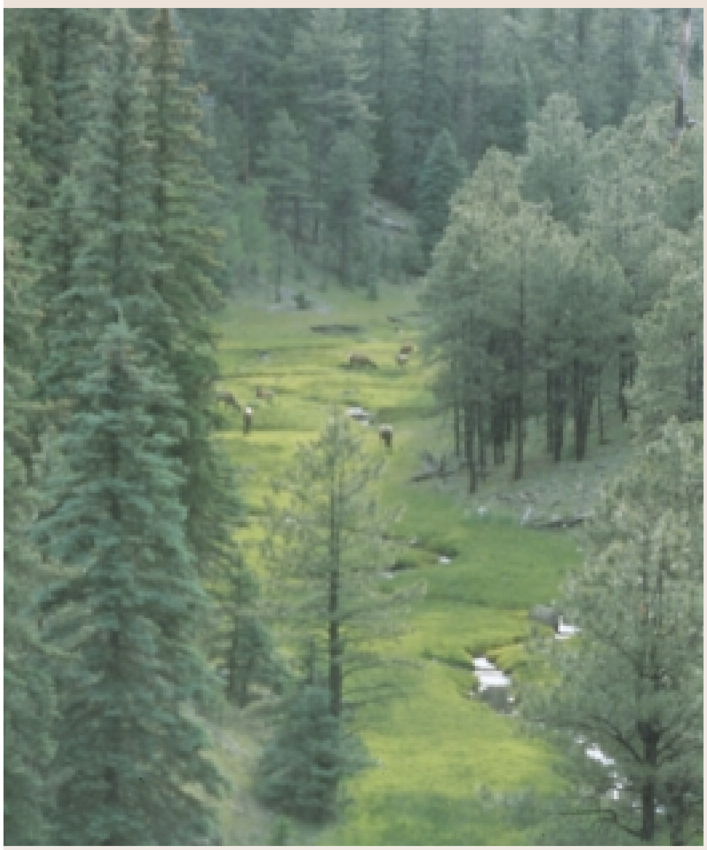
Preview Chapter 7's PFC section.

The Condition Continuum

*One helpful way to conceptualize the relationship between the current and reference conditions is to think of stream corridor conditions as occurring on a "condition continuum." At one end of this continuum, conditions may be categorized as being natural, pristine, or unimpaired by human activities. A headwater wilderness stream could exist near this end of the continuum (**Figure 4.11**). At the other end of the continuum, stream corridor conditions may be considered severely altered or impaired. Streams at this end of the continuum could be totally "trashed" streams or completely channelized water conduits.*

In concept, present conditions in the stream corridor exist somewhere along this condition continuum. The condition objective for stream restoration from an ecological perspective should be as close to the dynamic equilibrium as possible. It should be noted, however, that once other important considerations, such as political, economic, and social values, are introduced during the establishment of restoration goals and objectives, the target may shift to restoring the stream to some condition that lies between the present situation and dynamic equilibrium.

The proper functioning condition (PFC) concept is used as a minimum target in western riparian areas and can be the basis on which to plan additional enhancements (Pritchard et al.1993, rev. 1995).



(a)

(b)

Figure 4.11: Condition continuum. *The condition continuum runs from (a) untouched by humans to (b) severely impaired.*

Source: L. Goldman.

Causes of Altered or Impaired Conditions

Conditions that provide the impetus for stream corridor restoration activities include degraded stream channel conditions and degraded habitat. A thorough analysis of the cause or causes of these alterations or impairments is fundamental to identifying management opportunities and constraints and to defining realistic and attainable restoration objectives.

As discussed in Chapter 3, for every stream corridor structural attribute and function that is altered or impaired, there may be a causal chain of events responsible for the impairment. As a result, when conducting a problem analysis, it is useful to consider factors that affect stream corridor ecological condition at different levels or scales:

- Landscape
- Stream corridor and reach

Common Impaired or Degraded Stream Corridor Conditions

The following list provides some examples of impaired stream corridor conditions. A more complete list of these effects is provided in Chapter 3.

- *Stream aggradation—filling (rise in bed elevation over time)*
- *Stream degradation—incision (drop in bed elevation over time)*
- *Streambank erosion*
- *Impaired aquatic habitat*
- *Impaired riparian habitat*
- *Impaired terrestrial habitat*
- *Loss of gene pool of native species*
- *Increased peak flood elevation*
- *Increased bank failure*
- *Lower water table levels*
- *Increase of fine sediment in the corridor*
- *Decrease of species diversity*
- *Impaired water quality*
- *Altered hydrology*

Landscape Factors Affecting Stream Corridor Condition

When analyzing landscape-scale factors that contribute to existing stream corridor conditions, disturbances that result in changes in water and sediment delivery to the stream and in sources of contamination should be considered. In alluvial stream corridors, for example, anything that changes the historical balance between delivery of sediment to the channel and sediment-transport capacity of the stream will elicit a change in channel conditions. When sediment deliveries increase relative to sediment-transport capacities, stream aggradation usually occurs; when sediment-transport capacities increase relative to sediment delivery, stream incision usually occurs. How the channel responds to changes in flow and sediment regime depends on the magnitude of change in runoff and sediment and the type of sediment load being transported by the stream—suspended sediment or bedload.

The analysis of watershed effects on channels is aided by the use of standard hydrologic, hydraulic, and sediment transport tools. Depending on the available data, results may range from highly precise to quantitative. Altered flow regimes, for example, might be readily discernible if the stream has a long-term gauge record. Otherwise, numerical runoff modeling techniques might be needed to place an approximate magnitude on the

Accelerated Bank Erosion: The Importance of Understanding a Causal Chain of Events

*To illustrate the concept of a causal chain of events, consider the problem of accelerated bank erosion (**Figure 4.12**). Often the cause of accelerated bank erosion might be attributed to increases in peak runoff or sediment delivery to a stream when a surrounding watershed is undergoing land use changes; to the loss of bank vegetation, which also increases the vulnerability of the bank to erosion; or to structures in the stream (e.g., bridge abutments) that redirect the water flow into the bank. In this case, determining that bank erosion has increased relative to some reference rate is central to the identification of an impaired condition. In addition, understanding the cause or causes of the increased erosion is a key step in effective problem analysis. It is critical to the solution of the problem that this understanding be factored into the development of restoration objectives and management alternatives.*

***Figure 4.12: Bank erosion.** The cause(s) of bank erosion should be identified.*

change in peak flows resulting from a change in land use conditions. Water developments such as storage reservoirs and diversions also must be factored into an analysis of altered watershed hydrology (**Figure 4.13**).

The effects of altered land use on sediment delivery to streams may be assessed using various analytical and empirical tools. These are discussed in Chapters 7 and 8. However, these tools should be used with some caution unless they have been verified and calibrated with actual instream sediment sampling data or measured reservoir sedimentation rates.

The stream channel itself might provide some clues as to whether it is experiencing an increase or decrease in sediment delivery from the watershed relative to sediment-transport capacity. Special attention should be paid to channel capacities and depositional features such as sand or gravel bars. If flooding seems to be more frequent, it might be an indication that aggradation is occurring. Conversely, if there is evidence of channel entrenchment, such as exposed bridge pier or abutment footings, degradation is occurring. Similarly, if the number and size of gravel bars are significantly different from what is evident in historical photos, for example, the difference might be an indication that either aggradation or erosion has been enhanced. Care is needed when using the channel to interpret possible changes in watershed conditions since similar channel symptoms can also be caused by changes in conditions within the stream corridor itself or by natural variation of the hydrograph.

Stream Corridor and Reach Factors Affecting Stream Corridor Conditions

In addition to watershed factors affecting stream corridor conditions, it is important to consider disturbances at the stream corridor and reach scales. In general, stream corridor structural attributes and functions are greatly affected by several important categories of activities if they occur within the corridor. Chapter 3 explores these in more detail; the following are some of the activities that commonly impact corridor structure and function.

- Activities that alter or remove streambank and riparian vegetation (e.g., grazing, agriculture, logging, and urbanization), resulting in changes in the stability of streambanks, runoff and transport of contaminants, water quality, or habitat characteristics of riparian zones (**Figure 4.14**).
- Activities that physically alter the morphology of channels, banks, and riparian zones, resulting in effects such as the displacement of aquatic and riparian habitat and the disruption of the flow of energy and materials (e.g., channelization, levee construction, gravel mining, and access trails).
- Instream modifications that alter channel shape and dimensions, flow hydraulics, sediment-transport characteristics, aquatic habitat, and water quality (e.g., dams and grade stabilization measures, bank riprap, logs, bridge piers, and habitat “enhancement” measures) (**Figure 4.15**). In the case of logs, it might be the loss of such structures rather than their addition that alters flow hydraulics and channel structure.

Figure 4.13: Water releases below a dam.
Altering the flow regime of river below Hoover Dam altered the stream condition.

Altered riparian vegetation and physical modification of channels and floodplains are primary causes of impaired stream corridor structure and functions because their effects are both profound and direct. Addressing the causes of these changes might offer the best, most feasible opportunities for restoring stream corridors. However, the altered vegetation and physical modifications also may create some of the most significant challenges for stream corridor restoration by constraining the number or type of possible solutions.

It is important to remember that there are no simple analytical methods available for analyzing relationships

FAST FORWARD

Preview Chapters 7 and 8, Analytical and Empirical Tools section.

Figure 4.14: Residential development. *Urbanization can severely impair conditions critical for riparian vegetation by increasing impervious surfaces.*

between activities or events potentially disturbing the stream corridor and the structure and functions defining the corridor. However, there are modes by which stream corridor activities and structures can affect ecological conditions that involve both direct and indirect impacts. The box *Examples of How Activities Occurring Within the Corridor Can Affect Structure and Functions* provides some examples of the modes by which activities can affect stream corridor structure and functions.

FAST FORWARD

Preview Chapter 7's Quantitative Tools section.

In conducting the problem analysis, it is important to investigate the various modes of ecological interaction at the reach and system scales. The analysis might need to be subjective and deductive, in which case use of an interdisciplinary team is essential. In other cases, the analysis might be enhanced by application of available hydrologic, hydraulic, sedimentation, water quality, or habitat models.

Whatever the situation, it is likely that the analysis will require site-specific application of ecological principles aided by a few quantitative tools. It will rarely be possible to determine causative factors for resource impairment using uninterpreted results from off-the-shelf analytical models. Part III, Chapter 7, contains a detailed discussion of some of the quantitative tools available to assist in the analysis of the resource conditions within the stream corridor ecosystem.

Determination of Management Influence on Stream Corridor Conditions

Once the conditions have been identified and the causes of those conditions described, the key remaining question is whether the causative factors are a function of and responsive to management. Specific management factors that contribute to impairment might or might not have been identified with the causes of impairment previously identified.

Figure 4.15: Riparian vegetation and structure. *The loss of logs in a stream alters flow hydraulics and channel structure.*

To illustrate, consider again the example of increased bank erosion. An initial analysis of impaired conditions might identify causes such as land uses in the watershed that are yielding higher flows and sediment loads, loss of streambank vegetation, or redirection of flow from instream modifications. None of these, however, identify the role of management influences. For example, if higher water and sediment yields are a function of improper grazing management, the problem might be mitigated simply by altering grazing practices.

The ability to identify management influences becomes critical when identifying alternatives for restoration. Description of past management influences may prevent the repetition of previous mistakes and should facilitate prediction of future system response for evaluating alternatives. Recognition of management influences also is important for predicting the effectiveness of mitigation and the feasibility of specific treatments. Identifying the role of management is a key consideration when evaluating the ability of the stream corridor to heal itself (e.g., without management, with management, with management plus additional treatments). The identification of past management, both in the watershed and in the stream corridor, and its influence on those factors causing impairment will therefore help to sharpen the focus of the restoration effort.

Localized Impacts Affecting the Stream Corridor

Spatial considerations in stream corridor restoration are usually discussed at the landscape, corridor, and stream scales (e.g., connections to other systems, minimum widths, or maximum edge concerns). However, the critical failures in corridor systems can often occur at the reach scale, where a single break in continuity or other weakness can have a domino effect on the entire corridor. Just as uncontrolled watershed degradation can doom stream corridor restoration effectiveness, so can specific sites where critical problems exist that can prevent the whole corridor from functioning effectively.

Examples of weaknesses or problems at the reach scale that might affect the whole corridor are wide-ranging. Barriers to fish passage, lack of appropriate shade and resultant loss of water temperature moderation, breaks in terrestrial migration lands, or narrow points that make some animals particularly vulnerable to predators can often alter conditions elsewhere in the corridor. In addition, other sites might be direct or indirect source areas for problems, such as headcuts or rapidly eroding banks that contribute excessive sediment to the stream and instability to the system, or locations with populations of noxious exotic plant species that can spread to other parts of the corridor system. Some site-specific land use problems can also have critical impacts on corridor integrity, including chronic damage from grazing livestock, irrigation water returns, and uncontrolled storm water outflows.

Problem or Opportunity Statements for Stream Corridor Restoration

The final step in the process of problem/opportunity identification and analysis is development of concise statements to drive the restoration effort. *Problem/opportunity statements* not only serve as a general focus for the restoration effort but also become the basis for developing specific restoration objectives. Moreover, they form the basis for determining success or failure of the restoration initiative. Problem/opportunity statements are therefore critical for design of a relevant monitoring approach.

Examples of How Activities Occurring Within the Corridor Can Affect Structure and Functions

- *Direct disturbance or displacement of aquatic and/or riparian species or habitats*
- *Indirect disturbance associated with altered stream hydraulics and sediment-transport capacity*
- *Indirect disturbance associated with altered channel and riparian zone sedimentation dynamics*
- *Indirect disturbance associated with altered surface water-ground water exchanges*
- *Indirect disturbance associated with chemical discharges and altered water quality*

For maximum effectiveness, these statements should usually have the following two characteristics:

- They describe impaired stream corridor conditions that are explicitly stated in measurable units and can be related to specific processes within the stream corridor.
- They describe deviation from the desired reference condition (dynamic equilibrium) or proper functioning condition for each impaired condition.

CASE STUDY

Bluewater Creek

The watershed analysis and subsequent treatments performed at Bluewater Creek, New Mexico, demonstrate successful watershed and stream corridor restoration. Although most of the work has taken place on federal land, the intermixing of private lands and the values and needs of the varied publics concerned with the watershed make it a valuable case study. The project, begun in 1984, has a record of progress and improved land management. The watershed received the 1997 Chief's Stewardship Award from the Chief of the Forest Service and continues to host numerous studies and research projects.

Located in the Zuni mountains of north-central New Mexico, Bluewater Creek drains a 52,042-acre watershed that enters Bluewater Lake, a 2,350-acre reservoir in the East Rio San Jose watershed. Bluewater Creek and Lake provide the only opportunity to fish for trout and other coldwater species and offer a unique opportunity for water-based recreation in an otherwise arid part of New Mexico.

The watershed has a lengthy history of complex land uses. Between 1890 and 1940, extensive logging using narrow-gauge railroad technology cut over much of the watershed. Extensive grazing of livestock, uncontrolled fires, and some mining activity also occurred. Following logging by private enterprises, large portions of the watershed were sold to the USDA Forest Service in the early 1940s. Grazing, some logging, extensive roading, and increased recreational use continued in the watershed. The Mt. Taylor Ranger District of the Cibola National Forest now manages 86 percent of the watershed, with significant private holdings (12.5 percent) and limited parcels owned by the state of New Mexico and Native Americans.

In the early 1980s, local citizens worked with the Soil Conservation Service (now Natural Resources Conservation Service) to begin a Resource Conservation and Development (RC&D) project to protect water quality in the stream and lake as well as limit lake sedimentation harming irrigation and recreation opportunities. Although the RC&D project did not develop, the Forest Service, as the major land manager in the watershed, conducted a thorough analysis on the lands it managed and implemented a restoration initiative and monitoring that continue to this day.

The effort has been based on five goals: (1) reduce flood peaks and prolong baseflows, (2) reduce soil loss and resultant downstream channel and lake sedimentation, (3) increase fish and wildlife productivity, (4) improve timber and range productivity, and (5) demonstrate proper watershed analysis and treatment methods. Also important is close adherence to a variety of legal requirements to preserve the environmental and cultural values of the watershed, particularly addressing the needs of threatened, endangered, and sensitive plant and animal species; preserving the rich cultural history of the area; and complying with requirements of the Clean Water Act.

For analysis purposes, the watershed was divided into 13 subwatersheds and further stratified based on vegetation, geology, and slope. Analysis of data gathered measuring ground cover transects and channel analysis from August 1984 through July 1985 resulted in eight major conclusions: (1) areas forested with mixed conifer and ponderosa pine species were generally able to handle rainfall and snowmelt runoff; (2) excessive peak flows, as well as normal flows continually undercut steep channel banks, causing large volumes of bank material to enter the stream and lake system; (3) most perennial and intermittent channels were lacking the riparian vegetation they needed to maintain streambank integrity; (4) most watersheds had an excessive number of roads (**Figure 4.16**); (5) trails caused by livestock, particularly cattle, concentrate runoff into small streams and erodible areas; (6) several key watersheds suffered from livestock overuse and improper grazing management systems; (7) some instances of timber management practices were exacerbating watershed problems;

Figure 4.16: Vehicle traffic through wet meadow in Bluewater Creek, NM. *(May 1984.) Such traffic compacts and damages soil, changes flow patterns, and induces gully erosion.*

Figure 4.17: Recently installed treatment. *(April 1987.) Porous fence revetment designed to reduce bank failure.*

Figure 4.18: Porous fence revetment aided by bank sloping. *(August 1987.) The photo shows initial revegetation during first growing season following treatment installation.*

and (8) excessive runoff in some subwatersheds continued to degrade the main channel.

*Based on the conclusions of the analysis, a broad range of treatments were prescribed and implemented. Some were active (e.g., construction of particular works or projects); others were more passive (e.g., adjustments to grazing strategies). Channel treatments such as small dams, gully headcut control structures, grade control structures, porous fence revetments (**Figures 4.17, 4.18, and 4.19**), and channel crossings (**Figure 4.20**) were used to affect flow regimes, channel stability, and water quality. Riparian plantings, riparian pastures, and beaver management programs were also established, and meander reestablishment and channel relocation were conducted. Land treatments, such as the establishment of best management practices (BMPs) for livestock, timber, roads, and fish and wildlife, were developed to prevent soil loss and maintain site productivity.*

In a few cases, land and channel treatments were implemented simultaneously (e.g., livestock drift fences and seasonal area closures). Additional attention was paid to improved road management practices, and unnecessary roads were closed.

Results of the project have largely met its goals, and the watershed is more productive and enjoyable for a broad range of goods, services, and values. Although one weakness of the project was the lack of a carefully designed monitoring and

Figure 4.19: Porous fence revetments after two growing seasons. (September 1988.) Vegetation is noticeably established over first growing season.

Figure 4.20: Multiple elevated culvert array at crossing of wet meadow. (June 1997.) The culvert spreads flow and decreases erosion energy, captures sediment upstream, reduces flood peaks, and prolongs baseflows.

evaluation plan, observers generally agree that the completed treatments continue to perform their designed function, while additional treatments add to the success of the project.

Most of the small in-channel structures are functioning as designed. The meander reestablishment has lengthened the channel and decreased gradient in a critical reach. The channel relocation project has just completed its first year, and initial results are promising. Beaver have established themselves along the main channel of Bluewater Creek, providing significant habitat for fish and wildlife, as their ponds capture sediment and moderate flood peaks. The watershed now provides a more varied and robust population of fish and wildlife species. Changes in road management have yielded significant results. Road closures have removed traffic from sensitive areas, and reconstruction of two key roads has reduced sediment damages to the stream. Special attention to road crossings of wet meadows has begun to rehabilitate scores of acres dewatered by improper crossings. Range management techniques (e.g., combined allotments, improved fencing, and more modern grazing strategies) are improving watershed condition. A limited timber management program on the federal property has had beneficial impacts on the watershed, but significant timber harvest on private lands provided a cause for concern, particularly regarding compliance with Clean Water Act best management practices.

The local citizens who use the watershed have benefited from the improved conditions. Recreation use continues to climb.

Problem/Opportunity Statements

Problem/Opportunity statements should follow directly from the analysis of existing and reference stream corridor conditions. These statements can be viewed as an articulation of some of the potential benefits that can be realized through restoration of the structure and functions of the stream corridor. For example, problem statements might focus on the impaired structural attributes and functions needing attention, while associated opportunities might focus on reintroduction of native species that were previously eliminated from the system. Problem/Opportunity statements can also focus on the economic benefits of a proposed restoration initiative. By identifying such economic benefits to local landowners, it may be possible to increase the number of private citizens participating in the planning process.

Example problem statement:

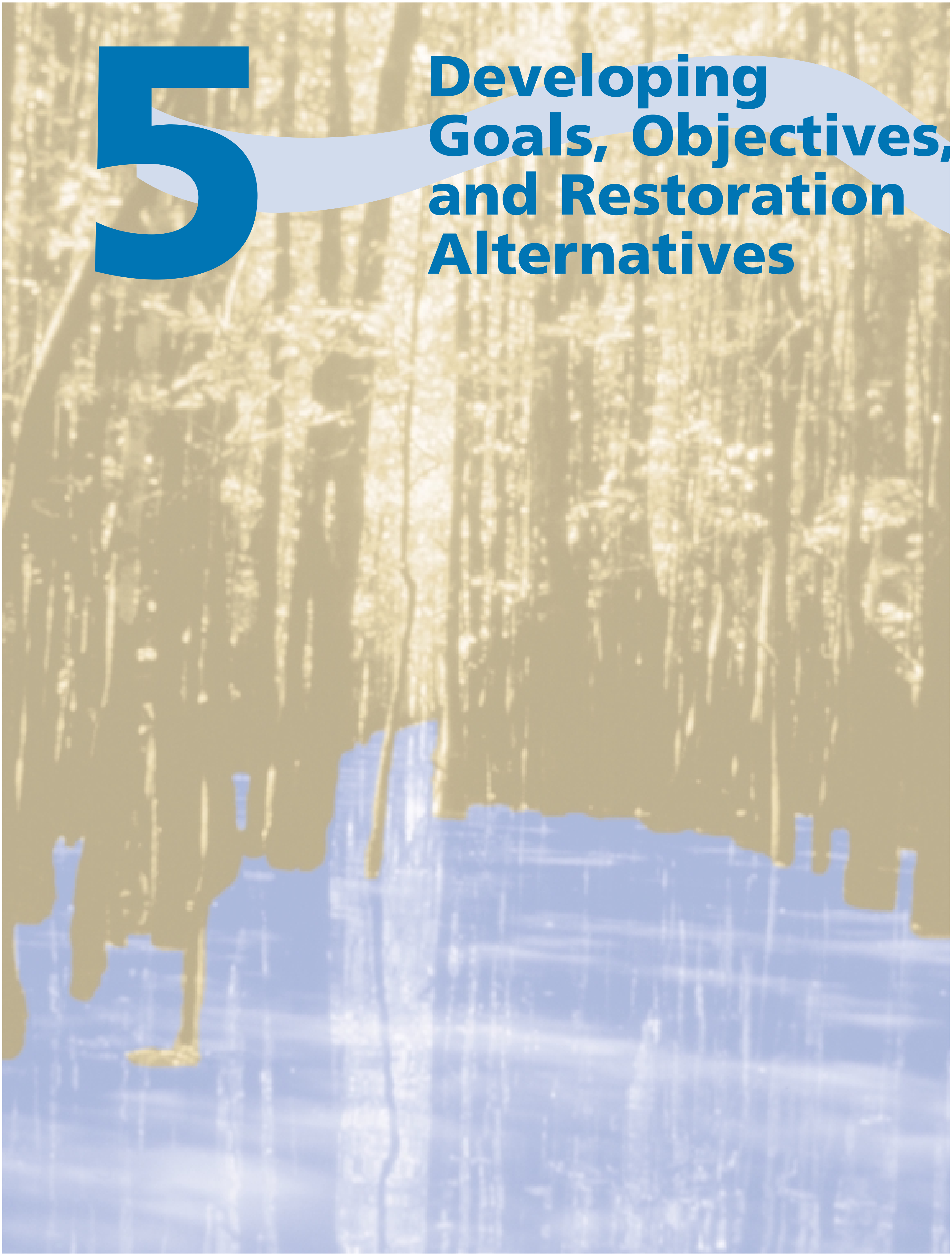
Coarse sediment	Geomorphic Input
from past	Time Frame
mass wasting	Watershed Process
in unit 3	Hillslope Unit Locator
associated with clearcut logging	Activity
on unstable slopes is	Conditions and Modifiers
reducing pools	Channel Effects
on segments 1 and 2	Locator
and degrading summer rearing habitat.	Resource Effects

Example opportunity statements:

- *To prevent streambank erosion and sediment damage and provide quality streamside vegetation through bioengineering techniques—Four Mile Run, Virginia.*
- *To protect approximately 750 linear feet of Sligo Creek through the construction of a parallel pipe system for storm water discharge control—Sligo Creek, Maryland.*
- *To enhance the creek through reconstruction of instream habitat (e.g., pools and riffles)—Pipers Creek, Washington.*
- *To reintroduce nongame fish and salamanders in conjunction with implementing several stream restoration techniques and eliminating point source discharges—Berkeley Campus Creek, California.*

Example statements adapted from Center for Watershed Protection 1995.

5 Developing Goals, Objectives, and Restoration Alternatives



5.A Developing Restoration Goals and Objectives

- *How are restoration goals and objectives defined?*
- *How do you describe desired future conditions for the stream corridor and surrounding natural systems?*
- *What is the appropriate spatial scale for the stream corridor restoration?*
- *What institutional or legal issues are likely to be encountered during a restoration?*
- *What are the means to alter or remove the anthropogenic changes that caused the need for the restoration (i.e., passive restoration)?*

5.B Alternative Selection and Design

- *How does a restoration effort target solutions to treat causes of impairment and not just symptoms?*
- *What are important factors to consider when selecting among various restoration alternatives?*
- *What role does spatial scale, economics, and risk play in helping to select the best restoration alternative?*
- *Who makes the decisions?*
- *When is active restoration needed?*
- *When are passive restoration methods appropriate?Chapter 6: Implement, Monitor, Evaluate, and Adapt*

5 Developing Goals, Objectives, and Restoration Alternatives

Once the basic organizational steps have been completed and the problems/opportunities associated with the stream corridor have been identified, the next two stages of the restoration plan development process can be initiated. These two stages, the development of restoration goals and objectives and alternative selection and design, require input from all partners. The advisory group should work in collaboration with the decision maker(s) and technical teams.

During the objective development, alternative selection, and design stages, it is important that continuity be maintained among the fundamental steps of the restoration process. In other words, planners must work to ensure a logical flow and relationship between problem and opportunity statements, restoration goals and objectives, and design.

Remember that the restoration planning process can be as complex as the stream corridor to be restored. A project might involve a large number of landowners and decision makers. It might also be fairly simple, allowing planning through a streamlined process. In either case, proper planning will lead to success.

Proper planning in the beginning of the restoration process will save time and money for the life of the project. This is *often accomplished by managing the causes rather than the symptoms.*

This chapter is divided into two sections that describe the basic steps of defining goals and objectives, selecting alternatives, and designing restoration measures.

Section 5.A: Developing Restoration Goals and Objectives

Restoration objectives are essential for guiding the development and implementation of restoration efforts and for establishing a means to measure progress and evaluate success. This section outlines some of the major considerations that need to be taken into account in developing restoration goals and objectives for a restoration plan.

Although active restorations that include the installation of designed measures are common, the "no action" or passive alternative might be more ecologically desirable, depending on the specific goals and time frame of the plan.

Section 5.B: Alternative Selection and Design

The selection of restoration alternatives is a complex process that is intended to address the identified problems/opportunities and accomplish restoration goals and objectives. Some of the important factors to consider in designing restoration measures, as well as some of the supporting analysis that facilitates alternative selection, are discussed.

5.A Developing Restoration Goals and Objectives

Developing goals and objectives for a stream corridor restoration effort follows problem/opportunity identification and analysis. The goals development process should mark the integration of the results of the assessment of existing and desired stream corridor structure and functions with important political, economic, social, and cultural values. This section presents and explains some of the fundamental components of the goal and objective development process.

Components of the Goal and Objective Development Process

- Define the desired future condition.
- Identify scale considerations.
- Identify restoration constraints and issues.
- Define goals and objectives.

Defining Desired Future Stream Corridor Conditions

The development of goals and objectives should begin with a rough outline, as discussed in Chapter 4, and with the definition of the *desired future condition* of the stream corridor and surrounding landscape (**Figure 5.1**). The desired future condition should represent the common vision of all participants. This clear, conceptual picture is necessary to serve both as a foundation for more specific goals and objectives and as a target toward which implementation strategies can be directed.

The vision statement should be consistent with the overall ecological goal of restoring stream corridor structure and functions and bringing the system as close to a state of dynamic equilibrium or proper functioning condition as possible.

The development of this vision statement should be seen as an opportunity for participants to articulate an ambitious ecological vision. This vision will ultimately be integrated with important social, political, economic, and cultural values.

Identifying Scale Considerations

In developing stream corridor restoration goals and objectives it is important to consider and address the issue of scale. The scale of stream corridor restoration efforts can vary greatly, from working on a short reach to managing a large river basin corridor. As discussed

Figure 5.1: Example of future conditions. *The desired future condition should represent the common vision of all participants.*

CASE STUDY

Chesapeake Bay Program

A unique partnership that spanned across all scales of the Chesapeake Bay watershed was formed in 1983. The Chesapeake Bay Agreement was signed that year by the District of Columbia, the state of Maryland, the Commonwealths of Pennsylvania and Virginia, the Chesapeake Bay Commission (a tri-state legislative body), and the federal government represented by the Environmental Protection Agency to coordinate and direct the restoration of the Chesapeake Bay. Recognizing that local cooperation would be vital in implementing any efforts, the Executive Committee created the Local Government Advisory Committee (LGAC) in 1987. The LGAC acts as a conduit to communicate current efforts in the Program to the local level, as well as a platform for local governments to voice their perceptions, ideas, and concerns. The Land Growth and Stewardship Subcommittee was formed in 1994 to encourage actions that reduce the impacts of growth on the Bay and address other issues related to population growth and expansion in the region.

Figure 5.2: Chesapeake Bay. *The Chesapeake Bay is a unique estuarine ecosystem protected through interagency cooperation.*
Source: C. Zabawa.

*The Chesapeake Bay was the first estuary targeted for restoration in the 1970s. Based on the scientific data collected during that time, the agreement targeted 40 percent reductions in nutrients, nitrogen, and phosphorus by the year 2000. The committee has been instrumental in moving up the tributaries of the bay and improving agricultural practices, removing nutrients, and educating the millions of residents about their role in improving the quality of the bay. Success has been marked by reduction in nutrients and an increase in populations of striped bass and other species (**Figure 5.2**). Recent fish kills in the watershed rivers, however, are reminders that maintaining the health of the Chesapeake Bay is a continuing challenge.*

Success at the local level is key to the success of the overall program. Chesapeake Bay Communities' Making the Connection *catalogs some of the local initiatives to restore local environments and improve the condition of the bay. In Lancaster County, Pennsylvania, for example, a Stream Team was formed to preserve and restore the local streams. Its primary role is to coordinate restoration efforts involving local landowners, volunteers, and available programs. In one case, the Stream Team was able to arrange materials for a local fishing group and a farmer to fence a pasture stream and plant trees. With continuous efforts such as this, the Chesapeake Bay will become cleaner one tributary at a time.*

previously, it is important to recognize, however, that the functions of a specific streambank or reach ecosystem are not performed in isolation and are linked to associated ecosystems in the surrounding landscape. As a result, goals and objectives should recognize the stream corridor and its surrounding landscape.

The Landscape Scale

Technical considerations in stream corridor restoration usually encompass the landscape scale as well as the stream corridor scale. These considerations may include political, economic, historical, and/or cultural values; natural resource management concerns; and biodiversity (Landin 1995). The following are some important issues relevant to the landscape scale.

Regional Economic and Natural Resource Management Considerations

Regional economic priorities and natural resource objectives should be identified and evaluated with respect to their likely influence on the restoration effort. It is important that restoration goals and objectives reflect a clear understanding of the concerns of the people living in the region and the immediate area, as well as the priorities of resource agencies responsible for managing lands within the restoration target area and providing support for the initiative (**Figure 5.3**).

In many highly developed areas, restoration may be driven largely by a general recognition that stream corridors provide the most satisfactory opportunities to repair and preserve natural environments in the midst of increasingly dense human occupation. In wildland areas, stream corridor restoration might be pursued as part of an overall ecosystem management program or to address the requirements of a particular endangered species.

Land Use Considerations

As discussed in Chapter 2, many of the characteristics and functions of the stream corridor are controlled by hydrologic and geomorphic conditions in the watershed, particularly as they influence streamflow regime, sediment movement, and inputs of nutrients and pollutants (Brinson et al. 1995).

As introduced in Chapter 3, changes in land use and increases in development are a concern, particularly because they can cause rapid changes in the delivery of storm water to the stream system, thereby changing the basic hydrologic patterns that determine stream configuration and plant community distribution (**Figure 5.4**). In addition, future development can influence what the stream corridor will be expected to accomplish in terms of processing or storing floodwaters or nutrients, or with respect to providing wildlife habitat or recreation opportunities.

REVERSE

Review Chapters 2 and 3.

Figure 5.3: Western stream—landscape scale. *Developing goals and objectives requires the consideration of important social, economic, ecological, and natural resource factors at the landscape scale.*

Figure 5.4: Urban stream corridor. *Population growth and land use trends, such as urbanization, should be considered when developing restoration goals and objectives.*

Landscape concerns pertinent to developing goals and objectives for stream corridor restoration should also include an assessment of land use and projected development trends in the watershed. By making an effort to accommodate predictable future land use and development patterns, degradation of stream corridor conditions can be prevented or reduced.

Biodiversity Considerations

The continuity that corridors provide among different areas and ecosystem types has often been cited as a major tool for maintaining regional biodiversity because it facilitates animal movement (particularly for large mammals) and prevents isolation of plant and animal populations. However, there has been some dispute over the effectiveness of corridors to accomplish these objectives and over the creation of inappropriate corridors having adverse consequences (Knopf 1986, Noss 1987, Simberloff and Cox 1987, Mann and Plummer 1995).

Where corridor restoration is intended to result in establishing connectivity on a landscape scale, management objectives and options should reflect natural patterns of plant community distribution and should be built to provide as much biodiversity as possible. In many instances, however, the driving force behind restoration is the protection of certain threatened, endangered, game, or other specially targeted species. In these cases a balance must be struck. A portion of the overall restoration plan can be directed toward the life requirements of the targeted species, but on the whole the goal should be a diverse community (**Figure 5.5**).

The Stream Corridor Scale

Each stream corridor targeted for restoration is unique. A project goal of restoring multiple ecological functions might encompass the channel systems, the active floodplain, and possibly adjacent hill slopes or other buffer areas that have the potential to directly and indirectly influence the stream or protect it from surrounding land uses (Sedell et al. 1990). A wide corridor is

Figure 5.5: Animal population dynamics. *Restoration plans may target species, but biodiversity should be the basic goal of restoration.*

most likely to include a range of biotic community types and to perform many of the stream functions (floodwater and sediment storage, nutrient processing, fish and wildlife habitat, and others) that the restoration effort is intended to restore. In many cases, however, it will not be possible to reestablish the original corridor width, and restoration will be focused on a narrower strip of land directly adjacent to the channel.

Where narrow corridors are established through urban or agricultural landscapes, certain functions might be restored (e.g., stream shading), while others might not (e.g., wildlife movement). In particular, very narrow corridors, such as western riparian areas, may function largely as edge habitat and will favor unique and sometimes opportunistic plant and animal species. In some situations, creating a large amount of edge habitat might be detrimental to species that require large forested habitat or are highly vulnerable to predation or nest parasitism and disturbances.

The corridor configuration and restoration options depend to a large extent on the pattern of land ownership and use at the stream corridor scale. Corridors that traverse agricultural land may involve the interests of many individual landowners with varying levels of commitment to or interest in the restoration initiative.

Often, landowners will not be inclined to remove acreage from production or alter land use practices without incentive. In urban settings, citizen groups may have a strong voice in the objectives and layout of the corridor. On large public land holdings, management agencies might be able to commit to the establishment and management of stream corridors and their watersheds, but the incorporation of competing interests (timber, grazing, mining, recreation) that are not always consistent with the objectives of the restoration plan can be difficult. In most cases, the final configuration of the corridor should balance multiple and often conflicting objectives, including optimizing ecological structure and function and accommodating the diverse needs of landowners and other participants.

The Reach Scale

A reach is the fundamental unit for design and management of the stream corridor. In establishing goals and objectives, each reach must be evaluated with regard to its landscape and individual characteristics, as well as their influence on stream corridor function and integrity. For example, steep slopes adjacent to a channel reach must be considered where they contribute potentially significant amounts of runoff, subsurface flow, sediment, woody debris, or other inputs. Another reach might be particularly active with respect to channel migration and might warrant expanding the corridor relative to other reaches to accommodate local stream dynamics.

Identifying Restoration Constraints and Issues

Once participants have reached consensus on the desired future condition and examined scale considerations, attention should be given to identifying *restoration constraints and issues*. This process is important in that it helps identify limitations associated with establishing specific restoration goals and objectives. Moreover, it provides the information that will be needed when integrating ecological, social, political, and economic values.

Due to the innumerable potential challenges involved in identifying all of the constraints and issues, it is often help-

FAST FORWARD

Preview Chapter 6's Adaptive Management section.

ful to rely on the services of the interdisciplinary technical teams. Team members support one another and provide critical expertise and the experience necessary to investigate potential constraints. The following are some of the restoration constraints and issues, both technical and nontechnical, that should be considered in defining restoration goals and objectives.

Technical Constraints

Technical constraints include the availability of data and restoration technologies. In terms of data availability, it is important that the technical team begin by compiling and analyzing data available on stream corridor structure and functions. Analyzing these data will enable the identification of information gaps and should allow the restoration effort to proceed, even though all of the information might not be at hand. It should be noted that there is usually a wealth of technical information available either in published sources or in public agency offices as unpublished source material.

In addition to data availability, a second technical constraint might involve the tools or techniques used to analyze or collect stream corridor data. Some restoration techniques and methodologies are not complete and might not be sufficient to conduct the restoration effort. It is also generally known that technology transfer and dissemination associated with available techniques are far behind the existing information base, and field personnel might not readily have access to needed information. It is important that the technical teams are up-to-date with restoration technology and are prepared to modify implemented plans through adaptive management as necessary.

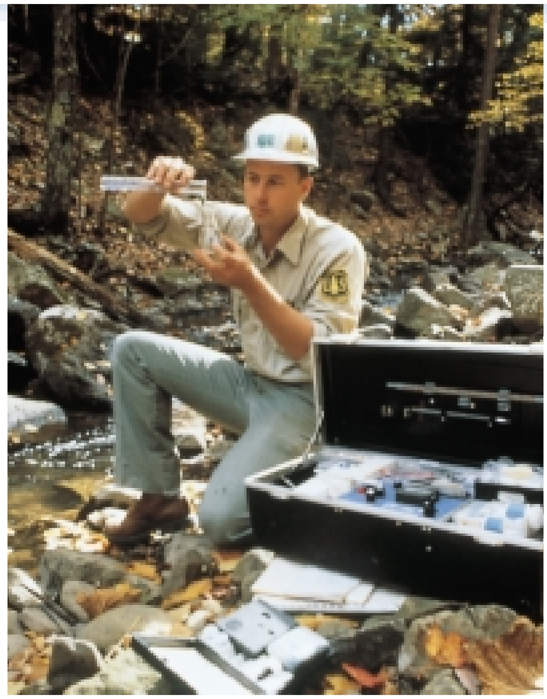


Figure 5.6: Field sampling. *Collecting the right kinds of data with the proper quality control and translating that data into information useful for making decisions is a challenge.*

Quality Assurance, Quality Control

The success of a stream corridor restoration plan depends on the following:

- Efficient and accurate use of existing data and information.
- Reliable collection of new data that are needed, recognizing the required level of precision and accuracy (**Figure 5.6**).
- Interpretation of the meaning of the data, including translating the data into information that can be used to make planning decisions.
- A locally led, voluntary approach.

The concept of quality assurance or quality control is not new. When time, materials, or money are to be expended, results should be as reliable and efficiently derived as possible. Provisions for quality control or quality assurance can be built into the restoration plan, especially if a large number of contractors, volunteers, and other people not directly under the control of the planners are involved (Averett and Schroder 1993).

Many standards, conventions, and protocols exist to ensure the quality or reliability of information used for planning a restoration (Knott et al. 1992), including the following:

- Sampling
- Field analytical equipment
- Laboratory testing equipment
- Standard procedures
- Training
- Calibrations
- Documentation
- Reviews
- Delegations of authority
- Inspections

The quality of work and the restoration actions can be ensured through the following (Shampine et al. 1992, Stanley et al. 1992, Knott et al. 1993):

- Training to ensure that all persons fully understand what is expected of them.
- Products that are produced on time and that meet the plan's goals and objectives.
- Established procedures for remedial actions or adaptive management, which means being able to make adjustments as monitoring results are analyzed.

Nontechnical Constraints

Nontechnical constraints consist of financial, political, institutional, legal and regulatory, social, and cultural constraints, as well as current and future land and water use conflicts. Any one of these has the potential to alter, postpone, or even stop a restoration initiative. As a result, it is important that the advisory group and decision maker consider appointing a technical team to investigate these issues prior to defining restoration goals and objectives.

Contained below is a brief discussion of some of the nontechnical issues that can play a role in restoration initiatives. Although many general examples and case studies offer experience on addressing nontechnical constraints, the nuances of each issue can vary by initiative.

Land and Water Use Conflicts

Land and water use conflicts are frequently a problem, especially in the western United States. The historical, social, and cultural aspects of grazing, mining, logging, water resources development and use, and unrestricted use of public land are emotional issues that require coordination and education so that local and regional citizens understand what is being proposed in the restoration initiative and what will be accomplished.

Financial Issues

Planning, design, implementation, and other aspects of the restoration initiative must stay within a budget. Since most restoration efforts involve public agencies, the institutional, legal, and regulatory protocols and bureaucracies can delay restoration and increase costs. It is extremely important to recognize these problems early to keep the initiative on schedule and preclude or at least minimize cost overruns.

In some cases, funds might be insufficient to accomplish restoration. The means to undertake the initiative can often be obtained by seeking out and working with a broad variety of cost- and work-sharing partners; seeking out and working with volunteers to perform

Permits

Federal, state, or local permits might be required for some types of stream restoration activities. Some states, such as California, require permits for any activity in a streambed. Placement of dredged or fill material in waters of the United States requires a Clean Water Act (CWA) Section 404 permit from the US Army Corps of Engineers or, when the program has been delegated, from the state. The CWA requires the application of the Section 404(b)(1) guidelines issued by the Environmental Protection Agency in determining whether discharge should be allowed. A permit issued under Section 10 of the Rivers and Harbors Act of 1899 might also be required for activities that change the course, condition, location, or capacity of navigable waters.

Activities that could trigger the need for a CWA Section 404 permit include, but are not limited to, re-creation of gravel beds, sand bars, and riffle and pool habitats; wetland restoration; placement of tree root masses; and placement of revetment on channel banks. CWA Section 404 requires that a state or tribe (one or both as appropriate) certify that an activity requiring a Section 404 permit is consistent with the state's or tribe's water quality standards. Given the variety of actions covered by the CWA, as well as jurisdiction issues, it is vital to contact the Corps of Engineers Regulatory Branch and appropriate state officials early in the planning process to determine the conditions triggering the need for permits as well as how to best integrate permit compliance needs into the planning and design of the restoration initiative. Chances are that a well-thought-out planning and design process will address most, if not all, the information needs for evaluation or certification of permit applications. Federal issuance of a permit triggers the need for compliance with the National Environmental Policy Act (see National Environmental Policy Act Considerations*).*

***Figure 5.7: Field volunteers.** Volunteers assisting in the restoration effort can be an effective way to combat financial constraints.*
Source: C . Zabawa.

various levels of field work, as well as to serve as knowledgeable experts for the effort; costing the initiative in phases that are affordable; and other creative approaches (**Figure 5.7**). Logistical support by a local sponsor or community in the form of labor, boats, and other equipment should not be overlooked.

Not all restorations are complex or costly. Some might be as simple as a slight change in the way that resources are managed in and along the stream corridor, involving only minor costs. Other restorations, however, may require substantial funds because of the complexity and extent of measures needed to achieve the planned restoration goals.

National Environmental Policy Act Considerations

The National Environmental Policy Act (NEPA) of 1969 established the nation's policy to protect and restore the environment and the federal responsibility to use "all practicable means and measures ... to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social and economic and other requirements of present and future generations of Americans." NEPA focuses on major federal actions with the potential to significantly affect the human environment. The Council on Environmental Quality's regulations implementing NEPA require the federal agency taking action to develop alternatives to a proposed action, to analyze and compare the impacts of each alternative and the proposed action, and to keep the public informed and involved throughout the project planning and implementation. Although NEPA does not mandate environmentally sound decisions, it has established a decision-making process that ultimately encourages better, wiser, and fully informed decisions.

When considering restoration of a stream corridor, it is important to determine early on whether a federal action will occur. Federal actions that might be associated with a stream corridor restoration initiative include, but are by no means limited to, a decision to provide federal funds for a restoration initiative, a decision to significantly alter operation and maintenance of federal facilities on a river system, or the need for a federal permit (e.g., a Clean Water Act Section 404 permit for placement of dredged or fill material in waters of the United States).

In addition, many states have environmental impact analysis statutes patterned along the same lines as NEPA. Consultation with state and local agencies should occur early and often throughout the process of developing a stream corridor restoration initiative. Jointly prepared federal and state environmental documentation is routine in some states and is encouraged.

The federal requirement to comply with NEPA should be integrated with the planning approach for developing a restoration plan. When multiple federal actions are required to fully implement a restoration initiative, the identity of the lead federal agency(s) and cooperating agencies should be established. This will facilitate agency adoption of the NEPA document for subsequent decision making.

Institutional and Legal Issues

Each restoration effort has its own unique set of regulatory requirements, which can range from almost no requirements to a full range of local, county, state, and federal permits. Properly planned restoration efforts should meet or exceed the intent of both federal and non-federal requirements. Restoration planners should contact the appropriate local, state, and federal agencies and involve them early in the process to avoid conflicts with these legal requirements.

Typical institutional and legal requirements cover a wide range of issues. Locally, restoration planners must be concerned with zoning permits and state and county water quality permits. Most federally sponsored and/or funded initiatives require compliance with the National Environmental Policy Act and the Endangered Species Act. Initiatives that receive federal support must comply with the National Historic Preservation Act and the Wild and Scenic Rivers Act. Permits might also be required from the US Army Corps of

Example Goals and Objectives

*The following is an excerpt from of a restoration plan used for restoration of Wheaton Branch, a severely degraded urban stream in Maryland. The **goal** of the project was to control storm water flows and improve water quality.*

OBJECTIVES	ALTERNATIVES
(1) Remove urban pollutants	Upstream pond retrofit
(2) Stabilize channel bundles	Install a double-wing deflector, imbricated riprap, and brush
(3) Control hydrologic regime retrofit	Upstream storm water management pond
(4) Recolonize stream community	Fish reintroduction

Adapted from Center for Watershed Protection 1995.

Engineers under Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899.

Defining Restoration Goals

Restoration goals should be defined by the decision maker(s) with the consensus of the advisory group and input from the interdisciplinary technical team(s) and other participants. As noted earlier, these goals should be an integration of two important groups of factors:

- Desired future condition (ecological reference condition).
- Social, political, and economic values.

Considering Desired Future Condition

As discussed earlier, the desired ecological future condition of the stream corridor is frequently based on predevelopment conditions or some commonly accepted idea of how the natural stream corridors looked and functioned. Consequently, it represents the ideal situation for restoration, whether or not this reference condition is attainable. This ideal situation has been given the term "potential," and it may be described as the highest ecological status an area can attain, given no political, social, or economic constraints (Prichard et al. 1993). When applied to the initiative, however, this statement might require modification to provide realistic and more specific goals for restoration.

Factoring In Constraints and Issues

In addition to the desired future ecological condition, definition of restoration goals must also include other considerations. These other factors include the important political, social, and economic values as well as issues of scale. When these considerations are factored into the analysis, realistic project goals can be identified. The goals provide the overall purpose for the restoration effort and are based on a stream corridor's capability or its ideal ecological condition.

Defining Primary and Secondary Restoration Goals

The identification of realistic goals is a key ingredient for restoration success since it sets the framework for adaptive management within a realistic set of expectations. Unrealistic restoration goals create unrealistic expectations and potential disenchantment among stakeholders when those expectations are unfulfilled.

In defining realistic restoration goals, it might be helpful to divide these goals into two separate, yet connected, categories—primary and secondary.

Primary Restoration Goals

Primary goals should follow from the problem/opportunity identification and analysis, incorporate the participants' vision of the desired future condition, and reflect a recognition of project constraints and issues such as spatial scale, needs found in baseline data collection, practical aspects of budget and human resources requirements, and special requirements for certain target or endangered species. Primary goals are usually the ones that initiated the project, and they may focus on issues such as bank stabilization, sediment management, upland soil and water conservation, flood control, improved aquatic and terrestrial habitat, and aesthetics.

Secondary Restoration Goals

Secondary goals should be developed to either directly or indirectly support the primary goals of the restoration effort. For example, hiring displaced forestry workers to install conservation practices in a forested watershed or region could serve the secondary goal of revitalizing a locally depressed economy, while also contributing to the primary goal of improving biodiversity in the restoration area.

Defining Restoration Objectives

Objectives give direction to the general approach, design, and implementation of the restoration effort. *Restoration objectives* should support the goals and also flow directly from problem/opportunity identification and analysis.

Restoration objectives should be defined in terms of the same conditions identified in the problem analysis and should specifically state which impaired stream corridor condition(s) will be moved toward which particular reference level or desired condition(s). The reference conditions provide a gauge against which to measure the success of the restoration effort; restoration objectives should therefore identify both impaired stream corridor conditions and a quantitative measure of what constitutes unimpaired (restored) conditions. Restoration objectives expressed in terms of measurable stream corridor conditions provide the basis for monitoring the success of the project in meeting condition objectives for the stream corridor.

Cultural Resource Considerations and the National Historic Preservation Act

Concepts Useful in Defining Restoration Goals and Objectives

Value*: Social/economic values associated with a change from one set of conditions to another. Often, these values are not economic values, but rather amenity values such as improved water quality, improved habitat for native aquatic or riparian species, or improved recreational experiences. Because stream corridor restoration often requires a monetary investment, the benefits of restoration need to be considered not only in terms of restoration costs, but also in terms of values gained or enhanced.*

Tolerance*: Acceptable levels of change in conditions in the corridor. Two levels of tolerance are suggested:*

(1) Variable "management" tolerance that is responsive to social concerns for selected areas.

(2) Absolute "resource" tolerance or minimal acceptable permanent resource damage.

Stream corridors in need of restoration usually (but not always) exceed these tolerances.

Vulnerability*: How susceptible a stream's present condition is to further deterioration if no new restoration actions are implemented. It can be conceptualized as the ease with which the system might move away from dynamic equilibrium. For example, an alpine stream threatened by a headcut induced by a poorly placed culvert might be extremely vulnerable to subsequent incision. Conversely, a forested stream that has sluiced to bedrock because large woody debris was lost from the system might be much less vulnerable to further deterioration.*

Responsiveness*: How readily or efficiently restoration actions will achieve improved stream corridor conditions. It can be conceptualized as the ease with which the system can be moved toward dynamic equilibrium. For example, a rangeland stream that has become excessively wide and shallow might respond very rapidly to grazing management by establishing a more natural cross section that is substantially narrower and deeper. On the other hand, an agricultural stream that has deeply incised following channelization might not readily reestablish grade or channel pattern in response to improved watershed or riparian vegetation conditions.*

Self-Sustainability*: The degree to which the restored stream can be expected to continue to maintain its restored (but dynamic) condition. The creation or establishment of dynamic equilibrium should always be a goal. However, it might be that intensive short-term maintenance is necessary to ensure weeds and exotic vegetation do not get a foothold. The short-term and longer-term goals and objectives to ensure sustainability need to be carefully considered relative to funding, proximity of the site to population concentrations, and caretakers.*

CASE STUDY

Restoration of the Elwha River Ecosystem

The construction of numerous hydropower projects fueled the economic growth of the Pacific Northwest during the early 1900s. With the seemingly inexhaustible supply of anadromous salmonids, little care was taken to reduce or mitigate the consequent impacts to these fish (Hoffman and Winter 1996). Two hydropower dams built on the Elwha River, on Washington's Olympic Peninsula, were no exception.

The 108 ft. high Elwha Dam (**Figure 5.8**) was built from 1910–13 about five miles from the river mouth. Although state law required a fishway, one was not built. As a result, salmon and steelhead populations immediately declined, some to extinction, and remaining populations have been confined to the lower five miles ever since. The 210 ft. high Glines Canyon Dam (**Figure 5.9**) was built from 1925–27 about eight miles upstream of the first dam, also without fish passage facilities. Glines was licensed for a period of 50 years in 1925 while the Elwha Dam has never been licensed.

In 1968, the project owner filed a license application for Elwha Dam and filed a relicense application for the Glines Canyon Dam in 1973. The Federal Energy Regulatory Commission (FERC) did not actively pursue the licensing of these two projects until the early 1980s when federal and state agencies, the Lower Elwha Klallam Tribe (Tribe), and environmental groups filed petitions with FERC to intervene in the licensing proceeding. The option of dam removal to restore the decimated fish runs was raised in most of these petitions, and FERC addressed dam removal in a draft environmental impact statement (EIS). Nonetheless, it was apparent that disagreements remained over numerous issues, and that litigation could take a decade or more.

Congressional representatives offered to broker a solution. In October 1992, President George Bush signed Public Law 102-495 (the Elwha River Ecosystem and Fisheries Restoration Act; the Elwha Act), which is a negotiated settlement involving all parties to the FERC proceeding. The Elwha Act voids

Figure 5.8: Elwha Dam. Fish passages were not constructed when the dam was built in 1910–1913.

FERC's authority to issue long-term licenses for either dam, and it confers upon the Secretary of the Interior the authority to remove both dams if that action is needed to fully restore the Elwha River ecosystem and native anadromous fisheries. In a report to the Congress (DOI et al. 1994), the Secretary concluded that dam removal was necessary to meet the goal of the Elwha Act. Subsequently, Interior completed the EIS process FERC had begun but using the new standard of full ecosystem restoration rather than "balancing" competing uses as FERC is required to do (NPS 1995).

Interior analyzed various ways to remove the dams and manage the 18 million cubic yards (mcy) of sediments that have accumulated in the two reservoirs since dam construction. The preferred alternative for the Glines Canyon Dam is to spill the reservoir water over successive notches constructed in the concrete gravity-arch section, allowing layers of the dam to be removed with a crane under dry conditions (NPS 1996). Standard diamond wire-saw cutting and blasting techniques are planned. Much of the dam, including the left and right side concrete abutments and spillway, will be retained to allow for the interpretation of this historic structure.

The foundation of the Elwha Dam failed during reservoir filling in 1912, flooding downstream areas such as the Tribe's reservation at the mouth of the river. A combination of blasted rock, fir mattresses, and other fill was used to plug the leak (NPS 1996). To avoid a similar failure during removal, the reservoir will be partially drained and the river diverted into a channel constructed through the bedrock footing of the left abutment. This will allow the fill material and original dam structure to be removed under dry conditions. Following removal of this material, the river will be diverted back to its historic location and the bedrock channel refilled. Since the Elwha Dam was built in an area that is religiously and culturally important to the Tribe, all structures will be removed.

The 18 mcy of accumulated sediment consists of about 9.2 mcy of silt and clay (<0.075 mm), 6.2 mcy of sand (0.075-<5 mm), 2.0 mcy of gravel (5-<75 mm), and .25 mcy of cobbles (75-<300 mm). The coarse material (i.e., sand and larger) is considered a resource that is lacking in the river below the dams, the release of which will help restore the size and function of a more natural and dynamic river channel, estuary, and nearshore marine areas. The silt- and clay-sized particles are also reduced in the lower river, but resuspension of this material may cause the loss of aquatic life and adversely affect water users downstream for the approximately two to three years this process is expected to last (NPS 1996). Nevertheless, the preferred alternative incorporates the natural erosive and transport capacity of the river to move this material downstream, although roughly half of the fine and coarse materials will remain in the newly dewatered reservoir areas. Water quality and fisheries mitigation actions are planned to reduce the impacts of sediment releases during and following dam removal. Revegetation actions will be implemented on the previously logged slopes for stabilization purposes and to accelerate the achievement of old-growth characteristics. The old reservoir bottoms will be allowed to revegetate naturally; "greenup" should occur within three to five years.

(a)

(b)

Figure 5.9: Glines Canyon Dam. *(a) Before removal and (b) simulation after removal.*

Following the removal of both dams, the salmon and steelhead runs are expected to total about 390,000 fish, compared to about 12,000 to 20,000 (primarily hatchery) fish. These fish will provide over 800,000 pounds of carcass biomass (NPS 1995). About 13,000 pounds of this biomass is marine-derived nitrogen and phosphorous, the benefits of which will cascade throughout the aquatic and terrestrial ecosystem. The vast majority of wildlife species are expected to benefit from the restoration of this food resource and the recovery of over 700 acres of important lowland habitat. Restoration of the fish runs will also support the federal government's trust responsibility to the Tribe for its treaty-reserved harvest rights. More wetlands will be recovered than will be lost from draining the reservoirs.

As in the case of restoration goals, it is imperative that restoration objectives be realistic for the restoration area and be measurable. Objectives must therefore be based on the site's expected capability and not necessarily on its unaltered natural potential. It is much more useful to have realistic objectives reflecting stream corridor conditions that are both achievable and measurable than to have vague, idealistic objectives reflecting conditions that are neither.

For example, an overall restoration goal might be to improve fish habitat. Several supporting objectives might include the following:

- Improve water temperature by providing shade plants.
- Construct an instream structure to provide a pool as a sediment trap.
- Work with local landowners to encourage near-stream conservation efforts.

If these objectives were to be used as success criteria, however, they would require more specific, measurable wording. For example, the first objective could be written to state that buttonbush planted along streambanks exhibit a 50 percent survival rate after three growing seasons and are not less than 5 feet in height. This vegetative cover results in a net reduction in water temperature within the stream. It should be noted that this issue of success or evaluation criteria is critical to stream corridor restoration. This is explored in more detail in Chapters 6 and 9.

5.B Alternative Selection and Design

The selection of technically feasible alternatives and subsequent design are intended to solve the identified problems, realize restoration opportunities, and accomplish restoration goals and objectives. Alternatives range from making minor modifications and letting nature work to total reconstruction of the physical setting. An efficient approach is to conceptualize, evaluate, and select general solutions or overall strategies before developing specific alternatives.

This section focuses on some of the general issues and considerations that should be taken into account in the selection and design of stream corridor *restoration alternatives*. It sets the stage for the more detailed presentation of restoration design in Chapter 8 of this document.

Important Factors to Consider in Designing Restoration Alternatives

The design of restoration alternatives is a challenging process. In developing alternatives, special consideration should be given to managing causes as opposed to treating symptoms, tailoring restoration design to the appropriate scale (landscape/corridor/stream/reach), and other scale-related issues.

Managing Causes vs. Treating Symptoms

When developing restoration alternatives, three questions regarding the factors that influence conditions in the stream corridor must be addressed. These are critical questions in determining whether a passive, nonstructural alternative is appropriate or whether a more active restoration alternative is needed.

FAST FORWARD

Preview Chapter 8's restoration design section

Alternative Selection and Design Considerations

Supporting Analyses for Selecting Alternatives

- *Feasibility study*
- *Cost-effectiveness analysis*
- *Risk assessment*
- *Environmental impact analysis*

Factors to Consider in Alternative Design

- *Managing causes vs. treating symptoms*
- *Landscape/Watershed vs. corridor reach*
- *Other spatial and temporal considerations*

1. What have been the implications of past management activities in the stream corridor (a cause-effects analysis)?
2. What are the realistic opportunities for eliminating, modifying, mitigating, or managing these activities?
3. What would be the response of impaired conditions in the corridor if these activities could be eliminated, modified, mitigated, or managed?

If the causes of impairment can realistically be eliminated, complete ecosystem restoration to a natural or unaltered condition might be a feasible objective and the focus of the restoration activity will be clear. If the causes of impairment cannot realistically be eliminated, it is critical to identify what options exist to manage either the causes or symptoms of altered conditions and what effect, if any, those management options might have on the subject conditions.

If it is not feasible to manage the cause(s) of impaired conditions, then mitigating the impacts of disturbance(s) is an alternative method of implementing sustainable stream corridor restoration. By choosing mitigation, the focus of the restoration effort might then be on addressing only the symptoms of impaired conditions.

When disturbance cannot be fully eliminated, a logical planning process must be used to develop alternative management options. For example, in analyzing bank erosion, one conclusion might be that accelerated watershed sediment delivery has produced lateral instability in the stream system, but modification of land-use patterns causing the problem is not a feasible management op-

Figure 5.10: Streambank erosion. *In designing alternatives for bank erosion it is important to assess the feasibility of addressing the cause of the problem (e.g., modify land uses) or treating the symptom (e.g., install bank-erosion control structures).*

tion at this time (**Figure 5.10**). It might therefore still be possible to develop a channel erosion condition objective and to identify treatments such as engineered or soil-bioengineered bank erosion control structures, but it will not be possible to return the stream corridor to its predisturbance condition. Other resource implications of increased watershed sediment delivery will persist (e.g., altered substrate conditions, modified riffle-pool structure, and impaired water quality).

It is important to note that in treating causes, a danger always remains that in treating one symptom of impairment, another unwanted change in stream corridor conditions will be triggered. To continue with the erosion example, bank hardening in one location might interfere with sedimentation processes critical to floodplain and riparian habitats, or it might simply transfer lateral instabilities from one location in a stream reach to some other location.

Core Elements of Restoration Alternatives

At a minimum, alternatives should contain a management summary of proposed activities, including an overview of the following elements:

- *Detailed site description containing relevant discussion of all variables having a bearing on that alternative.*
- *Identification and quantification of existing stream corridor conditions.*
- *Analysis of the various causes of impairment and the effect of management activities on these impaired conditions and causes in the past.*
- *Statement of specific restoration objectives, expressed in terms of measurable stream corridor conditions and ranked in priority order.*
- *Preliminary design alternatives and feasibility analysis.*
- *Cost-effectiveness analysis for each treatment or alternative.*
- *Assessment of project risks.*
- *Appropriate cultural and environmental clearances.*
- *Monitoring plan linked to stream corridor conditions.*
- *Anticipated maintenance needs and schedule.*
- *Alternative schedule and budget.*
- *Provision to make adjustments per adaptive management.*

Landscape/Watershed vs. Corridor/Reach

The design and selection of alternatives should address the following relationships:

- Reach to stream
- Stream to corridor
- Corridor to landscape
- Landscape to region

Characterizing those relationships requires a good inventory and analysis of conditions and functions on all levels including stream structure (both vertical and horizontal) and human activities within the watershed.

The restoration design should include innovative solutions to prevent or mitigate, to the extent possible, negative impacts on the stream corridor from upstream land uses. Land use activities within a watershed may vary widely within generalized descriptions of urban, agricultural, recreation, etc. For example, urban residential land use could comprise neighborhoods of manicured lawns, exotic plants, and roof runoff directed to nearby storm sewers. Or residential use might be composed of neighborhoods with native cover types, overhead canopy, and roof runoff flowing to wetland gardens. Restoration

REVERSE

Review Chapter 1's Dynamic Equilibrium section.

design should address the storm water flows, pollutants, and sediment loadings from these different land uses that could impact the stream corridor.

Since it is usually not possible to remove the human activities that disturb stream corridors, where seemingly detrimental activities like gravel mining, damming, and road crossings are present in the watershed or in the stream corridor itself, restoration design should provide the best possible solutions for maintaining optimum stream corridor functions while meeting economic and social objectives (**Figure 5.11**).

Other Time and Space Considerations

Restoration design flexibility is critical to long-term success and achievement of dynamic equilibrium. Beyond the stream corridor is an entire landscape that functions in much the same way as the corridor. When designing and choosing alternatives, it is important to consider the effect of the restoration on the entire landscape. A wide, connected, and diverse stream corridor will enhance the functions of the landscape as well as those of the corridor. Connectivity and width also increase the resiliency of the stream corridor to landscape perturbations and stress, whether induced naturally or by humans.

Figure 5.11: Stream buffers in agricultural areas. *It is not possible to remove human activity from the corridor. Design alternatives should provide the best possible way of achieving the desired goals without negating the activity.*

Alternatives should also be relatively elastic, although time and physical boundaries might not be so flexible. As discussed in Chapter 1, dynamic equilibrium requires that the restoration design be allowed an opportunity to mold itself to the changing conditions of the corridor over time and to the disturbances that are a part of the natural environment. Alternatives should be weighed against one another by considering how they might react to increasing land pressures, climate changes, and natural perturbations. Structure should be planned to provide necessary functions at each phase of the corridor's development.

A possible restoration design concept is Forman and Godron's (1986) "string of lights." Over time, the variations among landscape elements mean that some provide more opportunities for desired functions than others. A stream corridor connection provides a pathway through the landscape matrix such that it can be thought of as a string of lights in which some turn on and burn brightly for a time, while others fade away for a short time (**Figure 5.14**). As the string between these lights, the stream corridor is critical to the long-term stability of landscape functions. Alternatives could therefore fit the metaphor of a string of lights to sustain the corridor through time.

Supporting Analyses for Selecting Restoration Alternatives

Once the restoration alternatives have been defined, the next step is to evaluate all the feasible alternatives and management options. In conducting this evaluation it is important to apply several different screening criteria that allow the consideration of a diverse number of factors. In general, the application of the following supporting analytical approaches ensures the selection of the best alternative or group of alternatives for the restoration initiative:

- Cost-effectiveness and incremental cost analysis
- Evaluation of benefits
- Risk assessment
- Environmental impact analysis

Figure 5.14: "String of lights." *Patches along the stream corridor provide habitat in an agricultural setting.*
Source: C. Zabawa.

Cost-Effectiveness and Incremental Cost Analyses

In its National Strategy for the Restoration of Aquatic Ecosystems, the National Research Council (NRC) states that, in lieu of benefit-cost analysis, the evaluation and ranking of restoration alternatives should be based on a framework of incremental cost analysis: "Continually questioning the value of additional elements of a restoration by asking whether the actions are 'worth' their added cost is the most practical way to decide how much restoration is enough" (NRC 1992). As an example, the Council cites the approach where "a justifiable level [of output] is chosen in recognition of the incremental costs of increasing [output] levels and as part of a negotiation process with affected interests and other federal agencies" (NRC 1992).

As described below, cost-effectiveness analysis is performed to identify the least-cost solution for each possible level of nonmonetary output under consideration. Subsequent incremental cost analysis reveals the increases in cost that accompany increases in the level of output, asking the question "As we increase the scale of this project, is each subsequent level of additional output worth its additional cost?"

Data Requirements: Solutions, Costs, and Outputs

Cost-effectiveness and incremental cost analyses may be used for any scale of planning problem, ranging from local, site-specific problems to problems at the more extensive watershed and ecosystem scales. Regardless of the problem-solving scale, three types of data must be obtained before conducting the analyses: a list of solutions and, for each solution, estimates of its ecosystem or other nonmonetary effects (outputs) and estimates of its economic effects (costs).

The term "solutions" is used here to refer generally to techniques for

CASE STUDY

Meander Reconstruction on the J. Bar S. Winter Feeding Area

January 1, 1997, was an eventful time for Asotin Creek, Washington, residents. In a period of less than a year, two large flood events occurred, causing extreme damage at numerous sites throughout the watershed.

The ordinary high flow (often referred to as channel forming or bankfull flow) is the natural size channel a river will seek, over time. Asotin Creek's flows exceeded the ordinary high flow 10 times at Asotin and Headgate parks.

*One impacted site is on the South Fork of Asotin Creek. This site, referred to as the J. Bar S. winter feeding site (**Figure 5.12**) and owned by Jake and Dan Schlee, received floods more than 10 times the ordinary high flow. Previous to January 1, the stream was located over a hundred feet away from the haysheds and feeding area. When large amounts of rock, cobble, and gravel collapsed into the right side of the stream corridor, the entire channel was directed toward the winter feeding area and hayshed. This redirection of flood flows undermined and eroded away thousands of tons of valuable topsoil and property, threatening the loss of the hayshed and corral. Fences and alternative water sources were destroyed. The challenges for stream restoration at this site were numerous because of the potential bridge constriction at the bottom, excessive downcutting, and limited area within which to work (**Figure 5.13**).*

The Asotin County Conservation District put an interdisciplinary team together in the spring of 1997 to develop a plan and alternative for the J. Bar S. site. An innovative approach referred to as meander reconstruction was proposed by the interdisciplinary team to correct the problem and restore some natural capabilities of the stream. It was accepted by the landowners and Asotin County Conservation District. Some natural capabilities are the dissipation of flood energy over floodplains and maintenance of a stable ordinary high flow channel.

***Figure 5.12: The J. Bar S. winter feeding area.** This area received floods more than 10 times the ordinary high flow.*

Additional benefits to the approach would be to reestablish proper alignment with the bridge and restore fish habitat. This alternative was installed within the last 2 weeks of September 1997. Care was used to move young steelhead out of the old channel while the new meandering channel was built. Other practices on site such as alternative water sources and fencing are soon to follow.

The meander reconstruction was designed to address both the landowners' concerns and stream processes. Although on-site stream restoration cannot resolve problems higher up in the watershed, it can address immediate concerns regarding fish habitat and streambank stability. Numerous pools with woody debris were introduced to enhance salmon rearing and resting habitat. The pools were designed and set to a scour pattern unique to this stream type. This meander reconstruction is the first of its kind in the state of Washington.

Figure 5.13: South Fork of Asotin Creek restoration site. *(a) Before reconstruction and (b) after reconstruction.*

*The principal funding for this project was provided by the Bonneville Power Administration (BPA) (**Table 5.1**). The BPA funds are used to help implement the Asotin Creek Model Watershed Plan, which is part of the Northwest Power Planning Council's "Strategy for Salmon." The moneys for funding by BPA are generated from power rate payers in the Northwest. The purpose for funding is to improve the fish habitat component of the "Strategy for Salmon," which is one of the four elements referred to as the four H's—harvest management, hatcheries and their practices, survival at hydroelectric dams, and fish habitat improvement.*

Table 5.1: Project costs for J. Bar S. winter feeding area meander reconstruction and upstream revetments.

Projects	Costs
Reconstruction meanders	$10,200
Upstream revetments	$2,800
Fencing	$400
Riparian/streambank plantings and potential operation and maintenance *(to be completed)*	$3,500

Note: Original estimate in April 1997 was $26,600

The Instream Flow Incremental Methodology

*The Instream Flow Incremental Methodology (IFIM) is designed for river system management. IFIM is composed of models linked to describe the spatial and temporal habitat features of a given river (**Figure 5.15**). It uses hydrologic analyses to describe, evaluate, and compare water use throughout a river system to understand the limits of water supply. Its organizational framework is useful for evaluating and formulating alternative water management options. Ultimately, the goal of any IFIM application is to ensure the preservation or enhancement of fish and wildlife resources. Emphasis is placed on displaying data from several years to understand variability in both water supply and habitat.*

IFIM is meant to be implemented in five sequential phases—problem identification, study planning, study implementation, alternatives analysis, and problem resolution. Each phase must precede the remaining phases, though iteration is necessary for complex projects.

Problem Identification

The first phase has two parts—a legal-institutional analysis and a physical analysis. The legal-institutional analysis identifies all affected or interested parties, their concerns, information needs, relative influence or power, and the potential decision process (e.g., brokered or arbitrated). The physical analysis determines the physical location and geographic extent of probable physical and chemical changes to the system and the aquatic resources

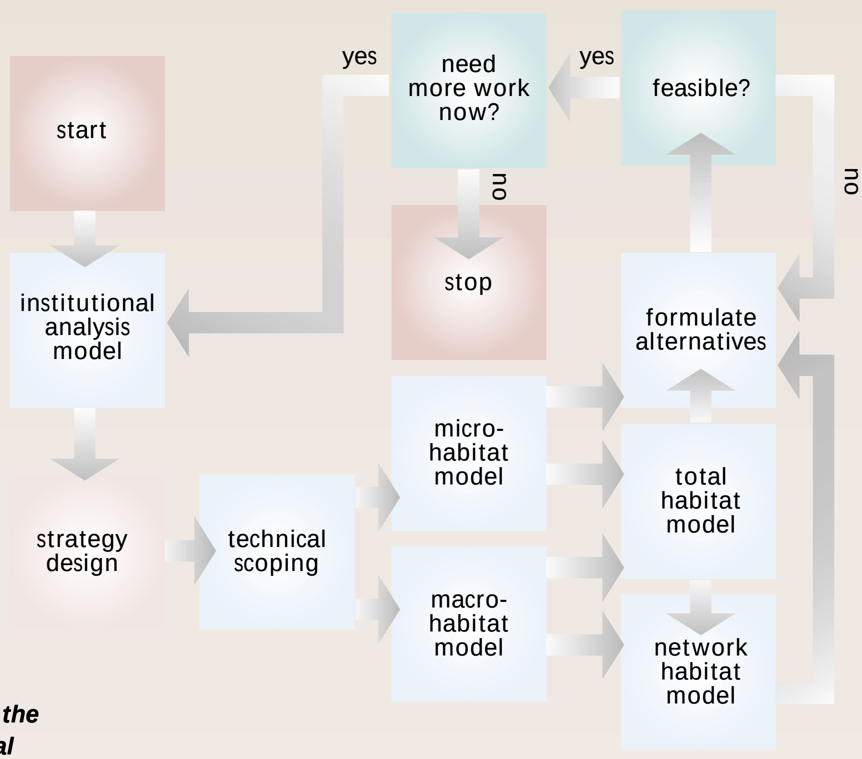


Figure 5.15: Overview of the instream flow incremental methodology. *IFIM describes the spatial and temporal habitat features of a given river.*

of greatest concern, along with their respective management objectives.

Study Planning

The study planning phase identifies information needed to address project concerns, information already available, information that must be obtained, and data and information collection methods. Study planning should result in a concise, written plan that documents all aspects of project execution and costs. It should also identify pertinent temporal and spatial scales of evaluation.

Hydrologic information chosen to represent the baseline or reference condition should be reexamined in detail during this phase to ensure that biological reference conditions are adequate to evaluate critical life history phases of fish populations.

Study Implementation

The third phase consists of several sequential activities—data collection, model calibration, predictive simulation, and synthesis of results. Data are collected for physical and chemical water quality, habitat suitability, population analysis, and hydrologic analysis. IFIM relies heavily on models because they can be used to evaluate new projects or new operations of existing projects. Model calibration and quality assurance are key during this phase to obtain reliable estimates of the total habitat available for each life stage of each species over time.

Alternatives Analysis

The alternatives analysis phase compares all alternatives, including a preferred alternative and other alternatives, with the baseline condition and can lead to new alternatives that meet the multiple objectives of the involved parties. Alternatives are examined for:

- *Effectiveness: Are objectives sustainable?*
- *Physical feasibility: Are water supply limits exceeded?*
- *Risk: How often does the biological system collapse?*
- *Economics: What are the costs and benefits?*

Problem Resolution

This final phase includes selection of the preferred alternative, appropriate mitigation measures, and a monitoring plan. Because biological and economic values differ, data and models are incomplete or imperfect, opinions differ, and the future is uncertain, IFIM relies heavily on professional judgment by interdisciplinary teams to reach a negotiated solution with some balance among conflicting social values.

A monitoring plan is necessary to ensure compliance with the agreed-upon flow management rules and mitigation measures. Post-project monitoring and evaluation should be considered when appropriate and should be mandatory when channel form will respond strongly to the selected new flow and sediment transport conditions.

For More Information on IFIM

The earliest and best documented application of IFIM involved a large hydroelectric project on the Terror River in Alaska (Lamb 1984, Olive and Lamb 1984). Another application involved a Section 404 permit on the James River, Missouri (Cavendish and Duncan 1986). Nehring and Anderson (1993) discuss the habitat bottleneck hypothesis. Stalnaker et al. (1996) discuss the temporal aspects of instream habitats and the identification of potential physical habitat bottlenecks. Relations between habitat variability and population dynamics are described by Bovee et al. (1994). Thomas and Bovee (1993) discuss habitat suitability criteria. IFIM has been used widely by state and federal agencies (Reiser et al. 1989, Armour and Taylor 1991). Additional references and information on available training can currently be obtained from the Internet at http://www.mesc.nbs.gov/rsm/IFIM.html.

accomplishing planning objectives. For example, if faced with a planning objective to "Increase waterfowl habitat in the Blue River Watershed," a solution might be to "Construct and install 50 nesting boxes in the Blue River riparian zone." Solutions may be individual management measures (for example, clear a channel, plant vegetation, construct a levee, or install nesting boxes), plans (various combinations of management measures), or programs (various combinations of plans, perhaps at the landscape scale).

Cost estimates for a solution should include both financial implementation costs and economic opportunity costs. Implementation costs are direct financial outlays, such as costs for design, real estate acquisition, construction, operation and maintenance, and monitoring. The opportunity costs of a solution are any current benefits available with the existing state of the watershed that would be foregone if the solution were implemented. For example, restoration of a river ecosystem might require that some navigation benefits derived from an existing river channel be given up to achieve the desired restoration. It is important that the opportunity costs of foregone benefits be accounted for and brought to the table to inform the decision-making process.

The level to which a solution accomplishes a planning objective is measured by the solution's output estimate. Historically, environmental outputs have been expressed as changes in populations (waterfowl and fish counts, for example) and in physical dimensions (acres of wetlands, for example). In recent years, output estimates have been derived through a variety of environmental models such as the U.S. Fish and Wildlife Service's Habitat Evaluation Procedures (HEP), which summarize habitat quality and quantity for specific species in units called "habitat units." Models for ecological communities and ecosystems are in the early stages of development and application and might be more useful at the watershed scale.

Cost-Effectiveness Analysis

In *cost-effectiveness analysis*, solutions that are not rational (from a production perspective) are identified and can be screened out from inclusion in subsequent incremental cost analysis.

Cost-effectiveness screening is fairly straightforward when monetary values are easily assigned. The "output" or nonmonetary benefits of restoration actions are more difficult to evaluate. These benefits may include changes in intangible values of habitat, aesthetics, nongame species populations, and others. The ultimate goal, however, is to be able to weigh objectively all of the benefits of the restoration against its costs.

There are two rules for cost-effectiveness screening. These rules state that solutions should be identified as inefficient in production, and thus not cost-effective, if (1) the same level of output could be produced by another solution at less cost or (2) a greater level of output could be produced by another solution at the same or less cost.

For example, look at the range of solutions in **Figure 5.16**. Applying Rule 1, Solution C is identified as inefficient in production: why spend $3,600 for 100 units of output when 100 units can be obtained for $2,600 with Solution B, a savings of $1,000? In this example, Solution C could also be screened out by the application of Rule 2: why settle for 100 units of output with Solution C when 20 additional units can be provided by Solution E at the same cost? Also by applying Rule 2, Solution D is screened out: why spend $4,500 for 110

Solution	Units of Output	Total Cost ($)
No action	0	0
A	80	2,000
B	100	2,600
C	100	3,600
D	110	4,500
E	120	3,600
F	140	7,000

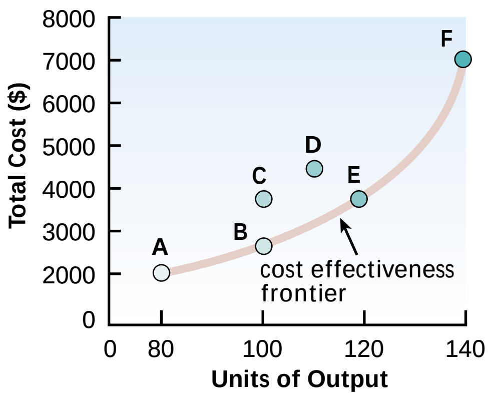


Figure 5.16: Cost effectiveness frontier. *This graph plots the solutions' total cost (vertical axis) against their output levels (horizontal axis).*

units when 10 more units could be produced by E for $900 less cost?

Figure 5.16 shows the "cost-effectiveness frontier" for the solutions listed in the table. This graph, which plots the solutions' total cost (vertical axis) against their output levels (horizontal axis), graphically depicts the two screening rules. The cost-effective solutions delineate the cost-effectiveness frontier. Any solutions lying inside the frontier (above and to the left), such as C and D, are not cost-effective and should not be included in subsequent incremental cost analysis.

Incremental Cost Analysis

Incremental cost analysis is intended to provide additional information to support a decision about the desired level of investment. The analysis is an investigation of how the costs of extra units of output increase as the output level increases. Whereas total cost and total output information for each solution is needed for cost-effectiveness analysis, incremental cost analysis requires data showing the difference in cost (incremental cost) and the difference in output (incremental output) between each solution and the next-larger solution.

Continuing with the previous example, the incremental cost and incremental output associated with each solution are shown in **Figure 5.17**. Solution A would provide 80 units of output at a cost of $2,000, or $25 per unit. Solution B would provide an additional 20 units of output (100 – 80) at an additional cost of $600 ($2,600 – $2,000). The incremental cost per unit (incremental cost divided by incremental output) for the additional 20 units B provides over A is, therefore, $30. Similar computations can be made for solutions E and F. Solutions C and D have been deleted from the analysis because they were previously identified as inefficient in production.

As shown in **Figure 5.17,** the incremental cost per unit is measured on the vertical axis; both total output and incremental output can be measured on the horizontal axis. The distance from the origin to the end of each bar indicates total output provided by the corresponding solution. The width of the bar associated with each solution identifies the incremental amount of output that would be provided over the previous, smaller-scaled solution; for example, Solution E provides 20 more units of output than Solution B . The height of the bar illustrates the cost per unit of that additional output; for example, those 20 additional units obtainable through Solution E cost $50 each.

Solution	Level of Output		Cost ($)		
	Total Output	Incremental Output	Total Cost	Incremental Cost	Incremental Cost Incremental Output
No action	0	0	0	0	0
A	80	80	2,000	2,000	25
B	100	20	2,600	600	30
E	120	20	3,600	1,000	50
F	140	20	7,000	3,400	170

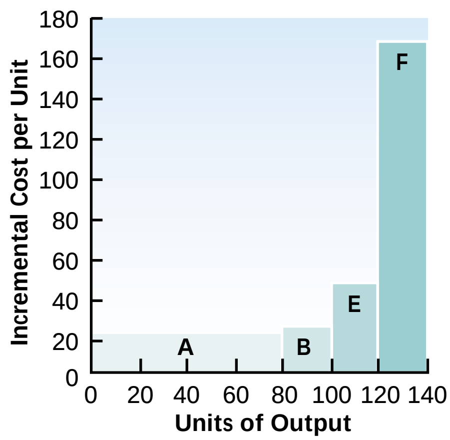


Figure 5.17: Incremental cost and output display. *This graph plots the cost per unit (vertical axis) against the total output and incremental output (horizontal axis).*

Decision Making—"Is It Worth It?"

The table in Figure 5.17 presents cost and output information for the range of cost-effective solutions under consideration in a format that facilitates the investment decision of which (if any) solution should be implemented. This decision process begins with the decision of whether it is "worth it" to implement Solution A.

Figure 5.17 shows Solution A provides 80 units of output at a cost of $25 each. If it is decided that these units of output are worth $25 each, the question becomes "Should the level of output be increased?" To answer this question, look at Solution B, which provides 20 more units than Solution A. These 20 additional units cost $30 each. "Are they worth it?" If "yes," look to the next larger solution, E, which provides 20 more units than B at $50 each, again asking "Are they worth it?" If it is decided that E's additional output is worth its additional cost, look to F, which provides 20 more units than E at a cost of $170 each.

Cost-effectiveness and incremental cost analyses will not result in the identification of an "optimal" solution as is the case with cost-benefit analysis. However, they do provide information that decision makers can use to facilitate and support the selection of a single solution. Selection may also be guided by decision guidelines such as output "targets" (legislative requirements or regulatory standards, for example), minimum and maximum output thresholds, maximum cost thresholds, sharp breakpoints in the cost-effectiveness or incremental cost curves, and levels of uncertainty associated with the data.

In addition, the analyses are not intended to eliminate potential solutions from consideration, but rather to present the available information on costs and outputs in a format to facilitate plan selection and communicate the decision process. A solution identified as "inefficient in production" in cost-effectiveness analysis might still be desirable; the analysis is intended to make the other options and the associated trade-offs explicit. Reasons for selecting "off the cost-effectiveness curve" might include considerations that were not captured in the output model being used, or uncertainty present in cost and output estimates. Where such issues exist, it is important that they be explicitly introduced to the decision process. After all, the purpose of conducting cost-effectiveness and incremental cost analyses is to provide more, and hopefully better, information to support decisions about investments in environmental (or other nonmonetary) resources.

Evaluation of Benefits

Cost-effectiveness and incremental cost analyses are but one approach for evaluating restoration projects. More broadly defined approaches, sometimes referred to as benefit maximization, fall into three categories (USEPA 1995a):

1. Prioritized benefits are ranked by preference or priority, such as best, next best, and worst. Available information might be limited to qualitative descriptions of benefits, but might be sufficient.
2. Quantifiable benefits can be counted but not priced. If benefits are quantifiable on some common scale (e.g., percent removal of fine sediment as an index of spawning substrate improvement), a cost per unit of benefits that identifies the most efficient producer of benefits can be devised (similar to the previously described cost effectiveness and incremental cost analyses).
3. Nonmonetary benefits can be described in monetary terms. For example, when restoration provides better fish habitat than point source controls would provide, the monetary value of improved fish habitat (e.g., economic benefits of better fishing) needs to be described. Assigning a monetary value to game or commercial species might be relatively easy; other benefits of improved habitat quality (e.g., improved aesthetics) are not as easily determined, and some (e.g., improved biodiversity) cannot be quantified monetarily. Each benefit must, therefore, be analyzed differently.

Key considerations in evaluating benefits include timing, scale, and value. The short-term and long-term benefits of each project must be measured. In addition, potential benefits and costs must be considered with respect to results on a local level versus a watershed level. Finally, there are several ways to value the environment based on human use and appreciation. Commercial fish values can be calculated, recreational or sport-fishing values can be estimated by evaluating the costs of travel and expenditures, some aesthetic and improved flood control values can be estimated through changes in real estate value, and social values (such as wildlife, aesthetics, and biodiversity) can be estimated by surveying people to determine their willingness to pay.

Risk Assessment

Stream-corridor restoration involves a certain amount of risk that, regardless of the treatment chosen, restoration efforts will fail. To the extent possible, an identification of these risks for each alternative under consideration is a useful tool for analysis by the decision maker. A thorough risk assessment is particularly important for those large-scale restoration efforts which involve significant outlays of labor and money or where a significant risk to human life or property would occur downstream should the restoration fail.

A primary source of risk is the uncertainty associated with the quality of data used in problem analysis or restoration design. Data uncertainty results from errors in data collection and analysis, external influences on resource variables, and random error associated with certain statistical procedures (e.g., regression analysis). Data uncertainty is usually handled by application of statistical procedures to select confidence intervals that estimate the quality of the data used for analysis and design.

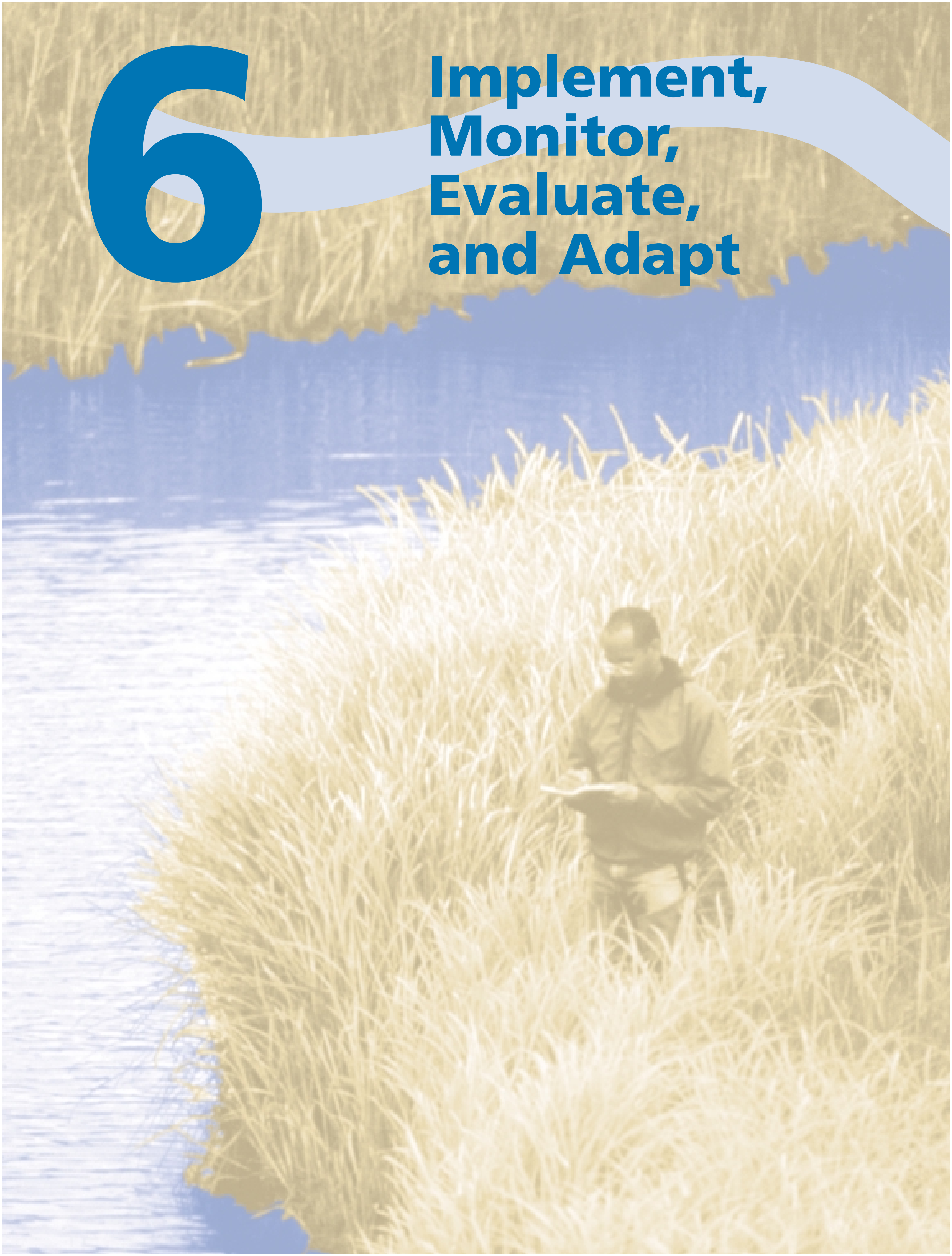
The first source of risk is the possibility that design conditions will be exceeded by natural variability before the project is established. For example, if a channel is designed to pass a 50-year flood on the active floodplain, but it takes 5 years to establish riparian vegetation on that floodplain, there is a certain risk that the 50-year flood will be exceeded during the 5 years it takes to establish natural riparian conditions on the floodplain. A similar situation would exist where a revegetation treatment requires a certain amount of moisture for vegetation establishment and assumes the worst drought of record does not occur during the establishment period. This kind of risk is readily amenable to statistical analysis using the binomial distribution and is presented in several existing reports on hydrologic risk (e.g., Van Haveren 1986).

Environmental Impact Analysis

The fact that the impetus behind any stream corridor restoration initiative is recovery or rehabilitation does not necessarily mean that the proposal is without adverse effects or public controversy. Short-term and long-term adverse impacts might result. For example, implementation activity such as earthwork involving heavy equipment might temporarily increase sedimentation or soil compaction. Furthermore, restoration of one habitat type is probably at the expense of another habitat type; for example, recreating habitat to benefit fish might come at the expense of habitat used by birds.

Some alternatives, such as total exclusion to an area, might be well defined scientifically but have little social acceptability. Notwithstanding the environmental impacts and trade-offs, both fish and birds have active constituencies that must be involved and whose concerns must be acknowledged. Therefore, careful environmental impact analysis considers the potential short- and long-term direct, indirect, and cumulative impacts, together with full public involvement and disclosure of both the impacts and possible mitigating measures. This is no less important for an initiative to restore a stream corridor than for any other type of related activity.

6 Implement, Monitor, Evaluate, and Adapt



6.A Restoration Implementation

- *What are the steps that should be followed for successful implementation?*
- *How are boundaries for the restoration defined?*
- *How is adequate funding secured for the duration of the project?*
- *What tools are useful for facilitating implementation?*
- *Why and how are changes made in the restoration plan once implementation has begun?*
- *How are implementation activities organized?*
- *How are roles and responsibilities distributed among restoration participants?*
- *How is a schedule developed for installation of the restoration measures?*
- *What permits and regulations will be necessary before moving forward with restoration measures?*

6.B Restoration Monitoring, Evaluation, and Adaptive Management

- *What is the role of monitoring in stream corridor restoration?*
- *When should monitoring begin?*
- *How is a monitoring plan tailored to the specific objectives of a restoration initiative?*
- *Why and how is the success or failure of a restoration effort evaluated?*
- *What are some important considerations in developing a monitoring plan to evaluate the restoration effort?*

6 Implementing, Monitoring, Evaluating, and Adapting

The development of restoration goals and objectives and the formulation and selection of restoration alternatives does not mark the end of the restoration plan development process. Successful stream corridor restoration requires careful consideration of how the restoration design will be implemented, monitored, and evaluated. In addition, it requires a commitment to long-term planning and management that facilitates adaptation and adjustment in light of changing ecological, social, and economic factors.

This chapter focuses on the final stages of restoration plan development. It presents the basics of restoration implementation, monitoring, evaluation, and management within a planning context. Specifically, the administrative and planning elements associated with these activities are discussed in detail. This chapter is intended to set the stage for the technical or "how to" discussion of restoration implementation, monitoring, maintenance, and management presented in Chapter 9. The present chapter is divided into two main sections.

Section 6.A: Restoration Implementation

The first section examines the basics of restoration implementation. It includes a discussion of all aspects relevant to carrying out the design, including funding, *incentives, division of responsibilities, and the actual implementation process.*

Section 6.B: Restoration Monitoring, Evaluation, and Adaptive Management

Once the basic design is executed, the monitoring, evaluation, and adaptation process begins. This section explores some of the basic considerations that need to be addressed in examining and evaluating the success of the restoration initiative. In addition, it emphasizes the importance of making adjustments to the restoration design based on information received during the monitoring and evaluation process. Note especially that the plan development process can be reiterated if conditions in or affecting the stream corridor change or if perceptions or goals change due to social, economic, or legal developments.

6.A Restoration Implementation

Implementation is a critical component of the stream corridor restoration process. It includes all the activities necessary to execute the restoration design and achieve restoration goals and objectives. Although implementation is typically considered the "doing," not the "planning," successful restoration implementation demands a high level of advance scheduling and foresight that constitutes planning by any measure.

Securing Funding for Restoration Implementation

An essential component of any stream corridor restoration initiative is the availability of funds to implement the restoration design. As discussed in Chapter 4, identifying potential funding sources should be one of the first priorities of the advisory group and decision maker. By the time the restoration initiative reaches the implementation stage, however, the initial identification of sources should be translated into tangible resource allocations. In other words, all needed funding should be secured so that restoration implementation can be initiated. It is important to remember that financing might ultimately come from several sources. All benefactors, both public and private, should be identified and appropriate cost-sharing arrangements should be developed.

An important element of securing funding for restoration is linking the available resources to the specific activities that will be part of implementation. Specifically, it should be the responsibility of the restoration planners to categorize the various activities that will be part of the restoration, determine how much each activity will cost to implement, and determine how much funding is available for each activity. In performing this analysis it should be noted that funding need not be thought of exclusively in terms of available "cash." Often many of the activities that are part of the restoration effort can be completed with the work of the staff of a participating agency or other organization.

Securing Funding for Anacostia Restoration Initiatives

The Anacostia Watershed Restoration Committee annually seeks funding for many restoration initiatives. In FY91, more than 50 projects were funded by over a dozen local, state, and federal agencies. Funding sources are matched with appropriate watershed projects. In about half a dozen cases, special funding came from federal agencies like the Corps of Engineers, USDA, and EPA. The overwhelming majority of projects, however, involved a skillful coordination of existing sources of support from state and local governmental programs combined with additional help from nongovernmental organizations such as Trout Unlimited and from other citizen volunteers. The signatory agencies (e.g., the District of Columbia, Prince George's and Montgomery Counties, and the state of Maryland) fund most of the storm water retrofit, monitoring, and demonstration projects, as well as public participation activities.

*A key element in maximizing resources from existing programs is the organization of special technical assistance teams for priority subwatersheds (**Figure 6.1**). Subwatershed Action Plan (SWAP) coordinators carry out public education and outreach efforts, and they also assist in comparing the management needs of their subwatersheds with activities of local government. Because many of the problems in the Anacostia relate to urban storm water runoff, many infrastructure projects can have a bearing on restoration needs. When such infrastructure projects are identified, SWAP coordinators try to coordinate with the project sponsor and involve the sponsor in the Anacostia program. If possible, the SWAP coordinator attempts to integrate the retrofit and management objectives of the program and the project.*

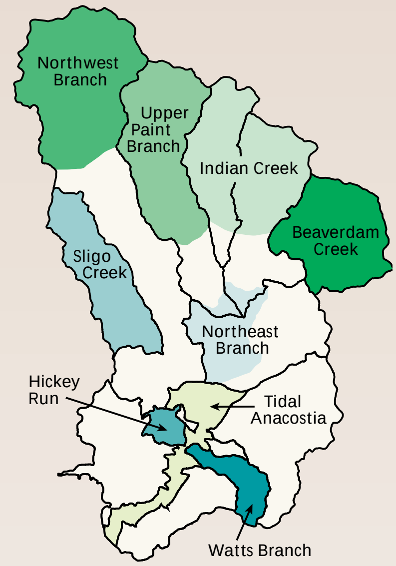


Figure 6.1: Anacostia Basin. *Nine priority subwatersheds compose the Anacostia Basin.* Source: MWCOG 1997. Reprinted by permission.

It is important to note that there might be insufficient funding to carry out all of the activities outlined in the stream corridor restoration design. In this situation, planners should recognize that this is, in fact, a common occurrence and that restoration should proceed. An effort should be made, however, to prioritize restoration activities, execute them as effectively and efficiently as possible, and document success. Typically, if the restoration initiative is demonstrated as producing positive results and benefits, additional funding can be acquired.

Identifying Tools to Facilitate Restoration Implementation

In addition to securing funding, it is important to identify the various tools and mechanisms available to facilitate the implementation of the restoration design. Tools available to the stream corridor restoration practitioner include a mix of both nonregulatory or incentive-based mechanisms and regulatory mechanisms. The *Tools for Facilitating the Implementation of Stream Corridor Restoration Measures* box contains a list and description of some of these tools.

As discussed in Chapter 4, the use of incentives can be effective in obtaining participation from private landowners

REVERSE

Review Chapter 4's conservation easement section.

Important Components of Restoration Implementation

- *Securing Funding for Restoration Implementation*
- *Identifying Tools to Facilitate Implementation*
- *Dividing Implementation Responsibilities*
- *Installing Restoration Measures*

in the corridor and in gaining their support for the restoration initiative (**Figure 6.2**). Incentive programs involving cost shares, tax advantages, or technical assistance can encourage private landowners to implement restoration measures on their property, even if the results of these practices are not directly beneficial to the owner.

In addition to incentives, regulatory approaches are an important option for stream corridor restoration. Regulatory programs can be simple, direct, and easy to enforce. They can be effectively used to control land use and various land use activities.

***Figure 6.2**: Landowner participation.*
Restoration on private lands can be facilitated by landowners.

Deciding which tool, or combination of tools, is most appropriate for the restoration initiative is not an easy endeavor. The following is a list of some important tips that should be kept in mind when selecting among these tools (USEPA 1995a).

- Without targeted and effective education programs, technical assistance and cost sharing alone will not ensure implementation.
- Enforcement programs can also be costly because of the necessary inspections and personnel needed to make them effective.
- The most successful efforts appear to use a mix of both regulatory and incentive-based approaches. An effective combination might include variable cost-share rates, market-based incentives, and regulatory backup coupled with support services (governmental and private) to keep controls maintained and properly functioning.

Dividing Implementation Responsibilities

With funding in place and restoration tools and activities identified, the focus should shift to dividing the responsibilities of restoration implementation among the participants. This process involves identifying all the relevant players, assigning responsibilities, and securing commitments.

Identifying the Players

The identification of the individuals and organizations that will be responsible for implementing the design is

Tools for Facilitating the Implementation of Stream Corridor Restoration Measures

Education	*Programs that target the key audience involved with or affected by the restoration initiative to elicit awareness and support. Programs can include technical information as well as information on the benefits and costs of selected measures.*
Technical Assistance	*One-to-one interaction between professionals and the interested citizen or landowner. Includes provision of recommendations and technical assistance about restoration measures specific to a stream corridor or reach.*
Tax Advantages	*Benefits that can be provided through state and local taxing authorities or by a change in the federal taxing system that rewards those who implement certain restoration measures.*
Cost-share to Individuals	*Direct payment to individuals for installation of specific restoration measures. Most effective where the cost-share rate is high enough to elicit widespread participation.*
Cross-compliance Among Existing Programs	*A type of quasi-regulatory incentive/disincentive that conditions benefits received on meeting certain requirements or performing in a certain way. Currently in effect through the 1985, 1990, and 1996 Farm Bills.*
Direct Purchase of Stream Corridors or of Lands Causing the Greatest Problems	*Direct purchase of special areas for preservation or community-owned greenbelts in urban areas. Costs of direct purchase are usually high, but the results can be very effective. Sometimes used to obtain access to critical areas whose owners are unwilling to implement restoration measures.*
Nonregulatory Site Inspections	*Periodic site visits by staff of local, state, or federal agencies can be a powerful incentive for voluntary implementation of restoration measures.*
Peers	*Simple social acceptance by one's peers or members of the surrounding community, which can provide the impetus for an individual landowner to implement restoration measures. For example, if a community values the use of certain agricultural best management practices (BMPs), producers in those communities are more likely to install them.*

Tools for Facilitating the Implementation of Stream Corridor Restoration Measures (continued)

Direct Regulation of Land Use and Production Activities	*Regulatory programs that are simple, direct, and easy to enforce. Such programs can regulate land uses in the corridor (through zoning ordinances) or the kind and extent of activities permitted, or they can set performance standards for a land activity (such as retention of the first inch of runoff from urban property in the corridor).*
Easements	*Conservation easements on private property are excellent tools for implementing parts of a stream corridor restoration plan (see more detailed discussion in following box). Flowage easements may be a critical component in order to design, construct, and maintain structures and flow conditions.*
Donations	*In some instances, private landowners may be willing, or may be provided economic or tax incentives, to donate land to help implement a restoration initiative.*
Financing	*Normally, a restoration initiative will require multiple sources of funds, and no single funding source may be sufficient. Non-monetary resources may also be instrumental in successfully implementing a restoration initiative.*

essential to successful stream corridor restoration. Since the restoration partners are identified early in the planning process, at this point the focus should be on “reviewing” the list of participants and identifying the ones who are most interested in the implementation phase. Although some new players might emerge, most of the participants interested in the implementation phase will already have been involved in some aspect of the restoration effort (**Figure 6.4**). Typically, partners will change their participation as the process shifts from “evaluating” to “doing.”

The decision maker(s), with assistance from the advisory group, should identify the key partners that will be actively involved in the implementation process.

Assigning Responsibilities

To ensure the effective allocation of responsibilities among the various participants, the decision maker(s) and advisory group should rely on a special interdisciplinary technical team. Specifically, the technical team should oversee and manage the implementation process as well as coordinate the work of other participants, such as contractors and volunteers, involved with restoration implementation. The following are some of the responsibilities of the major participants involved in the implementation process.

Conservation Easements

*Conservation easements are an effective stream corridor management tool on private property regardless of whether the stream reach supports high biodiversity or the stream corridor would benefit from active restoration in conjunction with a modification of adjacent land use activities (**Figure 6.3**). Through a conservation easement, landowners receive financial compensation for giving up or modifying some of their development rights while the easement holder acquires the right to enforce restrictions on the use of the property.*

Specific details of a conservation easement are developed on a case-by-case basis. Only those activities which may be considered incompatible with stream corridor management objectives may be restricted. The value of a conservation easement is typically estimated as the difference between the values of the underlying land with and without the restrictions imposed by the conservation easement. Government agencies or nonprofit organizations must compensate landowners for the rights they are giving up, but not to exceed more than the results are worth to society. The fair market values of the land before and after an easement is established are based on the "highest and best" uses of the land with and without the restrictions imposed by the easement. Once a conservation easement is established, it becomes part of the title on the property, and any stipulations of the conservation easement are retained when the property is sold. Conservation easements may be established indefinitely or for 25 to 30 years.

Conservation easements may be established with federal agencies, such as the U.S. Fish and Wildlife Service or the Natural Resources Conservation Service, with state agencies, or through nonprofit organizations like The Nature Conservancy or Public Land Trusts. It is often beneficial for federal, state, or local governments to establish conservation easements in partnership with nonprofit organizations. These organizations can assist public agencies in acquiring and conveying easements more efficiently since they are able to act quickly, take advantage of tax incentives, and mobilize local knowledge and support.

Conservation easements are beneficial to all parties involved. The landowners benefit by receiving financial compensation for giving up the rights to certain land use activities, enhancing the quality of the natural resources present on their property, and, when applicable, eliminating problems associated with human use in difficult areas. The quality of the land will also increase as a result of providing increased fish and wildlife habitat, improving water quality by filtering and attenuating sediments and chemicals, reducing flooding, recharging ground water, and protecting or restoring biological diversity. Conservation easements are also beneficial to public resource agencies because, in addition to the public benefit of improved quality of the stream corridor's natural resources, they provide an opportunity for public agencies to influence resource use without incurring the political costs of regulation or the full financial costs of outright land acquisition.

Figure 6.3: Conservation easement. *Conservation easements are an effective tool for protecting valuable areas of the stream corridor.*

REVERSE

Review Chapter4's organizational consideration section.

Interdisciplinary Technical Team

As noted above, the interdisciplinary technical team is responsible for overseeing and coordinating restoration implementation and will assign implementation responsibilities. Before identifying roles, however, the technical team should establish some organizational ground rules. *Some Important Organizational Considerations for Successful Teamwork* reviews some of the important logistical issues that need to be addressed by the team. Organizational considerations are also addressed in Chapter 4.

In addition to establishing ground rules, the technical team should appoint a single project manager. This person must be knowledgeable about the structure, function, and condition of the stream corridor; the various elements of the restoration design; and the policies and missions of the various cooperating agencies, citizen groups, and local governments. When consensus-based decisions are not possible due to time limitations, the project manager must be able to make quick and informed decisions relevant to restoration implementation.

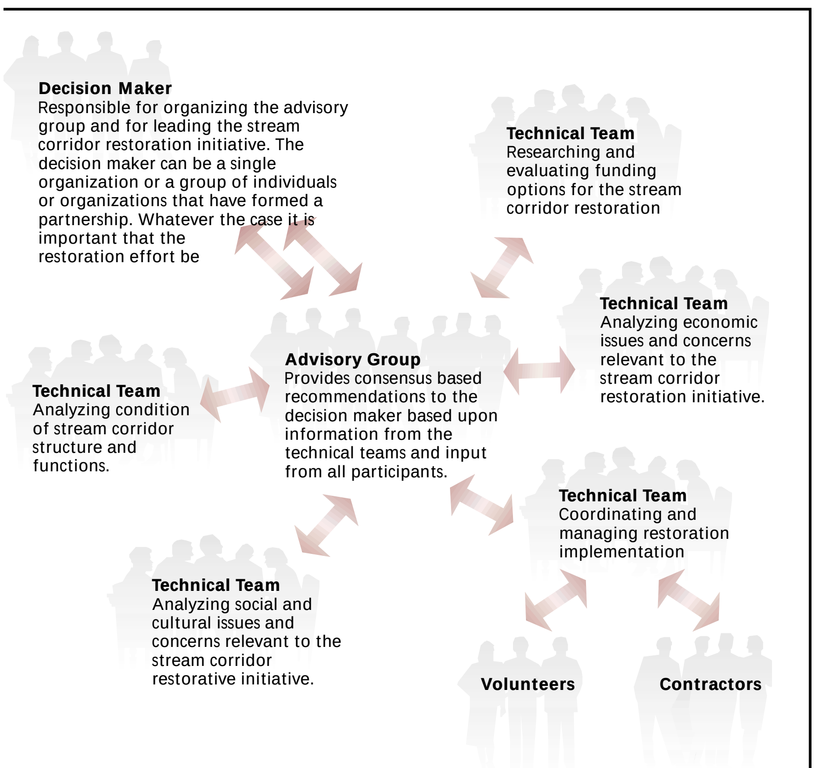


Figure 6.4: Communication flow. *This depicts a possible scenario in which volunteers and contractors may become actively involved.*

Once the organizational issues have been taken care of, the technical team can begin to address its coordination and management responsibilities. In general, the technical team must grapple with several major management issues during the implementation process. The following are some of the major questions that are essential to successful management:

- How much time is required to implement the restoration?
- Which tasks are critical to meeting the schedule?
- What resources are necessary to complete the restoration?
- Who will perform the various restoration activities?
- Is the implementation team adequately staffed?
- Are adequate lines of communication and responsibility established?
- Are all competing and potentially damaging interests and concerns adequately represented, understood, and addressed?

Volunteers

Volunteers can be very effective in assisting with stream corridor restoration (**Figure 6.5**). Numerous activities that are part of the restoration implementation process are suitable for volunteer labor. For example, soil bioengineering and other uses of plants to stabilize slopes are labor-intensive. Two crews of at least two people each are needed for all but the largest installations—one crew at the harvest location and the

Some Important Organizational Considerations for Successful Teamwork

Meeting Mechanics	▪ *How often will the team meet?* ▪ *Where?* ▪ *What will the agenda include?* ▪ *How do members get items on the agenda?* ▪ *Who will take minutes?* ▪ *How will minutes be distributed?* ▪ *Who will facilitate the meetings?*
Team Decision Making	▪ *How will the team make decisions (vote, consensus, advise only)?* ▪ *What decisions must be deferred to higher authorities?*
Problem Solving	▪ *How will problems be addressed?* ▪ *How will disagreements be resolved?* ▪ *What steps will be taken in the event of an impasse?*
Communication and Information	▪ *What additional information does the team need to function?* ▪ *How will necessary information be shared among team members, and by whom?* ▪ *Who handles public relations?*
Leadership Support	▪ *What is needed from supervisors and/or managers to ensure project success?*

other at the implementation site. However, a high level of skill or experience is often not required except for the crew leader, and training can commonly occur on the job. Restoration installations involving plant materials are therefore particularly suitable for youth, Job Corps, or volunteer forces.

It should be noted that the use of volunteers is not without some cost. Equipment, transportation, meals, insurance, and training might all be required, and each carries a real dollar need that must be met by the project budget or by a separate agency sponsoring the volunteer effort. However, those

Figure 6.5: Volunteer team. *Volunteers can perform important functions during the restoration implementation process.*

costs are still but a fraction of what would otherwise be needed for nonvolunteer forces.

Contractors

Contractors typically have responsibilities in the implementation of the restoration design. In fact, many restoration efforts require contracting due to the staff limitations of participating agencies, organizations, and landowners.

Contractors can assist in performing some of the tasks involved in implementing restoration design. Specifically, they can be hired to perform various tasks such as channel modification, installation of instream structures, and bank revegetation (**Figure 6.6**). All tasks performed by the contractor should be specified in the scope of the contract and should be subject to frequent and periodic inspection to ensure that they are completed within the proper specifications.

Figure 6.6: Contractor team. *Contractors can assist in performing tasks that might be involved in restoration such as installing bank stabilization measures.*
Source: Robin Sotir and Associates.

Although the contract will outline the role the contractor is to perform, it might be helpful for the technical team (or a member of the technical team) to meet with the contractor to establish a clear understanding of the respective roles and responsibilities. This preinstallation meeting might also be used to formally determine the frequency and mechanisms for reporting the progress of any installation activities. On the next page is a checklist of issues that are helpful in determining some of the roles and responsibilities associated with using contractors to perform restoration-related activities.

Securing Commitments

The final element of the division of responsibilities is securing commitments from the organizations and individuals that have agreed to assist in the implementation process. Two types of commitments are particularly important to ensuring the success of stream corridor restoration implementation (USEPA 1995):

- Commitments from public agencies, private organizations, individuals, and others who will fund and implement programs that involve restoration activities.
- Commitments from public agencies, private organizations, individuals, and others who will actually install the restoration measures.

One tool that can be used to help secure a commitment is a Memorandum of Understanding (MOU). An MOU is an agreement between two or more parties that is placed in writing. Essentially, by documenting what each party specifically agrees to, defining ambiguous concepts or terms, and outlining a conflict resolution process in the event of

Some Issues That Should Be Considered in Addressing Contractor Roles and Responsibilities

- *What constitutes successful completion of the contract obligations by the contractor?*
- *What is the planned order of work and necessary scheduling?*
- *Who is responsible for permitting?*
- *Where are utilities located and what are the related concerns?*
- *What is the relationship between the prime contractor and subcontractors? (In general, the chain of communication should always pass through the prime contractor, and the prime contractor's representative is always present on site. Normally, clients reserve the right to approve or reject individual subcontractors.)*
- *What records and reports will be needed to provide necessary documentation (forms, required job site postings, etc.)?*
- *What arrangements are needed for traffic control?*
- *What specific environmental concerns are present on the site? Who has permit responsibility, both for obtaining and for compliance?*

misunderstandings, an MOU serves to formalize commitments, avoid disappointment, and minimize potential conflict.

A second tool that can be effective is public accountability. As emphasized earlier, the restoration process should be an "open process" that is accessible to the interested public. Once written commitments have been made and announced, a series of periodic public meetings can be scheduled for the purpose of providing updates on the attainment of the various restoration activities being performed. In this way, participants in the restoration effort can be held accountable.

Installing Restoration Measures

A final element of stream corridor restoration implementation is the initiation of management and/or installation of restoration measures in accordance with the restoration design (**Figure 6.7**). If the plan involves construction, implementation responsibilities are often given to a private contractor. As a result, the contractor is required to perform a variety of restoration implementation activities, which can include large-scale actions like channel reconfiguration as well as small-scale actions like bank revegetation.

Whatever the scale of the restoration action, the process itself typically involves several stages. These stages generally include site preparation, site clearing, site construction, and site inspection. Each stage must be carefully executed to ensure successful installation of restoration measures. (See Chapter 9 for a more detailed explanation of this process.)

In addition to careful execution of the installation process, it is important that all actions be preceded by careful plan-

FAST FORWARD

Preview Chapter 9's restoration measures section.

ning. Such preinstallation planning is essential to achieve the desired restoration objectives and to avoid adverse environmental, social, and economic impacts that could result. The following is a discussion of some of the major steps that should be taken to ensure successful implementation of restoration-related installation actions.

REVERSE

Review Chapter 5's permit section.

Figure 6.7: Installation of erosion control fabric. *Installing measures can be considered a "mid-point" in restoration and not the completion. Preceding installation is the necessary planning, with monitoring and adaptive management subsequent to the installation.*

Determining the Schedule

Scheduling is a very important and highly developed component of implementation planning and management. For large-scale installation actions, scheduling is now almost always executed with the assistance of a computer-based software program. Even for small actions, however, the principles of scheduling are worth following.

Table 6.1: Examples of permit requirements for restoration activities.

Local/State				
Permits Required			**Activities Covered**	**Administered By**
Varies thresholds and definitions vary by state			e.g., clearing/grading, sensitive/critical areas, water quality, aquatic access	Local grading, planning, or building departments; various state departments
Federal				
Permits Required			**Activities Covered**	**Administered By**
Section 10, Rivers and Harbors Act of 1849			Building of any structure in the channel or along the banks of navigable waters of the U.S. that changes the course, condition, location, or capacity	U.S. Army Corps of Engineers
Section 404, Federal Clean Water Act	Letters of permission		Minor or routine work with minimum impacts	U.S. Army Corps of Engineers
	Nationwide permits	3	Repair, rehabilitation, or replacement of structures destroyed by storms, fire, or floods in past 2 years	
		13	Bank stabilization less than 500 feet in length solely for erosion protection	
		26	Filling of up to 1 acre of a non-tidal wetland or less than 500 linear feet of non-tidal stream that is either isolated from other surface waters or upstream of the point in a drainage network where the average annual flow is less than 5cfs	
		27	Restoration of natural wetland hydrology, vegetation, and function to altered and degraded non-tidal wetlands, and restoration of natural functions of riparian areas on private lands, provided a wetland restoration or creation agreement has been developed	
	Regional permits		Small projects with insignificant environmental impacts	
	Individual permits		Proposed filling or excavation that causes severe impacts, but for which no practical alternative exists; may require an environmental assessment	
Section 401, Federal Clean Water Act			Water quality certification	State agencies
Section 402, Federal Clean Water Act National Pollutant Discharge Elimination System (NPDES)			Point source discharges, as well as nonpoint pollution discharges	State agencies
Endangered Species Act Incidental Take Permit			Otherwise lawful activities that may take listed species	U.S. Fish and Wildlife Service

For tasks that are part of the actual installation work, scheduling is most efficiently done by the contractor actually charged with doing the work. All supporting activities, both before and during installation, must be carefully scheduled as well and should be the responsibility of the project manager.

Obtaining the Necessary Permits

Restoration installation actions conducted in or in contact with streams, wetlands, and other water bodies are subject to various federal, state, and local regulatory programs and requirements. At the federal level, a number of these are aimed at protecting natural resources values and the integrity of the nation's water resources. As discussed in Chapter 5, most of these require the issuance of permits by local, state, and federal agencies.

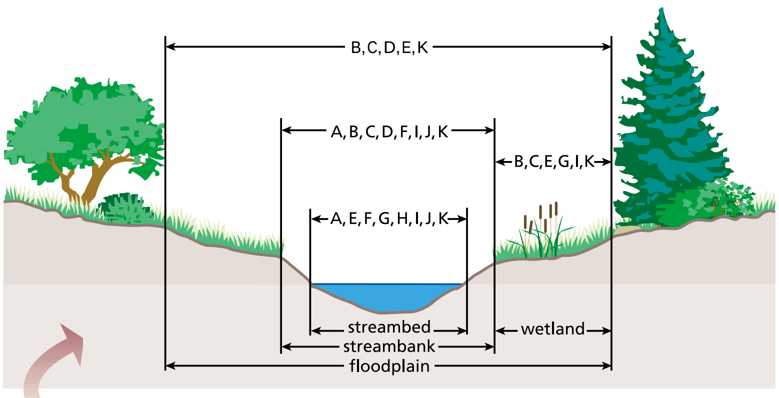
If the action will be conducted or assistance provided by a federal agency, the agency is required to comply with federal legislation, including the National Environmental Policy Act; sections 401, 402, and 404 of the Clean Water Act; the Endangered Species Act; Section 10 of the Rivers and Harbors Act of 1899; executive orders for floodplain management and wetland protection; and possibly other federal mandates depending on the areas that would be affected (see **Table 6.1**).

For example, under the Endangered Species Act, federal agencies must ensure that actions they take will not jeopardize the continued existence of listed threatened or endangered species or destroy or adversely modify their critical habitats (**Figure 6.8**). Where an action would jeopardize a species, reasonable and prudent alternatives must be implemented to avoid jeopardy. In addition, for federal agencies, an incidental take statement is required in those instances where there will be a "taking" of species associated with the federal action. For non-federal activities that might result in "taking" of a listed species, an incidental take permit is required.

Figure 6.8: Southwestern willow flycatcher. *Prior to initiating implementation activities, permits may be needed to ensure the protection of certain species such as the Southwestern willow flycatcher.*

Any work in floodplains delineated for the National Flood Insurance Program might also require participating communities to adhere to local ordinances and obtain special permits.

If the activity will affect lands such as historic sites, archaeological sites and remains, parklands, National Wildlife Refuges, floodplains, or other federal lands, meeting requirements under a number of federal, state, or local laws might be necessary. Familiarity with the likely requirements associated with the activities to be conducted and early contact with permitting authorities will help to minimize delays. Local grading, planning, or building departments are



Using this diagram, determine where your activity will occur. The letters refer to the permits listed below.

	Permit	Government Agency
A	Montana Stream Protection Act (124)	Montana Fish, Wildlife & Parks
B	Storm Water Discharge General Permits	Department of Environmental Quality
C	Streamside Management Zone Law	Department of Natural Resources & Conservation
D	Montana Floodplain and Floodway Management Act	Department of Natural Resources & Conservation
E	Short-term Exemption from Montana's Surface Water Quality Standards (3A)	Department of Environmental Quality
F	Montana Natural Streambed and Land Preservation Act (310)	Montana Association of Conservation Districts and Department of Natural Resources & Conservation
G	Montana Land-use License or Easement on Navigable Waters	Department of Natural Resources & Conservation/ Special Uses
H	Montana Water Use Act	Department of Natural Resources & Conservation
I	Federal Clean Water Act (Section 404)	U.S. Army Corps of Engineers
J	Federal Rivers and Harbors Act (Section 10)	U.S. Army Corps of Engineers
K	Other laws that may apply depending upon your location & activity	various agencies

Figure 6.9: Example of permits necessary for working in and around streams in Montana. *The number of permits required for an aquatic restoration effort may appear daunting but they are all necessary.*
Source: MDEQ 1996. Reprinted by permission.

usually the best place to begin the permit application process. They should be approached as soon as a conceptual outline of the project has been developed. At such a preapplication meeting, the project manager should bring such basic design information as the following:

- A site map or plan.
- A simple description of the restoration measures to be installed.
- Property ownership of the site and potential access route(s).
- Preferred month and year of implementation.

Whether or not that local agency claims jurisdiction over the particular activity, its staff will normally be aware of state and federal requirements that might be applicable. Local permit requirements vary from place to place and change periodically, so it is best to contact the appropriate agency for the most current information. In addition, different jurisdictions handle the designation of sensitive or critical areas differently. Work that occurs in the vicinity of a stream or wetland might or might not be subject to state or local permit requirements unique to aquatic environments. In addition, state and local agencies might regulate other aspects of a project as well.

The sheer number of permits required for an aquatic restoration effort might appear daunting, but much of the required information and many of the remedial measures are the same for all. **Figure 6.9** shows an example of how Montana's permitting requirements mesh with those at the federal level.

Holding Preinstallation Conferences

Preinstallation conferences should be conducted on site between the project manager and supervisor, crew foreman, and contractor(s) as appropriate. The purpose is to establish a clear understanding of the respective roles and responsibilities, and to formally determine the frequency and mechanisms for reporting the progress of the work. In a typical situation, the agency reviews consultant work, provides guidance in the interpretation of internal agency documents or guidelines, and takes a lead or at least supporting role in acquiring permits and satisfying the requirements imposed by regulatory agencies. An additional conference with any inspectors should be held with all affected contractors and field supervisors to avoid potential misunderstandings. Volunteers and noncontractor personnel should also be involved if they are critical to implementation.

At particularly sensitive sites, the need to avoid installation-related damage should be valued at least as highly as the need to complete the planned implementation actions as designed. An on-site meeting, if appropriate to the timing of installation and the seasonality of storms, can avoid many of the emergency problems that might otherwise be encountered in the future. At a minimum, the project manager or on-site superintendent and the local inspector(s) for the permitting jurisdiction(s) should attend. Other people with relevant knowledge and responsibility could also include the grading contractor's superintendent, the civil engineer or landscape architect responsible for the erosion and sediment control plans, a soil scientist or geologist, a biologist, and the plan checker(s) from the permitting jurisdiction(s) (**Figure 6.10**).

The meeting should ensure that all aspects of the plans are understood by the field supervisors, that the key actions and most sensitive areas of the site are recognized, that the sequence and schedule of implementing control measures are agreed upon, and that the mechanism for emergency response is clear. Any changes to the erosion and sediment control plan should be noted on the plan documents for future reference. Final copies of plans and permits should be obtained, and particular attention should be paid to changes that might have been recorded on submitted and approved plan copies, but not transferred to archived or contractor copies.

Involving Property Owners

If possible, the project manager should contact and meet with neighbors affected by the work, including those with site ownership, those granting access and other easements, and others nearby who might endure potential noise or dust impacts.

Securing Site Access

Obtaining right of entry onto private property can be a problematic and time-consuming part of restoration (**Figure 6.11**). Several types of access agreements with differing rights and obligations are available:

- *Right of entry* is the right to pass over the property for a specific purpose for a limited period of time. In many cases, if landowners are involved from the beginning, they will be aware of the need to enter private property. Various types of easements can accomplish this goal.

Figure 6.10: On-site meeting. *Many problems that might otherwise be encountered can be avoided by appropriately timed on-site meetings.*

- *Implementation easement* defines the location, time period, and purpose for which the property can be used during implementation.
- *Access easement* provides for permanent access across and on private property for maintenance and monitoring of a project. The geographic limits and allowable activities are specified.
- *Drainage easement* allows for the implementation and permanent maintenance of a drainage facility at a particular site. Usually, the property owner has free use of the property for any nonconflicting activities.
- *Fee acquisition* is the outright purchase of the property. It is the most secure, but most expensive, alternative. Normally, it is unnecessary unless the project is so extensive that all other potential activities on the property will be precluded.

In many cases little or no money may be exchanged in return for the easement because the landowner receives substantial property improvements, such as stabilized streambanks, improved appearance, better fisheries, and permanent stream access and stream crossings. In some instances, however, the proposed implementation is in direct conflict with existing or planned uses, and the purchase of an easement must be anticipated.

Locating Existing Utilities

Since most restoration efforts have a lower possibility of encountering utilities than other earthwork activities, special measures might not be necessary. If utilities are present, however, certain principles should be remembered (King 1987).

First, field location and highly visible markings are mandatory; utility atlases are notoriously incomplete or inaccu-

Figure 6.11: Site access. *In certain areas, access agreements, such as a right of entry or implementation easement, might have to be obtained to install restoration measures.*

rate. Utilities have a particular size and shape, not just a location, which might affect the nature or extent of adjacent implementation. They also require continuous support by the adjacent soil or temporary restraining structures. Rights-of-way might also create constraints during and after implementation. Even though all potential conflicts between utilities and the proposed implementation should be resolved during implementation planning, field discovery of unanticipated problems occurs frequently. Resolution comes only with the active involvement of the utility companies themselves, and the project manager should not hesitate to bring them on site as soon as a conflict is recognized.

Confirming Sources and Ensuring Material Standards

First, the project manager must determine the final sources of any required fill dirt and then arrange a pickup and/or delivery schedule. The project manager should also confirm the sources of nursery and donor sites for plant materials. Note, however, that delaying the initial identification of these sources until the time of site preparation almost guarantees that the project will suffer unexpected delays. In addition, it is important to double check with suppliers that all materials scheduled for delivery or pickup will meet the specified requirements. Early attention to this detail will avoid delays imposed by the rejection of substandard materials.

Characteristics of Successful Implementation

As was discussed earlier, successful restoration requires the efficient and effective execution of several core implementation activities, such as installing restoration measures, assigning responsibilities, identifying incentives, and securing funding. The Winooski River Case Study is a good example. Cutting across these core activities, however, are a few key concepts that can be considered characteristics of successful restoration implementation efforts.

Characteristics of Successful Implementation

- *Central responsibility in one person*
- *Thorough understanding of planning and design documents*
- *Familiarity with the site and its biological and physical framework*
- *Knowledge of laws and regulations*
- *Understanding of environmental control plans*
- *Communication among all parties involved in the project action*

Central Responsibility in One Person

Most restoration efforts are a product of teamwork, involving specialists from such disparate disciplines as biology, geology, engineering, landscape architecture, and others. Yet the value of a single identifiable person with final responsibility cannot be overemphasized. This project manager ignores the recommendations and concerns of the project team only at his or her peril. Rapid decisions, particularly during implementation, must nonetheless often be made. Rarely are financial resources available to keep all members of the design team on site during implementation, and even if some members are present, the time needed to achieve a consensus is simply not available.

Successful Implementation: The Winooski River Watershed Project, Vermont

In the late 1930s, an extensive watershed restoration effort known as "Project Vermont" was implemented in the Lower Winooski River Watershed, Chittenden County, Vermont. The project encompassed the lower 111 square miles (including 340 farms) of the 1,076-square-mile Winooski River Watershed.

*The Winooski River Watershed sustained severe damage from major floods during the 1920s and 1930s. In addition, overgrazing, poor soil conservation practices on cropland areas, encroachment to the streambanks, and forest clear-cutting also led to excessive erosion (**Figure 6.12**). Annual iceflows and jams during snowmelt runoff further exacerbated riverbank erosion. Throughout the watershed, both water and wind erosion were prevalent. In addition to problems in the low-lying areas, there were many environmental problems to address on the uplands. The soil organic matter was depleted in some areas, cropland had low productivity, pastures were frequently overgrazed, cover for wildlife was sparse, and forest areas had been clear-cut in many areas. In some cases, this newly cleared land was subject to grazing, which created additional problems.*

***Figure 6.12: Brushmattress and plantings after spring runoff in March 1938.** Note pole jetties. Brushmatting involves applying a layer of brush fastened down with live stakes and wire.*

The Soil Conservation Service (SCS) joined with the University of Vermont (UVM) and local landowners to formulate a comprehensive, low-input approach to restoring and protecting the watershed. One hundred eighty-nine farmers participated in developing conservation plans for their farms, which covered approximatey 57 square miles. Other cooperators applied practices to another 38-square-mile area. Their approach relied heavily on plantings or a combination of plantings and mechanical techniques to overcome losses of both land and vegetated buffer along the river corridor, and in the uplands to make agricultural land sustainable and to restore deteriorating forestland.

The measures, many of which were experimental at the time, were installed from 1938 to 1941 primarily by landowners. Landowners provided extensive labor and, occasionally, heavy equipment for earthmoving and transportation and placement of materials too heavy for laborers. SCS provided interdisciplinary (e.g., agronomy, biology, forestry, soil conservation, soil science, and engineering) technical assistance in the planning, design, and installation. UVM provided extensive educational services for marketing and operation and maintenance.

In the stream corridor, a variety of measures were implemented along 17 percent of the 33 river miles to control bank losses, restore buffers, and heal overbank floodflow channels. They included the following:

- *Livestock Exclusion: Heavy-use areas were fenced back 15 feet from the top of the bank on straight reaches, 200 feet or wider on the outsides of curves, and 200 feet wide in flood overflow entrance and exit sections.*
- *Plantings and Soil Bioengineering Bank Stabilization: Where the main current was not directed toward the treatment, streambanks were sloped back and planted with more than*

600,000 cuttings and 70,000 plants, primarily willow. Brushmattresses, which involved applying a layer of brush fastened down with live stakes and wire, were used to protect the bank until plantings could be made and established. Where streamflow was directed toward the bank, rock riprap was embedded at the toe up to 2 or more feet above the normal water line. Other toe protection techniques, such as pile jetties, were used.

- Structures: In reaches where nearshore water was deep (up to 14 feet) and bank voiding was occurring, whole tree deflectors were used to trap sediment and rebuild the voided section. Trees with butt diameters of 2 to 3 feet were placed longitudinally along the riverbank with branches intact and with butts and tops slightly overlapped. The butts were cabled to wooden piles driven 8 to 10 feet into the bank. The slope above the normal waterline was brush-matted and planted.
- Log pile check dams were constructed at the entrances of flood overflow channels and filled with one-person-size rocks for ballast. These served as barriers to overbank flow along channels sculpted by previous floods. They were installed in conjunction with extensive buffer plantings, and in some cases, whole tree barricades, that were laced down parallel to the river along the top of the denuded bank.
- At overbank locations where flow threatened buffer plantings, log cribs were inset parallel to the bank and filled with rock. Various tree species were planted as a 200-foot or wider buffer behind the cribs. The cribs provided protection needed until the trees became well established.

In the watershed, the conservation plans provided for comprehensive management for sustainable farming, grazing, forestry, and wildlife. The cropland practices included contour strips, contour tillage, cover crops, crop and pasture rotation, grass and legume plantings, diversions, grassed waterways, log culvert crossings, contour furrows in pastures, livestock fencing, planting of hedgerows, field border plantings, reforestation, and sustainable forest practices.

Figure 6.13: Same site (Figure 6.12) in April 1995. Note remnants of old jetties and heavy bank cover. Restoration measures are continuing to function well, more than 55 years after installation.

Wildlife habitat improvement practices provided connectivity among the cropland, pasture, and forest areas; hedgerow plantings as travelways, food sources, and cover; livestock exclusion areas to encourage understory herbaceous growth for cover and food sources; snags for small mammals and birds; and slash pile shelters as cover for rabbits and grouse.

One reason for this historic project's usefulness to modern environmental managers is the extensive documentation, including photos, maps, and detailed observations and records, available for many of the sites. Complete aerial photography is available from before, during, and after implementation. More than 600 photos provide a chronology of the measures, and three successive studies (Edminster and Atkinson 1949, Kasvinsky 1968, Ryan and Short 1995) document the performance of the project.

The restoration measures implemented are continuing to function well today, more than 55 years after installation. Tree plantings along the corridor have matured to diameters as great as 45 inches and heights exceeding 100 feet (**Figure 6.13**). The wooded river corridor averages 50 feet wider than it did in the 1930s. Some of the measures have failed, however, including all plantings without toe protection. Lack of maintenance and long-term follow-up also resulted in the failure of restoration efforts at several sites.

The Winooski River Watershed Project (continued)

Although the Winooski project was experimental in the 1930s, many of its elements were highly successful:

- *Recognition of the importance of landscape relationships and an emphasis on comprehensive treatment of the entire watershed rather than isolated, individual problem areas.*
- *Using an interdisciplinary technical team for planning and implementation.*
- *Strong landowner participation.*
- *Empowerment of landowners to carry out the restoration measures using low-cost approaches (often using materials from the farm).*
- *Fostering the use of experimental methods that are now recognized as viable biotechnical approaches.*

The success of restoration efforts depends more on having a competent project manager than on any other factor. The ideal project manager should be skilled in leadership, scheduling, budgeting, technical issues, human relationships, communicating, negotiating, and customer relations. Most will find this a daunting list of attributes, but an honest evaluation of a manager's shortcomings before restoration is under way might permit a complementary support team to assist the one who most commonly guides restoration to completion.

Thorough Understanding of Planning and Design Materials

Orchestrating the implementation of all but the simplest restoration efforts requires the integration of labor, equipment, and supplies, all within a context determined by requirements of both the natural system and the legal system. Designs must be adequate and based on a foundation of sound physical and biological principles, tempered with the experience of past efforts, both successful and unsuccessful. Schedules must anticipate the duration of specific implementation tasks, the lead time necessary to prepare for those tasks, and the consequences of inevitable delays. A manager who has little familiarity with the planning and design effort can neither execute the implementation plans efficiently nor adjust those plans in the face of unanticipated conditions. A certain amount of flexibility is key. Often specific techniques are tied to specific building material, for example. Adjustments are often made according to what is available.

Familiarity With the Reach

Existing site conditions are seldom as they appear on a set of engineering plans. Variability in landform and vegetation, surface water and ground water flow, and changing site conditions during the interval between initial design and final implementation are all inevitable. There is no substitute for familiarity with the site that extends beyond what is shown on the plans, so that implementation-period "surprises" are kept to a minimum (**Figure 6.14**). Similarly, when such surprises do occur,

Figure 6.14: Workers installing a silt fence. *Familiarity with on-site conditions is critical to successful implementation of restoration measures.*

a sound response must be based on the project manager's understanding of both the restoration goals and the likely behavior of the natural system.

Knowledge of Laws and Regulations

Site work in and around aquatic features is one of the most heavily regulated types of implementation in the United States (**Figure 6.15**). Restrictions on equipment use, season of the year, distance from the water's edge, and types of material are common in regulations from the local to the federal level. Not appreciating those regulations can easily delay implementation by a year or more, particularly if narrow seasonal windows are missed. The cost of a project can also multiply if required measures or mitigation are discovered late in the design or implementation process.

Understanding of Environmental Control Plans

A project in which a designed restoration measure is installed but the ecological structure and function of an area are destroyed is no success. The designer must create a workable plan for minimizing environmental degradation, but the best of plans can fail in the field through careless implementation.

Communication Among All Parties Involved in the Action

Despite the emphasis here on a single responsible project manager, the success of a project depends on regular, frequent, and open communication among all parties involved in implementation—manager, technical support people, contractor, crews, inspectors, and decision maker(s). No restoration effort proceeds exactly according to plans, and not every contingency can be predicted ahead of time. But well-established lines of communication can overcome most complications that arise.

Figure 6.15: Instream construction activity. *Site work in and around aquatic features is one of the most heavily regulated types of activity in the United States and should not be attempted without a sound knowledge of the relevant laws and regulations.*

6.B Restoration Monitoring, Evaluation, and Adaptive Management

FAST FORWARD

Preview Chapter 9's restoration monitoring management section.

The restoration effort is not considered complete once the design has been implemented. Monitoring, evaluation, and adaptive management are essential components that must be undertaken to ensure the success of stream corridor restoration. Each is carried out at a different level depending on the size and scope of the design.

Monitoring includes both pre- and post-restoration monitoring, as well as monitoring during actual implementation. All are essential to determining the success of the restoration design and require a complete picture or understanding of the structure and functions of the stream corridor. Monitoring provides needed information, documents chronological and other aspects of restoration succession, and provides lessons learned to be used in similar future efforts (Landin 1995).

Directly linked to monitoring are restoration evaluation and adaptive management. Using the information obtained from the monitoring process, the restoration effort should be evaluated to ensure it is functioning as planned and achieving the restoration goals and objectives. Even with the best plans, designs, and implementation, the evaluation will often result in the identification of some unforeseen problems and require midcourse correction either during or shortly following implementation. Most restoration efforts will require some level of oversight and on-site adaptive management.

This section examines some of the basics of restoration monitoring, evaluation, and adaptive management. A more detailed discussion on the technical aspects of restoration monitoring management is provided in Chapter 9 of this document.

Monitoring as Part of Stream Corridor Restoration Initiative

Restoration monitoring should be guided by predetermined criteria and checklists and allow for the recording of results in regular monitoring reports. The technical analyses in a monitoring report should reflect restoration objectives and should identify and discuss options to address deficiencies. For example, the report might include data summaries that indicate that forest understory conditions are not as structurally complex as expected in a particular management unit, that this finding has negative consequences for certain wildlife species, and that a program of canopy tree thinning is recommended to rectify the problem. The recommendation should be accompanied by an estimate of costs associated with the proposed action, a proposed schedule, and identification of possible conflicts with other restoration objectives.

Restoration Monitoring, Evaluation, and Adaptive Management

Restoration Monitoring

- *Progress Toward Objectives*
- *Regional Resource Priorities and Trends*
- *Watershed Activities*

Restoration Evaluation

- *Reasons to Evaluate Restoration Efforts*
- *A Conceptual Framework for Evaluation*

Monitoring plans should be conceived during the planning phase when the goals and performance criteria are developed for the restoration effort. Baseline studies required to provide more information on the site, to develop restoration goals, and to refine the monitoring plan often are conducted during the planning phase and can be considered the initial phase of the monitoring plan. Baseline information can form a very useful data set on prerestoration conditions against which performance of the system can be evaluated.

Monitoring during the implementation phase is done primarily to ensure that the restoration plans are correctly carried out and that the natural habitats surrounding the site are not unduly damaged.

Actual performance monitoring of the completed plan is done later in the assessment phase (**Figure 6.16**). Management of the system includes both management of the monitoring plan and application of the results to make midcourse corrections.

Finally, results are disseminated to inform interested parties of the progress of the system toward the intended goals.

Goals of a Restoration Monitoring Plan

- *Assess the performance of the restoration initiative relative to the project goals.*
- *Provide information that can be used to improve the performance of the restoration actions.*
- *Provide information about the restoration initiative in general.*

***Figure 6.16:* Monitoring of revegetation efforts.** *Monitoring the results of revegetation efforts is a critical part of restoring riparian zones along highly eroded channels.*

Components of a Monitoring Plan

Based on a thorough review of freshwater monitoring plans, some of which had been in place for over 30 years, the National Research Council (NRC) recommended the following factors to ensure a sound monitoring plan (NRC 1990):

- Clear, meaningful monitoring plan goals and objectives that provide the basis for scientific investigation.
- Appropriate allocation of resources for data collection, management, synthesis, interpretation, and analysis.
- Quality assurance procedures and peer review.
- Supportive research beyond the primary objectives of the plan.
- Flexible plans that allow modifications where changes in conditions or new information suggests the need.
- Useful and accessible monitoring information available to all interested parties.

The box, *Developing a Monitoring Plan*, shows the monitoring steps throughout the planning and implementation of a restoration. Each step is discussed in this chapter.

When to Develop the Monitoring Plan

The monitoring plan should be developed in conjunction with planning for the restoration. Once the goals and objectives have been established in the planning phase, the condition of the system must be considered.

Baseline monitoring enables planners to identify goals and objectives and provides a basis for assessing the performance of the completed restoration. Monitoring therefore begins with the determination of baseline conditions and continues through the planning and implementation of the restoration plan.

Developing a Monitoring Plan

Step 1: Define the Restoration Vision, Goals, and Objectives

The goals set for the restoration drive the monitoring plan design. Above all, it is important to do the following:

- Make goals as simple and unambiguous as possible.
- Relate goals directly to the vision for the restoration.
- Set goals that can be measured or assessed in the plan.

Developing Performance Criteria Involves:

- *Linking criteria to restoration goals.*
- *Linking criteria to the actual measurement parameters.*
- *Specifying the bounds or limit values for the criteria.*

Step 2: Develop the Conceptual Model

A conceptual model is a useful tool for developing linkages between planned goals and parameters that can be used to assess performance. In fact, a conceptual model is a useful tool throughout the planning process. The model forces persons planning the restoration to identify direct and indirect connections among the physical, chemical, and biological components of the ecosystem, as well as the principal components on which to focus restoration and monitoring efforts.

Baseline studies might be necessary to meet the following needs:

- To define existing conditions without any actions.
- To identify actions required to restore the system to desired functions and values.
- To help design the restoration actions.
- To help design the monitoring plan.

Step 3: Choose Performance Criteria

Link Performance to Goals

A link between the performance of the system and the planned goals is critical. If the goals are stated in a clear manner and can be reworded as a set of testable hypotheses, performance criteria can be developed. *Performance criteria* are standards by which to evaluate measurable or otherwise observable aspects of the restored system and thereby indicate the progress of the system toward meeting the planned goals. The closer the tie between goals and performance criteria, the better the ability to judge the success of the restoration efforts.

Developing a Monitoring Plan

A. Planning

Step 1: Define the restoration, vision, goals, and objectives

Step 2: Develop the conceptual model

Step 3: Choose performance criteria

- *Link performance to goals*
- *Develop the criteria*
- *Identify reference sites*

Step 4: Choose monitoring parameters and methods

- *Choose efficient monitoring parameters*
- *Review watershed activities*
- *Choose methods for sampling design, sampling, and sample handling/ processing*
- *Conduct sociological surveys*
- *Rely on instream organisms for evidence of project success*
- *Minimize the necessary measurements of performance*
- *Incorporate supplemental parameters*

Step 5: Estimate cost

- *Cost for developing the monitoring plan itself*
- *Quality assurance*
- *Data management*
- *Field sampling program*
- *Laboratory sample analysis*
- *Data analysis and interpretation*
- *Report preparation*
- *Presentation of results*

Step 6: Categorize the types of data

Step 7: Determine the level of effort and duration of monitoring

- *Incorporate landscape ecology*
- *Determine timing, frequency, and duration of sampling*
- *Develop statistical framework*
- *Choose the sampling level*

B. Implementing and Managing

- *Manager must have a vision for the life of the monitoring plan*
- *Roles and responsibilities must be clearly defined*
- *Enact quality assurance procedures*
- *Interpret the results*
- *Manage the data*
- *Provide for contracts*

C. Responding to the Monitoring Results

- *No action*
- *Maintenance*
- *Adding, abandoning, or decommissioning plan elements*
- *Modification of project goals*
- *Adaptive management*
- *Documentation and reporting*
- *Dissemination of results*

Primary Functions of Reference Sites

- *Can be used as models for developing restoration actions for a site.*
- *Provide a target to judge success or failure.*
- *Provide a control system by which environmental effects, unrelated to the restoration action, can be assessed.*

Develop the Criteria

The primary reason for implementing the monitoring plan must be kept in mind: to assess progress and to indicate the steps required to fix a system or a component of the system that is not successful.

Criteria are usually developed through an iterative process that involves listing measures of performance relative to goals and refining them to arrive at the most efficient and relevant set of criteria.

Identify Reference Sites

A reference site or sites should be monitored along with the restored site. Although pre- and post-implementation comparisons of the system are useful in documenting effects, the level of success can be judged only relative to reference systems.

Step 4: Choose Monitoring Parameters and Methods

Monitoring should include an overall assessment of the condition and development of the stream corridor relative to projected trends or "target" conditions. In some cases, this assessment may involve technical analyses of stream flow data, channel and bank condition, bedload measurements, and comparisons of periodic aerial photography to determine whether stream migration and debris storage and transport are within the range of equilibrium conditions. Monitoring may also include forest inventories, range condition assessments, evaluations of fish and wildlife habitat or populations, and measurements of fire fuel loading. In small rural or urban "greenbelt" projects, more general qualitative characterization of corridor integrity and quality might be sufficient.

Numerous monitoring programs and techniques have been developed for particular types of resources, different regions, and specific management questions. For example, general stream survey techniques are described by Harrelson et al. (1994), while a regional programmatic approach for monitoring streams in the context of forest management practices in the Northwest is described in Schuett-Hames et al. (1993). Similarly, monitoring of fish and wildlife habitat quality and availability can be approached from various avenues, ranging from direct sampling of animal populations to application of the habitat evaluation procedures developed and used by the U.S. Fish and Wildlife Service (1980a). Techniques specific to riparian zone monitoring are given by Platts et al. (1987).

Basic Questions to Ask When Selecting Methods for Monitoring

- *Does the method efficiently provide accurate data?*
- *Does the method provide reasonable and replicable data?*
- *Is the method feasible within time and cost constraints?*

Choose Efficient Monitoring Parameters

There are two critical steps in choosing efficient monitoring parameters. The first is to identify parameters to monitor. A scientifically based, relatively easily measured set of parameters that provide direct feedback on success or failure of restoration actions are identified. The NRC (1992) has recommended that at least three parameters should be selected and that they include physical, hydrological, and ecological measures. The second step is to select regional and system-specific parameters. Criteria development must be based on a thorough knowledge of the system under consideration.

Those responsible for resources in the stream corridor must be aware of changing watershed and regional resource priorities. The appropriate place to consider the implications of regional needs is in the context of periodic reevaluation of restoration objectives, which is a function of the monitoring process. Therefore, an annual monitoring report should include recognition of ongoing or proposed initiatives (e.g., changes in regulations, emphasis on restoration of specific fish populations, endangered species listings) that might influence priorities in the restored corridor. Awareness of larger regional programs may produce opportunities to secure funding to support management of the corridor.

Review Watershed Activities

The condition of the watershed controls the potential to restore and maintain ecological functions in the stream corridor. As discussed in Chapter 3, changes in land use and/or hydrology can profoundly alter basic stream interactions with the floodplain, inputs of sediment and nutrients to the system, and fish and wildlife habitat quality. Therefore, it is important that stream corridor monitoring include periodic review of watershed cover and land use, including proposed changes (**Figure 6.17**).

Figure 6.17: Urban sprawl. *Understanding changes in watershed land uses, such as increased urbanization, is an important aspect of restoration monitoring.*
Source: C. Zabawa.

Patterns of water movement through and within the stream corridor are basic considerations in developing objectives, design features, and management programs. Proposals to increase impervious surfaces, develop storm water management systems, or construct flood protection projects that reduce floodplain storage potential and increase surface and ground water consumption are all of legitimate concern to the integrity of the stream corridor. Stream corridor managers should be aware of such proposals and provide relevant input to the planning process. As changes are implemented, their probable influence on the corridor should be considered in periodic reevaluation of objectives and maintenance and management plans.

In rural settings, the corridor managers should be alert to land use changes in agricultural areas (**Figure 6.18**). Conversions between crop and pasture lands might require verification that fencing and drainage practices are consistent with agreed-upon BMPs or renegotiation of those agreements. Similarly, in wildland areas, major watershed management actions (timber har-

REVERSE

Review Chapter 3's land use and hydrology Sections.

vests, prescribed burn programs) should be evaluated to ensure that stream corridors are adequately considered.

Increasing development and urbanization may reduce the ability of the stream corridor to support a wide variety of fish and wildlife species and, at the same time, generate additional pressure for recreational uses. Awareness of development and population growth trends will allow a rational, rather than reactive, adjustment of corridor management and restoration objectives. Proposals for specific implementation activities, such as roads, bridges, or storm water detention facilities, within or near the stream corridor should be scrutinized so that concerns can be considered before authorization of the implementation.

Choose Methods for Sampling Design, Sampling, and Sample Handling and Processing

Parameters that might be included in a restoration monitoring plan are well established in the scientific literature. Any methods used for sampling a particular parameter should have a documented protocol (e.g., Loeb and Spacie 1994).

Conduct Sociological Surveys

Scientifically designed surveys can be used to determine changes in social attitudes, values, and perceptions from prerestoration planning through implementation phases. Such surveys may complement physical, chemical, and biological parameters that are normally considered in a monitoring plan. Sociological surveys can reveal important shifts in the ways a community perceives the success of a restoration effort.

Rely on Instream Organisms for Evidence of Project Success

The restoration evaluation should usually focus on aquatic organisms and instream conditions as the "judge and jury" for evaluating restoration success. Instream physical, chemical, and biological conditions integrate the other factors within the stream corridor. Instream biota, however, have shown sensitivity to complex problems not as well detected by chemical or physical indicators alone in state water quality monitoring programs. For instance, in comparing chemical and biological criteria, the state of Ohio found that biological criteria detected an impairment in 49.8 percent of the situations where no impairment was evident with chemical criteria alone. Agreement between chemical and biological criteria was evident in 47.3 percent of the cases, while chemical criteria detected an impairment in only 2.8 percent of the cases where biological criteria indicated attainment (Ohio EPA 1990). As a result, Ohio's Surface Water Monitoring and Assessment Program has recognized that biological criteria must play a key role in defining water quality standards and in evaluating and monitoring standards attainment if the goal to restore and maintain the physical, chemical, and biological integrity of Ohio's waters is to be met.

igure 6.18: Confinement farm. *ractitioners monitoring stream corridor restoration in rural areas should be aware of changes in agricultural land use.*

Minimize the Necessary Measurements of Performance

A holistic perspective is needed when monitoring restoration performance. Still, monitoring should focus narrowly on the fewest possible measurements or indicators that most efficiently demonstrate the overall condition of the stream corridor system and the success of the restoration effort. Costs and the ability to develop statistically sound data may quickly get out of hand unless the evaluation measures chosen are narrowly focused, are limited in number, and incorporate existing data and work wherever appropriate.

Existing data from state and federal agencies, community monitoring programs, educational institutions, research projects, and sportsmen's and other groups should be considered when planning for restoration evaluation. For example, turbidity data are generally more common than sediment data. If one of the objectives of a restoration effort is to reduce sediment concentrations, turbidity may provide a suitable surrogate measurement of sediment at little or no expense to restoration planners. **Table 6.2** provides some other examples of restoration objectives linked to specific performance evaluation tools and measures.

Incorporate Supplemental Parameters

Although the focus of the monitoring plan is on parameters that relate directly to assessment of performance, data on other parameters are often useful and may add considerably to interpretation of the results. For example, stream flow should be monitored if water temperature is a concern.

Step 5: Estimate Cost

Various project components must be considered when developing a cost estimate. These cost components include:

General Objectives	Potential Evaluation Tools and Criteria
Channel capacity and stability	Channel cross sections
	Flood stage surveys
	Width-to-depth ratio
	Rates of bank or bed erosion
	Longitudinal profile
	Aerial photography interpretation
Improve aquatic habitat	Water depths
	Water velocities
	Percent overhang, cover, shading
	Pool/riffle composition
	Stream temperature
	Bed material composition
	Population assessments for fish, invertebrates, macrophytes
Improve riparian habitat	Percent vegetative cover
	Species density
	Size distribution
	Age class distribution
	Plantings survival
	Reproductive vigor
	Bird and wildlife use
	Aerial photography
Improve water quality	Temperature
	pH
	Dissolved oxygen
	Conductivity
	Nitrogen
	Phosphorus
	Herbicides/pesticides
	Turbidity/opacity
	Suspended/floating matter
	Trash loading
	Odor
Recreation and community involvement	Visual resource improvement based on landscape control point surveys
	Recreational use surveys
	Community participation in management

Table 6.2: Environmental management.
Source: Kondolf and Micheli 1995.

- *Monitoring plan*. Development of a monitoring plan is an important and often ignored component of a monitoring cost assessment. The plan should determine monitoring goals, acceptable and unacceptable results, and potential contingencies for addressing unacceptable results (**Figure 6.19**). The plan should specify responsibilities of participants.
- *Quality assurance (QA)*. The monitoring plan should include an indepen-

dent review to ensure that the plan meets the restoration goals, the data quality objectives, and the expectations of the restoration manager. The major cost component of quality assurance is labor.

- *Data management*. Monitoring plans should have data management specifications that start with sample tracking (i.e., that define the protocols and procedures) and conclude with the final archiving of the information. Major costs include staff labor time for data management, data entry, database maintenance, computer time, and data audits.
- *Field sampling plan*. Sampling may range from the very simple, such as photo monitoring, wildlife observation, and behavioral observation (e.g., feeding, resting, movement), to the more complex, such as nutrient and contaminant measurement, water quality parameter measurement, plankton group measurement, productivity measurement in water column and substrate surface, macrophyte or vegetation sampling, and hydrological monitoring. The cost components for a complex plan may include the following:
  - Restoration management and field staff labor.
  - Subcontracts for specific field sampling or measurement activities (including costs of managing and overseeing the subcontracted activities).
  - Mobilization and demobilization costs.
  - Purchase, rental, or lease of equipment.
  - Supplies.
  - Travel.
  - Shipping.
- *Laboratory sample analysis*. Laboratory analyses can range from simple tests of water chemistry parameters such as turbidity, to highly complex and expensive tests, such as organic contaminant analyses and toxicity assays. The cost components of laboratory sample analysis are usually estimated in terms of dollars per sample.
- *Data analysis and interpretation*. Analysis and interpretation require the expertise of trained personnel and may include database management, which can be conducted by a data management specialist if the data are complex or by a technician or restoration manager if they are relatively straightforward.

Figure 6.19: Monitoring. *It is important to develop a framework for the monitoring protocol and a plan for monitoring evaluation.*

- *Report preparation.* One of the final steps in the monitoring plan is to prepare a report outlining the restoration action, monitoring goals, methods, and findings. These documents are meant to serve as interpretative reports, synthesizing the field and lab data analysis results. These reports are typically prepared by a research scientist with the aid of a research assistant. Report production costs depend on the type and quality of reports requested.
- *Presentation of results.* Though not often considered a critical component of a monitoring plan, presentation of plan results should be considered, including costs for labor and travel.

Step 6: Categorize the Types of Data

Several types of data gathered as part of the monitoring plan may be useful in developing the plan or may provide additional information on the performance of the system. The restoration manager should also be aware of available information that is not part of the monitoring plan but could be useful. Consultation with agency personnel, local universities and consultants, citizen environmental groups (e.g., Audubon chapters), and landowners in the area can reveal important information.

Step 7: Determine the Level of Effort and Duration

How much monitoring is required? The answer to this question is dependent on the goals and performance criteria for the restoration as well as on the type of ecological system being restored. A monitoring plan does not need to be complex and expensive to be effective.

Incorporate Landscape Ecology

The restoration size or scale affects the complexity of the monitoring required. As heterogeneity increases, the problem of effectively sampling the entire system becomes more complex. Consideration must be given to the potential effect on the restoration success of such things as road noise, dogs, dune buggies, air pollution, waterborne contamination, stream flow diversions, human trampling, grazing animals, and myriad other elements (**Figure 6.20**).

Types of Data Important to Various Phases of the Restoration

- *Restoration Planning*
  - *Develop baseline data at the site.*
- *Implementation of Restoration Plan*
  - *Monitor implementation activities.*
  - *Collect as-built or as-implemented information.*
- *Postimplementation*
  - *Collect performance data.*
  - *Conduct other studies as needed.*

Determine Timing, Frequency, and Duration of Sampling

The monitoring plan should be carried out according to a systematic schedule. The plan should include a start date, the time of the year during which field studies should take place, the frequency of field studies, and the end date for the plan. Timing, frequency, and duration are dependent on the aspects of system type and complexity, controversy, and uncertainty.

- *Timing*. The monitoring plan should be designed prior to conducting any baseline studies. A problem often encountered with this initial sampling is seasonality. Implementation may be completed in midwinter, when vegetation and other conditions are not as relevant to the performance criteria and goals of the restoration, which might focus on midsummer conditions.

  The field studies should be carried out during an appropriate time of the year. The driving consideration is the performance criteria. Because weather varies from year to year, it is wise to "bracket" the season with the sampling. For example, sampling temperature four times during the midsummer may be better than a single sampling in the middle of the season. Sampling can be performed either by concentrating all tasks during a single site visit or by carrying out one task or a similar set of tasks at several sites in a single day.

- *Frequency*. Frequency of sampling refers to the period of time between samplings. In general, "new" systems change rapidly and should be monitored more often than older systems. As a system becomes established, it is generally less vulnerable to disturbances. Hence, monitoring can be less frequent. An example of this is annual monitoring of a marsh for the first 3 years, followed by monitoring at intervals of 2 to 5 years for the duration of the planned restoration or until the system stabilizes.

- *Duration*. The monitoring plan should extend long enough to provide reasonable assurances either that the system has met its performance criteria or that it will or will not likely meet the criteria. A restored system should be reasonably self-maintaining after a certain period of time. Fluctuations on an annual basis in some parameters of the system will occur even in the most stable mature systems. It is important for the plan to extend to a point somewhere after the period of most rapid change and into the period of stabilization of the system.

igure 6.20: Streams n the (a) western ınd (b) eastern Jnited States. *The vide variability of tream structure and unction among different regions of the country makes standardized restoration evaluation difficult.*

a)

(b)

Develop a Statistical Framework

The monitoring study design needs to include consideration of statistical issues, including the location of sample collection, the number of replicate samples to collect, the sample size, and others. Decisions should be made based on an understanding of the accuracy and precision required for the data (**Figure 6.21**). The ultimate use of the data must be kept in mind when developing the sampling plan. It is useful to frequently ask, "Will this sampling method give us the answers we need for planning?" and "Will we be able to determine the success or performance of the restoration?"

Monitoring can consist of many different methods and can occur at varying locations, times, and intensities, depending on the conditions to be monitored. The costs or expenditures of time and resources also vary accordingly. The challenge is to design the monitoring plan to provide, in a cost-efficient and timely manner, accurate information to provide the rationale for decisions made throughout the planning process, and during and after implementation to assess success.

The accuracy of the data to define environmental conditions is of paramount concern, but the acceptable precision of the data can vary, depending on the target of concern. For example, if the amount of pesticides in surface water is a concern, it is much cheaper to assay for the presence of groups of pesticides than to test for specific ones. Also, if overall water quality conditions are needed, seasonal sampling of biological indicators may act as a surrogate for long-term sampling of specific chemical parameters.

Choose the Sampling Level

The appropriate level of sampling or the number of replicates under any particular field or laboratory sampling effort depends on the information required and the level of accuracy needed. Quantity and quality of information desired is in turn dependent in part on the expenditures necessary to carry out the identified components of the sampling plan.

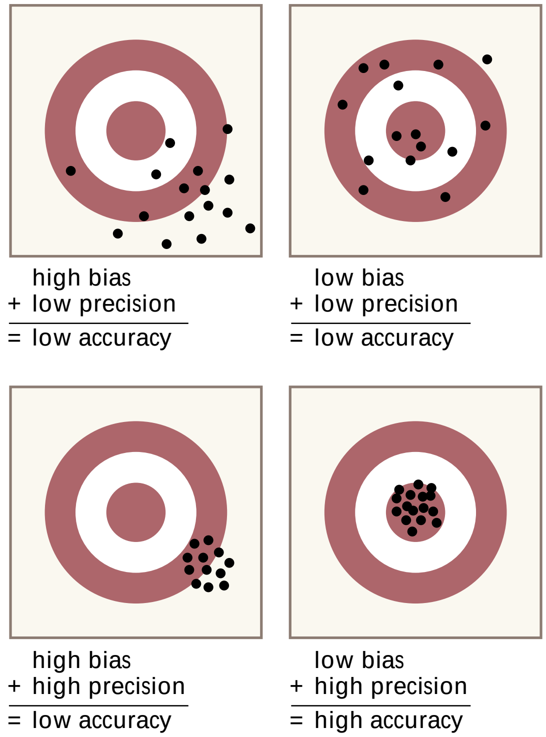


Figure 6.21: Patterns of shots at a target. *Monitoring design decisions should be made based on an understanding of the accuracy and precision required of the data.*
Source: Gilbert 1987 after Jessen 1978.

Implementing and Managing the Monitoring Plan

Management of the monitoring plan is perhaps the least appreciated but one of the most important components of restoration. Because monitoring continues well after implementation activities, there is a natural tendency for the plan to lose momentum, for the data to accumulate with little analysis, and for little documentation and dissemination of the information to occur. This section presents methods for preventing or minimizing these problems.

Envisioning the Plan

The restoration manager must have a vision of the life (i.e., duration) of the monitoring plan and must see how the plan fits into the broader topic of restoration as a viable tool for meeting the goals of participating agencies, organizations, and sponsors.

Determining Roles

Carrying out the monitoring plan is usually the responsibility of the restoration sponsor. However, responsibility should be established clearly in writing during the development of the restoration because this responsibility can last for a decade or more.

Ensuring Quality

The restoration manager should consider data quality as a high priority in the monitoring plan. Scientifically defensible data require that at least minimal quality assurance procedures be in place.

Interpreting Results

Results of the monitoring plan should be interpreted with objectivity, completeness, and relevance to the restoration objectives. The restoration manager and the local sponsor may share responsibility in interpreting the results generated by the monitoring plan. The roles of the restoration manager and local sponsor need to be determined before any data-gathering effort begins. Both parties should seek appropriate technical expertise as needed.

Managing Data

Data should be stored in a systematic and logical manner that facilitates analysis and presentation. Development of the monitoring plan should address the types of graphs and tables that will be used to summarize the results of the monitoring plan. Most monitoring data sets can be organized to allow direct graphing of the data using database or spreadsheet software.

Managing Contracts

One of the most difficult aspects of managing a monitoring plan can be management of the contracts required to conduct the plan. Most restoration requires that at least some of the work be contracted to a consultant or another agency. Because monitoring plans are frequently carried out on a seasonal basis, timing is important.

Restoration Evaluation

Directly linked to monitoring is the evaluation of the success of the restoration effort. Restoration evaluation is intended to determine whether restoration is achieving the specific goals identified during planning, namely, whether the stream corridor has reestablished and will continue to maintain the conditions desired.

Approaches to evaluation most often emphasize biological features, physical attributes, or both. The primary tool of evaluation is monitoring indicators of stream corridor structure, function, and condition that were chosen because they best estimate the degree to which restoration goals were met.

Evaluation may target certain aquatic species or communities as biological indicators of whether specific water quality or habitat conditions have been restored. Or, for example, evaluation may focus on the physical traits of the channel or riparian zone that were intentionally modified by project implementation (**Figure 6.22**). In any case, the job is not finished unless the condition and function of the modified stream corridor are assessed and adjustments, if necessary, are made. The time frame for evaluating restoration success can vary from months to years, depending on the speed of the stream system's response to the treatment applied. Therefore, performance evaluation often means a commitment to evaluate restoration long after it was implemented.

Reasons to Evaluate Restoration Efforts

The evaluation of stream corridor restoration is a key step that is often omitted. Kondolf and Micheli (1995) indicate that despite increased commitment to stream restoration, postrestoration evaluations have generally been neglected. In one study in Great Britain, only 5 of almost 100 river conservation enhancement projects had postimplementation appraisal reports (Holmes 1991).

Why do practitioners of restoration sometimes leave out the final evaluation process? One probable reason is that evaluation takes time and money and is often seen as expendable excess in a proposed restoration effort when it is misunderstood. It appears that the final restoration evaluation is sometimes abandoned so the remaining time and money can be spent on the restoration itself. Although an understandable temptation, this is not an acceptable course of action for most restoration efforts, and collectively the lack of evaluation slows the development and improvement of successful restoration techniques.

Protecting the Restoration Investment

Stream corridor restoration can be extremely costly and represent substantial financial losses if it fails to work properly. Monitoring during and after the restoration is one way to detect problems before they become prohibitively complex or expensive to correct.

Restoration may involve a commitment of resources from multiple agencies,

***Figure 6.22*: Instream modifications.** *Restoration evaluation may focus on the physical traits of the channel that were intentionally modified during project implementation such as the riffles pictured.*

REVERSE

Review Chapter 5's goals and objectives section.

groups, and individuals to achieve a variety of objectives within a stream corridor. All participants have made an investment in reaching their own goals. Reaching consensus on restoration goals is a process that keeps these participants aware of each others' aims. Evaluating restoration success should maintain the existing group awareness and keep participants involved in helping to protect their own investment.

Helping to Advance Restoration Knowledge for Future Applications

Restoration actions are relatively new and evolving and have the risk of failure that is inherent in efforts with limited experience or history. Restoration practitioners should share their experiences and increase the overall knowledge of restoration practices—those that work and those that do not. Shared experience is essential to our limited knowledge base for future restoration.

Maintaining Accountability to Restoration Supporters

The coalition of forces that make a restoration effort possible can include a wide variety of interest groups, active participants, funding sources, and political backers, and all deserve to know the outcome of what they have supported. Sometimes, restoration monitoring may be strongly recommended or required by regulation or as a condition of restoration funding. For example, the USEPA has listed an evaluation and reporting plan in guidance for grants involving restoration practices to reduce nonpoint source pollution. Requirements notwithstanding, it is worthwhile to provide the restoration effort's key financial supporters and participants with a final evaluation. Other benefits such as enhancing public relations or gaining good examples of restoration successes and publishable case histories, can also stem from well-designed, well-executed evaluations.

Acting on the Results

Identified goals and objectives, as discussed in Chapter 5, should be very clear and specific concerning the resulting on-site conditions desired. However, large or complex restoration efforts are sometimes likely to involve a wide range of goals. Restoration evaluations are needed to determine whether the restoration effort is meeting and will continue to meet specific goals identified during planning, to allow for mid-

Reasons to Prepare Written Documentation for the Monitoring Plan

- *Demonstrates that the monitoring plan is "happening."*
- *Demonstrates that the restoration meets the design specifications and performance criteria.*
- *Assists in discussions with others about the restoration.*
- *Documents details that may otherwise be forgotten.*
- *Provides valuable information to new participants.*
- *Informs decision makers.*

course adjustments, and to report on any unanticipated benefits or problems as a result of the program.

The results from a monitoring plan are an important tool for assessing the progress of a restoration and informing restoration decision makers about the potential need for action.

Alternative Actions

Because restoration involves natural systems, unexpected consequences of restoration activities can occur. The four basic options available are as follows:

- *No action.* If the restoration is generally progressing as expected or if progress is slower than expected but will probably meet restoration goals within a reasonable amount of time, no action is appropriate.
- *Maintenance.* Physical actions might be required to keep restoration development on course toward its goals.
- *Adding, abandoning, or decommissioning plan elements.* Significant changes in parts of the implemented restoration plan might be needed. These entail revisiting the overall plan, as well as considering changes in the design of individual elements.
- *Modification of restoration goals.* Monitoring might indicate that the restoration is not progressing toward the original goals, but is progressing toward a system that has other highly desirable functions. In this case, the participants might decide that the most cost-effective action would be to modify the restoration goals rather than to make extensive physical changes to meet the original goals for the restoration.

Adaptive Management

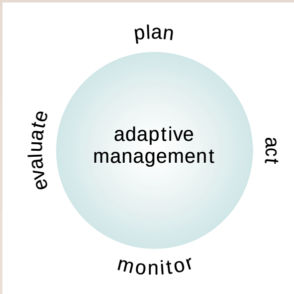
The expectations created during the decision to proceed with restoration

Adaptive management is not "adjustment management" but a way of establishing hypotheses early in the planning, then treating the restoration process as an experiment to test the hypotheses.

might not always influence the outcome, but they are certainly capable of influencing the opinions of participants and clients concerning the outcome. The first fundamental rule, then, is to set proper expectations for the restoration effort. If the techniques to be used are experimental, have some risk of failure, or are likely to need midcourse corrections, these facts need to be made clear. One effective way to set reasonable expectations from the beginning is to acknowledge uncertainty, evaluation of performance, and adjustments as part of the game plan.

Adaptive management involves adjusting management direction as new information becomes available (**Figure 6.23**). It requires willingness to experiment scientifically and prudently, and to accept occasional failures (Interagency Ecosystem Management Task Force 1995). Since restoration is a new science with substantial uncertainty, adaptive management to incorporate new midcourse information should be expected. Moreover, through adaptive management specific problems can be focused on and corrected.

It is recognized that restoration is uncertain. Therefore, it is prudent to allow for contingencies to address problems during or after restoration implementation. The progress of the system should be assessed annually. At that time, deci-



- Modify plans using monitoring, technical, and social feedback
- Track restoration policy, programs, and individual projects as feedback for further restoration policy and program redesign
- Restoration initiatives: recommend annual assessments
  - use monitoring data and other data/expertise
  - midcourse corrections or alternative actions
  - link reporting/monitoring schedules for midcourse corrections
- Manager may contract some/all monitoring, but periodically must visit sites, review reports, discuss with contractors.

Figure 6.23: Adaptive management. *Adjusting management direction as new information becomes available requires a willingness to experiment and accept occassional failures.*

sions can be made regarding any midcourse corrections or other alternative actions, including modification of goals. The annual assessments would use monitoring data and might require additional data or expertise from outside the restoration team. Because the overall idea is to make the restoration "work," while not expending large amounts of funds to adhere to inflexible and unrealistic goals, decisions would be made regarding the physical actions that might be needed versus alterations in restoration goals.

Restoration participants must remain willing to acknowledge failures and to learn from them. Kondolf (1995) emphasizes that even if restoration fails, it provides valuable experimental results that can help in the design of future efforts. Repeatedly, a cultural reluctance to admit failure perpetuates the same mistakes instead of educating others about pitfalls that might affect their efforts, too. Accepting failure reiterates the importance of setting appropriate expectations. Participants should all acknowledge that failure is one of the possible outcomes of restoration. Should failure occur, they should resist the natural temptation to bury their disappointment and instead help others to learn from their experience.

Documenting and Reporting

The monitoring report should also include a systematic review of changes in resource management priorities and watershed conditions along with a discussion of the possible implications for restoration measures and objectives. The review should be wide-ranging, including observations and concerns that might not require immediate attention but should be documented to ensure continuity in case of turnover in personnel. The monitoring report should alert project managers to proposed developments or regulation changes that could affect the restoration effort, so that feedback can be provided and stream corridor concerns can be considered during planning for the proposed developments.

Documentation and reporting of the progress and development of the restoration provide written evidence that the restoration manager can use for a variety of purposes. Three simple concepts are common among the best-documented restorations:

- A single file that was the repository of all restoration information was developed.
- The events and tasks of the restoration were recorded chronologically in a systematic manner.
- Well-written documents (i.e., planning and monitoring documents) were produced and distributed widely enough to become part of the general regional or national awareness of the restoration.

Main sections in a general format for a monitoring report should include title page, summary or abstract, introduction, site description, methods, results, discussion, conclusions, recommendations, acknowledgments, and literature cited.

Dissemination of the Results

Recipients of the report and other monitoring information should include all interested parties (e.g., all state and federal agencies involved in a permit action). In addition, complete files should be maintained. The audience can include beach-goers, birders, fishers, developers, industry representatives, engineers, government environmental managers, politicians, and scientists. The recipient list and schedule for delivery of the reports should be developed by the restoration manager. If appropriate, a meeting with interested parties should be held to present the results of the monitoring effort and to discuss the future of the restoration. Large, complex, and expensive restorations might have wide appeal and interest, and meetings on these restorations will require more planning. Presentations should be tailored to the audience to provide the information in the clearest and most relevant form.

Planning for Feedback During Restoration Implementation

A sound quality control/quality assurance component of the restoration plan incorporates the means to measure and control the quality of an activity so that it meets expectations (USEPA 1995a). Especially in restoration efforts that involve substantial earthmoving and other major structural modifications, risk of unintentional damage to water quality or aquatic biota exists. Midcourse monitoring should be part of the plan, both to guard against unexpected additional damage and to detect positive improvements (**Figure 6.24**).

Making a Commitment to the Time Frame Needed to Judge Success

The time required for system recovery should be considered in determining the frequency of monitoring.

- Data on fractions of an hour might be needed to characterize streamflow.

Figure 6.24: Streambank failure. *Midcourse monitoring will guard against unexpected damages.*

- Hourly data might be needed for water temperature and water quality.
- Weekly data might be appropriate to show changes in the growth rate of aquatic organisms.
- Monthly or quarterly data might be necessary to investigate annual cycles.
- Annual measures might be adequate to show the stability of streambanks.
- Organisms with long life spans, such as paddlefish or trees, might need to be assessed only on the order of decades (**Figure 6.25**).

The time of day for measurement should also be considered. It might be most appropriate to measure dissolved oxygen at dawn, whereas temperature might be measured most appropriately in the mid- to late afternoon. Migrations or climatic patterns might require that studies be conducted during specific months or seasons. For example, restoration efforts expected to result in increased baseflow might require studies only in late summer and early fall.

The expected time for recovery of the stream corridor could involve years or decades, which should be addressed in the duration of the study and its evaluation. Moreover, if the purpose of restoration is to maintain natural floodplain functions during a 10-year flood event, it might take years for such an event to occur and allow a meaningful evaluation of performance.

Some efforts have been made to integrate short- and long-term performance monitoring requirements into overall design. Bryant (1995) recently presented the techniques of a pulsed monitoring strategy involving a series of

Figure 6.25: Revegetated streambank. *Monitoring and evaluation must take into account the differences in life spans among organisms. Tree growth along the streambank will be evaluated on a much longer time scale than other restoration results.*

short-term, high-intensity studies separated by longer periods of low-intensity data collection. MacDonald et al. (1991) have described several different types of monitoring by frequency, duration, and intensity.

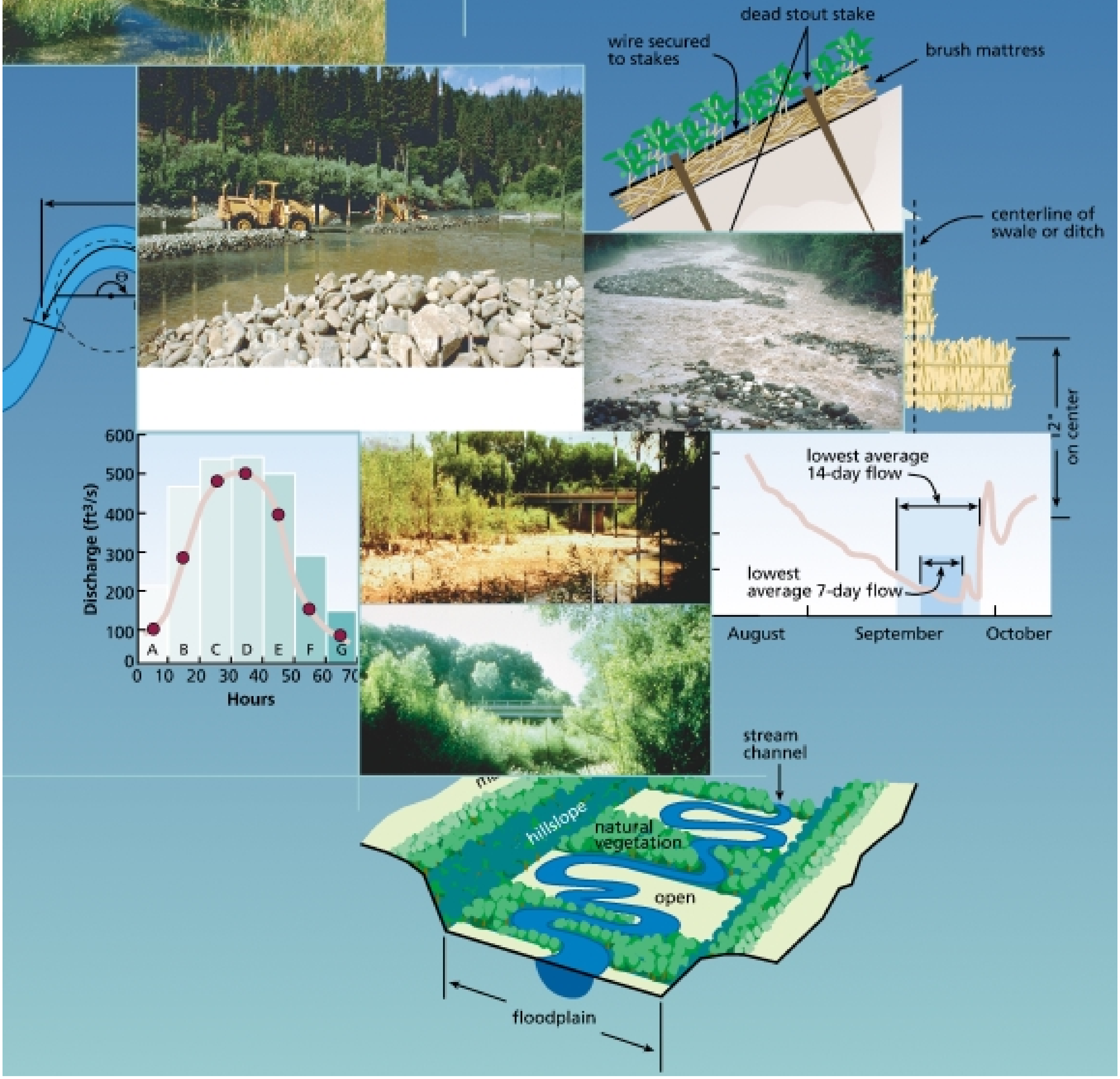
Evaluating Changes in the Sources of Stress as Well as in the System Itself

Restoration might be necessary because of stress currently affecting the stream corridor or because of damage in the past. It is critical to know whether the sources of stress are still present or are absent, and to incorporate treatment of the sources of stress as part of the restoration approach. In fact, some practitioners will not enter into a restoration effort that does not include reducing or eliminating the source of negative impacts because simply improving the stream itself will likely result in only temporary enhancements.

The beginning steps of ecological risk assessment are largely designed around characterization of an ecosystem's valued features, characterization of the stressors degrading the ecosystem, identification of the routes of exposure of the ecosystem to the stressors, and description of ecological effects that might result. If these factors are documented for restoration during its design and execution, it should be clear how evaluating performance should address each factor after completion. Has the source of stress, or its route of exposure, been diminished or eliminated? Are the negative ecological effects reversed or no longer present?

Part III

Applying Restoration Principles

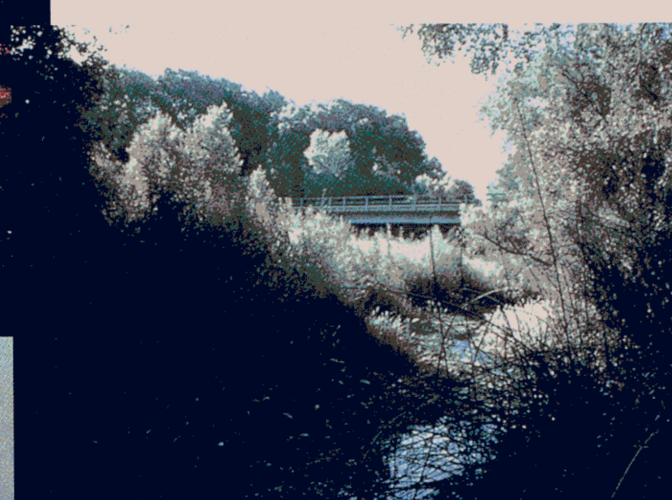


Applying Restoration Principles

Stream corridor functions are recognizable and definable for the smallest study area as well as for eco-regional levels. Because a corridor functions at all scales, the principles of restoration should be applied using those appropriate to the scale of concern.

Part III of this document is the "how to" section. The understanding gained in Part I and developed into a restoration plan in Part II is applied. Part III shows how condition analysis and design can lead to restoring corridor structure and the habitat, conduit, filter/barrier, source, and sink functions.

- ***Chapter 7** discusses the measurement and analysis of corridor condition. The analysis is broken down by scale and process.*
  - *Physical processes, structures, and functions*



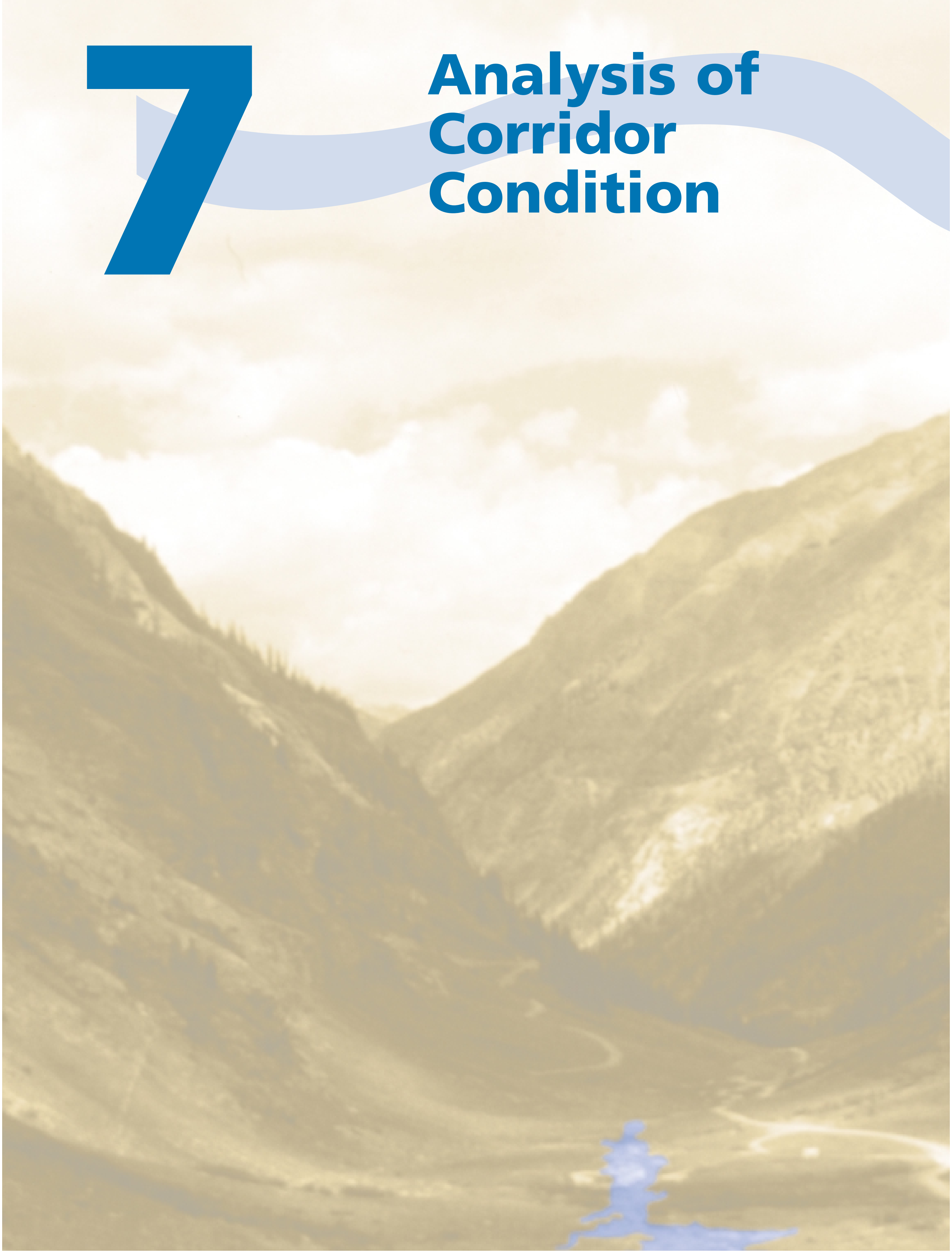
- *Geomorphic and hydrological*
- *Water chemistry*
- *Biological analysis*

  This breakdown allows the generation of a "picture" of stream corridor conditions that comes into clearer focus as one descends in scale from maps and aerial photographs to the streambed.

- ***Chapter 8*** *contains design guidance and techniques to restore stream corridor structure and functions. It is not, however, a cookbook of prescribed solutions.*
- ***Chapter 9*** *deals with construction topics that can occur after the stream corridor restoration design is complete and required permits are obtained. Careful construction and field inspection are necessary to ensure that the corridor is not degraded by construction activities. At the end of successful restoration, the stream must be managed, maintained, and monitored to ensure goals and objectives are being met.*

7

Analysis of Corridor Condition



7.A Hydrologic and Hydraulic Processes

- *How does the stream flow and why is this understanding important?*
- *Is streamflow perennial, ephemeral or intermittent?*
- *What is the discharge, frequency and duration of extreme high and low flows?*
- *How often does the stream flood?*
- *How does roughness affect flow levels?*
- *What is the discharge most effective in maintaining the stream channel under equilibrium conditions?*
- *How does one determine if equilibrium conditions exist?*
- *What field measurements are necessary?*

7.B Geomorphic Processes

- *How do I inventory geomorphic information on streams and use it to understand and develop physically appropriate restoration plans?*
- *How do I interpret the dominant channel adjustment processes active at the site?*
- *How deep and wide should a stream be?*
- *Is the stream stable?*
- *Are basin-wide adjustments occurring, or is this a local problem?*
- *Are channel banks stable, at-risk, or unstable?*
- *What measurements are necessary?*

7.C Chemical Processes

- *How do you measure the condition of the physical and chemical conditions within a stream corridor?*
- *Why is quality assurance an important component of stream corridor analysis activities?*
- *What are some of the water quality models that can be used to evaluate water chemistry data?*

7.D Biological Characteristics

- *What are some important considerations in using biological indicators for analyzing stream corridor conditions?*
- *Which indicators have been used successfully?*
- *What role do habitat surveys play in analyzing the biological condition of the stream corridor?*
- *How do you measure biological diversity in a stream corridor?*
- *What is the role of stream classification systems in analyzing stream corridor conditions?*
- *How can models be used to evaluate the biological condition of a stream corridor?*
- *What are the characteristics of models that have been used to evaluate stream corridor conditions?*

7

Analysis of Corridor Condition

Section 7.A: Hydrologic Processes

Understanding how water flows into and through stream corridors is critical to developing restoration initiatives. How fast, how much, how deep, how often, and when water flows are important basic questions that must be answered in order to make appropriate decisions about the implementation of a stream corridor's restoration.

Section 7.B: Geomorphic Processes

This section combines the basic hydrologic processes with the physical or geomorphic functions and characteristics. Water flows through streams but is affected by the kinds of soils and alluvial features within the channel, in the floodplain, and in the uplands. The amount and kind of sediments carried by a stream is largely a determinant of its equilibrium characteristics, including size, shape, and profile. Successful implementation of the stream corridor restoration, whether active (requiring direct intervention) or passive, (removing only disturbance factors), depends on an understanding of how water and sediment are related to channel form and function, and on what processes are involved with channel evolution.

Section 7.C: Chemical Characteristics

The quality of water in the stream corridor is normally a primary objective of restoration, either to improve it to a desired condition, or to sustain it. Restoration initiatives should consider the physical and chemical characteristics that may not be readily apparent but that are nonetheless critical to the functions and processes of stream corridors. Chemical manipulation of specific characteristics usually involves the management or alteration of elements in the landscape or corridor.

Section 7.D: Biological Characteristics

The fish, wildlife, plants, and human beings that use, live in, or just visit the stream corridor are key elements to consider, not only in terms of increasing populations or species diversity, but also in terms of usually being one of the primary goals of the restoration effort. A thorough understanding of how water flows, how sediment is transported, and how geomorphic features and processes evolve is important. However, a prerequisite to successful restoration is an understanding of the living parts of the system and how the physical and chemical processes affect the stream corridor.

7.A Hydrologic Processes

Flow Analysis

Restoring stream structure and function requires knowledge of flow characteristics. At a minimum, it is helpful to know whether the stream is perennial, intermittent, or ephemeral, and the relative contributions of baseflow and stormflow in the annual runoff. It might also be helpful to know whether streamflow is derived primarily from rainfall, snowmelt, or a combination of the two.

Other desirable information includes the relative frequency and duration of extreme high and low flows for the site and the duration of certain stream flow levels. High and low flow extremes usually are described with a statistical procedure called a frequency analysis, and the amount of time that various flow levels are present is usually described with a flow duration curve.

Finally, it is often desirable to estimate the channel-forming or dominant discharge for a stream (i.e., the discharge that is most effective in shaping and maintaining the natural stream channel). *Channel-forming* or *dominant discharge* is used for design when the restoration includes channel reconstruction.

Estimates of streamflow characteristics needed for restoration can be obtained from stream gauge data. Procedures for determining flow duration characteristics and the magnitude and frequency of floods and low flows at gauged sites are described in this section. The procedures are illustrated using daily mean flows and annual peak flows (the maximum discharge for each year) for the Scott River near Fort Jones, a 653-square-mile watershed in northern California.

Most stream corridor restoration initiatives are on streams or reaches that lack systematic stream gauge data. Therefore, estimates of flow duration and the frequency of extreme high and low flows must be based on indirect methods from regional hydrologic analysis. Several methods are available for indirect estimation of mean annual flow and flood characteristics; however, few methods have been developed for estimating low flows and general flow duration characteristics.

Users are cautioned that statistical analyses using historical streamflow data need to account for watershed changes that might have occurred during the period of record. Many basins in the United States have experienced substantial urbanization and development; construction of upstream reservoirs, dams, and storm water management structures; and construction of levees or channel modifications. These features have a direct impact on the statistical analyses of the data for peak flows, and for low flows and flow duration curves in some instances. Depending on basin modifications and the analyses to be performed, this could require substantial time and effort.

Flow Duration

The amount of time certain flow levels exist in the stream is represented by a *flow duration curve* which depicts the percentage of time a given streamflow was equaled or exceeded over a given period. Flow duration curves are usually based on daily streamflow (a record containing the average flow for each day) and describe the flow characteristics of a stream throughout a range of discharges without regard to the sequence of occurrence. A flow duration curve is the cumulative histogram of the set of all daily flows. The construction of flow duration curves is described by Searcy (1959), who recommends defining the cumulative histogram of streamflow by using 25 to 35 well-distributed class intervals of streamflow data.

Figure 7.1 is a flow duration curve that was defined using 34 class intervals and software documented by Lumb et al. (1990). The numerical output is provided in the accompanying table.

The curve shows that a daily mean flow of 1,100 cubic feet per second (cfs) is exceeded about 20 percent of the time or by about 20 percent of the observed daily flows. The long-term mean daily flow (the average flow for the period of record) for this watershed was determined to be 623 cfs. The duration curve shows that this flow is exceeded about 38 percent of the time.

For over half the states, the USGS has published reports for estimating flow duration percentiles and low flows at ungauged locations. Estimating flow duration characteristics at ungauged sites usually is attempted by adjusting data from a nearby stream gauge in a hydrologically similar basin. Flow duration characteristics from the stream gauge record are expressed per unit area of drainage basin at the gauge (i.e., in cfs/mi^2) and are multiplied by the drainage area of the ungauged site to estimate flow duration characteristics there. The accuracy of such a procedure is directly related to the similarity of the two sites. Generally, the drainage area at the stream gauge and ungauged sites should be fairly similar, and streamflow characteristics should be similar for both sites. Additionally, mean basin elevation and physiography should be similar for both sites. Such a procedure does not work well and should not be attempted in stream systems dominated by local convective storm runoff or where land uses vary significantly between the gauged and ungauged basins.

Flow Frequency Analysis

The frequency of floods and low flows for gauged sites is determined by analyzing an annual time series of maximum or minimum flow values (a chronological list of the largest or smallest flow that occurred each year). Although previously described in Chapter 1, *flow frequency* is redefined here because of its relevance to the sections that follow. Flow frequency is defined as the probability or percent chance of a given flow's being exceeded or not exceeded in any given year. Flow frequency is often expressed in terms of *recurrence interval* or the average number of years between exceeding or not exceeding the given flows. For example, a given flood flow that has a 100-year recurrence interval is expected to be exceeded, on average, only once in any 100-year period; that is, in any given year, the annual flood flow has a 1 percent chance or 0.01 probability of exceeding the 100-year flood. The exceedance probability, p, and the recurrence interval, T, are related in that one is the reciprocal of the other (i.e., $T = 1/p$). Statistical procedures for determining the frequency of floods and low flows at gauged sites follow.

As mentioned earlier, most stream corridor restoration initiatives are on streams or reaches lacking systematic stream gauge data; therefore, estimates of flow duration characteristics and the frequency of extreme high and extreme low flows must be based on indirect methods from regional hydrologic analysis.

Flood Frequency Analysis

Guidelines for determining the frequency of floods at a particular location using streamflow records are documented by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (IACWD 1982, Bulletin 17B). The guidelines described in Bulletin 17B are used by all federal agencies in planning activities involving water and related land resources. Bulletin 17B recommends fitting the Pearson Type III frequency distribution to the logarithms of the annual peak flows using sample statistics (mean, standard deviation, and skew) to estimate the distribution parameters. Procedures for outlier detection and adjustment, adjustment for historical data, development of generalized skew, and weighting of station and generalized skews are provided. The station skew is computed from the observed peak flows, and the generalized skew is a regional estimate determined from estimates at several long-term stations in the region. The US Army Corps of Engineers also has produced a user's manual for *flood frequency analysis* (Report CPD-13, 1994) that can aid in determining flood frequency distribution parameters. NRCS has also produced a manual (*National Engineering Handbook*, Section 4, Chapter 18) that can also be used in determining flood frequency distribution (USDA-SCS 1983).

Throughout the United States, flood frequency estimates for USGS gauging stations have been correlated with certain climatic and basin characteristics. The result is a set of regression equations that can be used to estimate flood magnitude for various return periods in ungauged basins (Jennings et al. 1994). Reports outlining these equations often are prepared for state highway departments to help them size culverts and rural road bridge openings.

Estimates of the frequency of peak flows at ungauged sites may be made by using these regional regression equa-

River Basin	a	b
Southeastern PA	61	0.82
Upper Salmon River, ID	36	0.68
Upper Green River, WY	28	0.69
San Francisco Bay Region, CA	53	0.93

$Q_{bf} = aA^b$

Figure 7.1: Flow duration curve and associated data tables. *Data for the Scott River, near Fort Jones, CA, 1951–1980, show that a flow of 1,100 cubic feet per second (cfs) is exceeded about 20 percent of the time.* Source: Lumb et al. (1990).

Sources of Daily Mean Discharge and Other Data from USGS Stream Gauges

Daily Mean Streamflow

Daily mean streamflow data needed for defining flow duration curves are published on a water-year (October 1 to September 30) basis for each state by the U.S. Geological Survey (USGS) in the report series Water Resources Data. The data collected and published by the USGS are archived in the National Water Information System (NWIS).

The USGS currently provides access to streamflow data by means of the Internet. The USGS URL address for access to streamflow data is http://water.usgs.gov. Approximately 400,000 station years of historical daily mean flows for about 18,500 stations are available through this source. The USGS data for the entire United States are also available from commercial vendors on two CD-ROMs, one for the eastern and one for the western half of the country (e.g., CD-ROMs for DOS can be obtained from Earth Info, and CD-ROMs for Windows can be obtained from Hydrosphere Data Products. Both companies are located in Boulder, Colorado.)

In addition to the daily mean flows, summary statistics are also published for active streamflow stations in the USGS annual Water Resources Data reports. Among the summary statistics are the daily mean flows that are exceeded 10, 50, and 90 percent of the time of record. These durations are computed by ranking the observed daily mean flows from $q_{(1)}$ to $q_{(n \cdot 365)}$ where n is the number of years of record, $q_{(1)}$ is the largest observation, and $q_{(365 \cdot n)}$ is the smallest observation. The ranked list is called a set of ordered observations. The $q_{(1)}$ that are exceeded 10, 50, and 90 percent of the time are then determined. Flow duration percentiles (quantiles) for gauged sites are also published by USGS in reports on low flow frequency and other streamflow statistics (e.g., Atkins and Pearman 1994, Zalants 1991, Telis 1991, and Ries 1994).

Peak Flow

Annual peak flow data needed for flood frequency analysis are also published by the USGS, archived in NWIS, and available through the internet at the URL address provided above. Flood frequency estimates at gauged sites are routinely published by USGS as part of cooperative studies with state agencies to develop regional regression equations for ungauged watersheds. Jennings et al. (1994) provide a nationwide summary of the current USGS reports that summarize flood frequency estimates at gauged sites as well as regression equations for estimating flood peak flows for ungauged watersheds. Annual and partial-duration (peaks-above-threshold) peak flow data for all USGS gauges can be obtained on one CD-ROM from commercial vendors.

tions, provided that the gauged and ungauged sites have similar climatic and physiographic characteristics.

Frequently the user needs only such limited information as mean annual precipitation, drainage area, storage in lakes and wetlands, land use, major soil types, stream gradients, and a topographic map to calculate flood magnitudes at a site. Again, the accuracy of the procedure is directly related to the hydrologic similarity of the two sites.

Similarly, in many locations, flood frequency estimates from USGS gauging stations have been correlated with certain channel geometry characteristics. These correlations produce a set of regression equations relating some channel feature, usually active channel width, to flood magnitudes for various return periods. A review of these equations is provided by Wharton (1995). Again, the standard errors of the estimate might be large.

Regardless of the procedure or source of information chosen for obtaining flood frequency information, estimates for the 1.5, 2, 5, 10, 25, and (record permitting) 50 and 100-year flood events may be plotted on standard log-probability paper, and a smooth curve may be drawn between the points. (Note that these are flood events with probabilities of 67, 50, 20, 10, 4, 2, and 1 percent, respectively.) This plot becomes the flood frequency relationship for the restoration site under consideration. It provides the background information for determining the frequency of inundation of surfaces and vegetation communities along the channel.

Low-Flow Frequency Analysis

Guidelines for *low-flow frequency analysis* are not as standardized as those for flood frequency analysis. No single frequency distribution or curve-fitting method has been generally accepted.

Flood Frequency Estimates

Flood frequency estimates also may be generated using precipitation data and applicable watershed runoff models such as HEC-1, TR-20, and TR-55. The precipitation record for various return-period storm events is used by the watershed model to generate a runoff hydrograph and peak flow for that event. The modeled rainfall may be from historical data or from an assumed time distribution of precipitation (e.g., a 2-year, 24-hour rainfall event). This method of generating flood frequency estimates assumes the return period of the runoff event equals the return period of the precipitation event (e.g., a 2-year rainfall event will generate a 2-year peak flow). The validity of this assumption depends on antecedent moisture conditions, basin size, and a number of other factors.

Vogel and Kroll (1989) provide a summary of the limited number of studies that have evaluated frequency distributions and fitting methods for low flows. The methodology used by USGS and USEPA is described below.

The hypothetical daily hydrograph shown in **Figure 7.2** is typical of many areas of the United States where the annual minimum flows occur in late summer and early fall. The climatic year (April 1 to March 31) rather than the water year is used in low-flow analyses so that the entire low-flow period is contained within one year.

Data used in low-flow frequency analyses are typically the annual minimum average flow for a specified number of consecutive days. The annual minimum 7- and 14-day low flows are illustrated in Figure 7.2. For example, the annual minimum 7-day flow is the annual minimum value of running 7-day means.

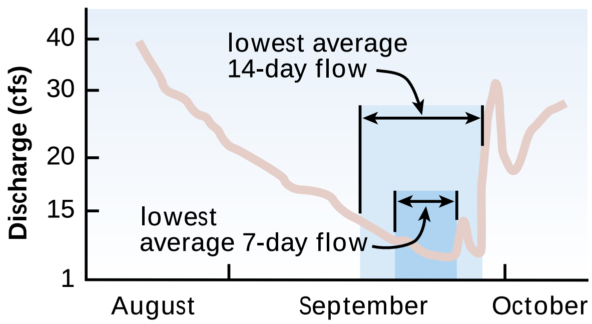


***Figure 7.2**: **Annual hydrograph displaying low flows.** The daily mean flows on the lowest part of the annual hydrograph are averaged to give the 7-day and 14-day low flows for that year.*

USGS and USEPA recommend using the Pearson Type III distribution to the logarithms of annual minimum d-day low flows to obtain the flow with a nonexceedance probability p (or recurrence interval T = 1/p). The Pearson Type III low-flow estimates are computed from the following equation:

$$X_{d,T} = M_d - K_T S_d$$

where:

$X_{d,T}$ = the logarithm of the annual minimum d-day low flow for which the flow is not exceeded in 1 of T years or which has a probability of p = 1/T of not being exceeded in any given year

M_d = the mean of the logarithms of annual minimum d-day low flows

S_d = the standard deviation of the logarithms of the annual minimum d-day low flows

K_T = the Pearson Type III frequency factor

The desired quantile, $Q_{d,T}$, can be obtained by taking the antilogarithm of the equation.

The 7-day, 10-year low flow ($Q_{7,10}$) is used by about half of the regulatory agencies in the United States for managing water quality in receiving waters (USEPA 1986, Riggs et al. 1980). Low flows for other durations and frequencies are used in some states.

Computer software for performing low-flow analyses using a record of daily mean flows is documented by Hutchison (1975) and Lumb et al. (1990). An example of a low-flow frequency curve for the annual minimum 7-day low flow is given in **Figure 7.3** for Scott River near Fort Jones, California, for the same period (1951 to 1980) used in the flood frequency analyses above.

From Figure 7.3, one can determine that the $Q_{7,10}$ is about 20 cfs, which is comparable to the 99th percentile (daily mean flow exceeded 99 percent of the time) of the flow duration curve (Figure 7.1). This comparison is consistent with findings of Fennessey and Vogel (1990), who concluded that the $Q_{7,10}$ from 23 rivers in Massachusetts was approximately equal to the 99th flow duration percentile. The USGS routinely publishes low flow estimates at gauged sites (Zalants 1991, Telis 1991, Atkins and Pearman 1994).

Following are discussions of different ways to look at the flows that tend to form and maintain streams. Restorations that include alterations of flows or changes in the dimensions of the stream must include engineering analyses as described in Chapter 8.

Channel-forming Flow

The *channel-forming* or *dominant discharge* is a theoretical discharge that if constantly maintained in an alluvial stream over a long period of time would produce the same channel geometry that is produced by the long-term natural hydrograph. Channel-forming discharge is the most commonly used single independent variable that is found to govern channel shape and form. Using a channel-forming discharge to design channel geometry is

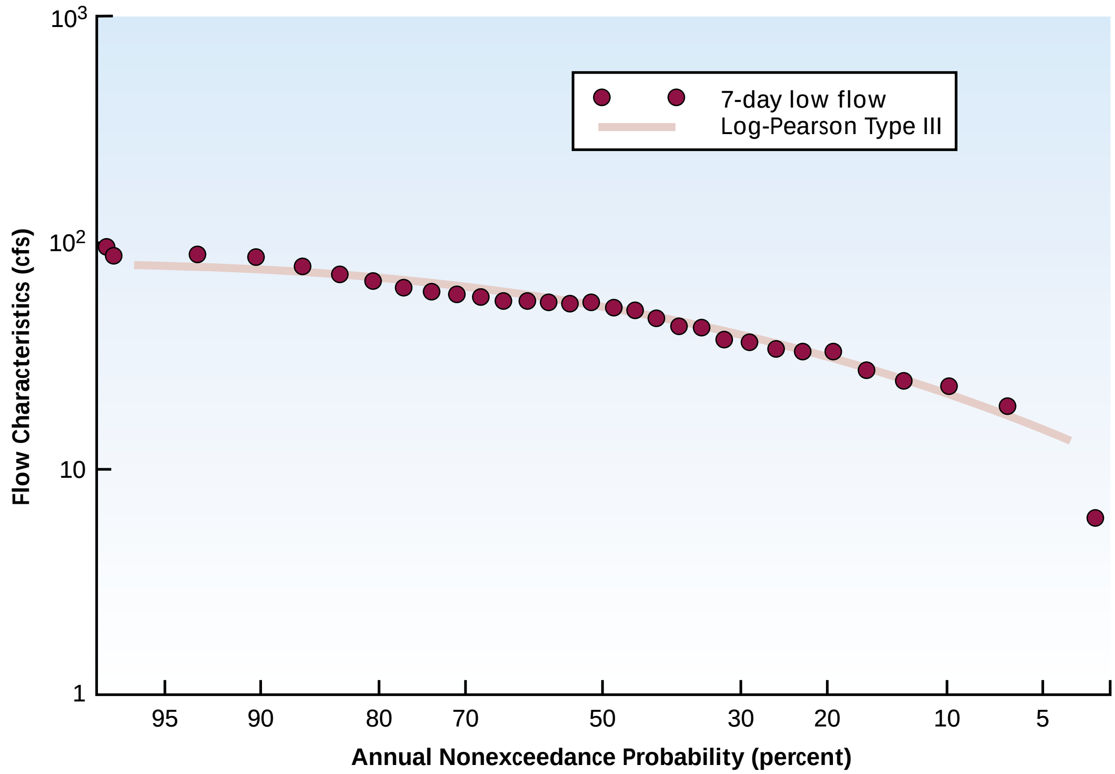


Figure 7.3: Annual minimum 7-day low flow frequency curve. *The $Q_{7,10}$ on this graph is about 20 cfs. The annual minimum value of 7-day running means for this gauge is about 10 percent.*

not a universally accepted technique, although most river engineers and scientists agree that the concept has merit, at least for perennial (humid and temperate) and perhaps ephemeral (semiarid) rivers. For arid channels, where runoff is generated by localized high-intensity storms and the absence of vegetation ensures that the channel will adjust to each major flood event, the channel-forming discharge concept is generally not applicable.

Natural alluvial rivers experience a wide range of discharges and may adjust their geometry to flow events of different magnitudes by mobilizing either bed or bank sediments. Although Wolman and Miller (1960) noted that “it is logical to assume that the channel shape is affected by a range of flows rather than a single discharge,” they concurred with the view put forward earlier by civil engineers working on “regime theory” that the channel-forming or dominant discharge is the steady flow that produces the same gross channel shapes and dimensions as the natural sequence of events (Inglis 1949). Wolman and Miller (1960) defined “moderate frequency” as events occurring “at least once each year or two and in many cases several or more times per year.” They also considered the sediment load transported by a given flow as a percentage of the total amount of sediment carried by the river during the period of record. Their results, for a variety of American rivers located in different climatic and physiographic regions, showed that the greater part (that is, 50 percent or more) of the total sediment load was carried by moderate flows rather than catastrophic floods. Ninety percent of the load was carried by events with a return period of less than 5 years. The precise form of the cumulative curve actually depends on factors such as the predominant mode of transport (bed load, suspended load, or mixed load) and the flow variability, which is influenced by the size and hydrologic characteristics of the watershed. Small watersheds generally experience a wider range of flows than large watersheds, and this tends to increase the proportion of sediment load carried by infrequent events. Thorough reviews of arguments about the conceptual basis of channel-forming discharge theory can be found in textbooks by Richards (1982), Knighton (1984), and Summerfield (1991).

Researchers have used various discharge levels to represent the channel-forming discharge. The most common are (1) bankfull discharge, (2) a specific discharge recurrence interval from the annual peak or partial duration frequency curves, and (3) effective discharge. These approaches are frequently used and can produce a good approximation of the channel-forming discharge in many situations; however, as discussed in the following paragraphs, considerable uncertainties are involved in all three of these approaches. Many practitioners are using specific approaches to determine channel-forming discharge and the response of stream corridors. Bibliographic information on these methods is available later in the document.

Because of the spatial variability within a given geographical region, the response of any particular stream corridor within the region can differ from that expected for the region as a whole. This is especially critical for streams draining small, ungauged drainage areas. Therefore, the expected channel-forming discharge of ungauged areas should be estimated by more than one alternative method, hopefully leading to consistent estimates.

Bankfull Discharge

The *bankfull discharge* is the discharge that fills a stable alluvial channel up to the elevation of the active floodplain. In many natural channels, this is the discharge that just fills the cross section without overtopping the banks, hence the term “bankfull.” This discharge is considered to have morphological significance because it represents the breakpoint between the processes of channel formation and floodplain formation. In stable alluvial channels, bankfull discharge corresponds closely with effective discharge and channel-forming discharge.

The stage vs. discharge or rating curve presented in **Figure 7.4** was developed for a hypothetical stream by computing the discharge for different water surface elevations or stages. Since discharges greater than bankfull spread across the active floodplain, stage increases more gradually with increasing discharge above bankfull than below bankfull, when flows are confined to the channel. Another method for determining the bankfull stage and discharge is to determine the minimum value on a plot relating water surface elevation to the ratio of surface width to area. The frequency of the bankfull discharge can be determined from a frequency distribution plot like Figure 7.1.

Bankfull stage can also be identified from field indicators of the elevation of the active floodplain. The corresponding bankfull discharge is then determined from a stage vs. discharge relationship.

Field Indicators of Bankfull Discharge

Various field indicators can be used for estimating the elevation of the stage associated with bankfull flow. Although the first flat depositional surface is often used, the identification of depositional surfaces in the field can be difficult and misleading and, at the very least, requires trained, experienced field personnel. After an elevation is selected as the bankfull, the stage vs. discharge curve can be computed to determine the magnitude of the discharge corresponding to that elevation.

The above relationships seldom work in incised streams. In an incised stream, the top of the bank might be a terrace (an abandoned floodplain), and indicators of the active floodplain might be found well below the existing top of bank. In this situation, the elevation of the channel-forming discharge will be well below the top of the bank. In addition, the difference between the ordinary use of the term "bankfull" and the geomorphic use of the term can cause major communication problems.

Field identification of bankfull elevation can be difficult (Williams 1978), but is usually based on a minimum width/depth ratio (Wolman 1955), together with the recognition of some discontinuity in the nature of the channel banks such as a change in its sedimentary or vegetative characteristics. Others have defined bankfull discharge as follows:

- Nixon (1959) defined the bankfull stage as the highest elevation of a river that can be contained within the channel without spilling water on the river floodplain or washlands.
- Wolman and Leopold (1957) defined bankfull stage as the elevation of the active floodplain.
- Woodyer (1968) suggested bankfull stage as the elevation of the middle bench of rivers having several overflow surfaces.
- Pickup and Warner (1976) defined bankfull stage as the elevation at which the width/depth ratio becomes a minimum.

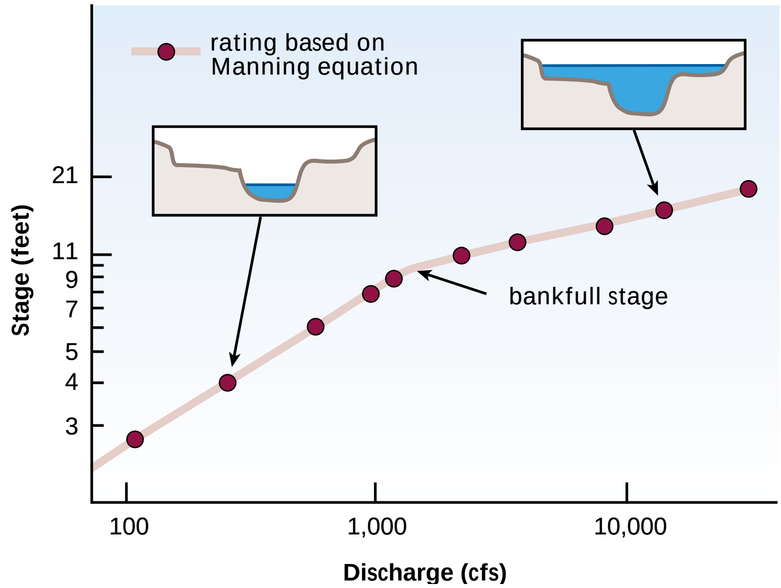


Figure 7.4: Determination of bankfull stage from a rating curve. *The discharge that corresponds to the elevation of the first flat depositional surface is the bankfull discharge.*

Bankfull stage has also been defined using morphologic factors, as follows:

- Schumm (1960) defined bankfull stage as the height of the lower limit of perennial vegetation, primarily trees.
- Similarly, Leopold (1994) states that bankfull stage is indicated by a change in vegetation, such as herbs, grasses, and shrubs.
- Finally, the bankfull stage is also defined as the average elevation of the highest surface of the channel bars (Wolman and Leopold 1957).

The field identification of bankfull stage indicators is often difficult and subjective and should be performed in stream reaches that are stable and alluvial (Knighton 1984). Additional guidelines are reviewed by Wharton (1995). In unstable streams, bankfull indicators are often missing, embryonic, or difficult to determine.

Direct determination of the discharge at bankfull stage is possible if a stream gauge is located near the reach of interest. Otherwise, discharge must be calculated using applicable hydraulic resistance equations and, preferably, standard hydraulic backwater techniques. This approach typically requires that an estimation of channel roughness be made, which adds to the uncertainty associated with calculated bankfull discharge.

The reader is cautioned that the indicators used to define the bankfull condition must be spelled out each time a bankfull discharge is used in a project plan or design.

Because of its convenience, bankfull discharge is widely used to represent channel-forming discharge. There is no universally accepted definition of bankfull stage or discharge that can be consistently applied, has general application, and integrates the processes that create the bankfull dimensions of the river. The reader is cautioned that the indicators used to define the bankfull condition must be spelled out each time a bankfull discharge is used in a project plan or design.

Determining Channel-Forming Discharge from Recurrence Interval

To avoid some of the problems related to field determination of bankfull stage, the *channel-forming discharge* is often assumed to be represented by a specific *recurrence interval* discharge. Some researchers consider this representative discharge to be equivalent to the bankfull discharge. Note that "bankfull discharge" is used synonymously with "channel-forming discharge" in this document. The earliest estimate for channel-forming discharge was the mean annual flow (Leopold and Maddock 1953). Wolman and Leopold (1957) suggested that the channel-forming discharge has a recurrence interval of 1 to 2 years. Dury (1973) concluded that the channel-forming discharge is approximately 97 percent of the 1.58-year discharge or the most probable annual flood. Hey (1975) showed that for three British gravel-bed rivers, the 1.5-year flow in an annual maximum series passed through the scatter of bankfull discharges measured along the course of the rivers. Richards (1982) suggested that in a partial duration series bankfull discharge equals the most probable annual flood, which has a 1 year return period. Leopold (1994) stated that most investigations have concluded that the bankfull discharge recurrence intervals ranged from 1.0 to 2.5 years. Pickup and Warner (1976) determined bankfull recurrence intervals ranged from 4 to 10 years on the annual series.

However, there are many instances where the bankfull discharge does not fall within this range. For example, Williams (1978) determined that approximately 75 percent of 51 streams that he analyzed appeared to have recurrence intervals for the bankfull discharge of between 1.03 and 5.0 years. Williams used the elevation of the active floodplain or the valley flat, if no active floodplain was defined at a station, as the elevation of the bankfull surface in his analyses. He did not establish whether these streams were in equilibrium, so the validity of using the top of the streambank as the bankfull elevation is in question, especially for those stations with valley flats. This might explain the wide range (1.02 to 200 years) he reported for bankfull discharge return intervals for streams with valley flats as opposed to active floodplains. The range in return intervals for 19 of the 28 streams with active floodplains was from 1.01 to 32 years. Nine of the 28 streams had bankfull discharge recurrence intervals of less than 1.0 year. It should be noted that only 3 of those 28 streams had bankfull discharge recurrence intervals greater than 4.8 years. About one-third of the active floodplain stations had bankfull discharges near the 1.5-year recurrence interval.

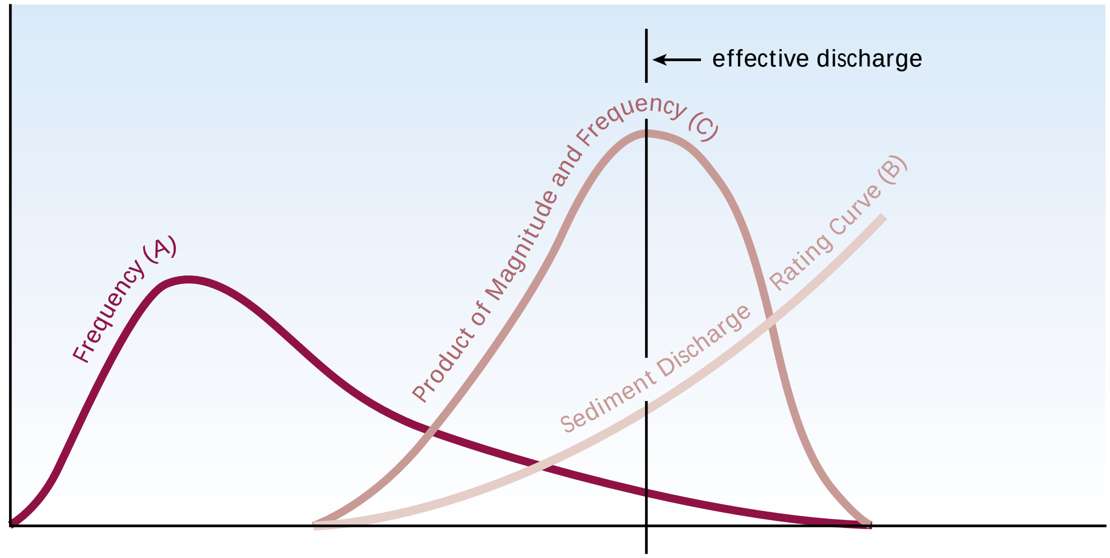


Figure 7.5: Effective discharge determination from sediment rating and flow duration curves. *The peak of curve C marks the discharge that is most effective in transporting sediment.*
Source: Wolman and Miller (1960).

Although the assumption that the channel-forming flow has a recurrence interval of 1 to 3 years is sufficient for reconnaissance-level studies, it should not be used for design until verified through inspection of reference reaches, data collection, and analysis. This is especially true in highly modified streams such as in urban or mined areas, as well as ephemeral streams in arid and semiarid areas.

Effective Discharge

The *effective discharge* is defined as the increment of discharge that transports the largest fraction of the sediment load over a period of years (Andrews 1980). The effective discharge incorporates the principle prescribed by Wolman and Miller (1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. An advantage of using the effective discharge is that it is a calculated rather than field-determined value. The effective discharge is calculated by numerically integrating the flow duration curve (A) and the sediment transport rating curve (B). A graphical representation of the relationship between sediment transport, frequency of the transport, and the effective discharge is shown in **Figure 7.5**. The peak of curve C marks the discharge that is most effective in transporting sediment and, therefore, does the most work in forming the channel.

For stable alluvial streams, effective discharge has been shown to be highly correlated with bankfull discharge. Of the various discharges related to channel morphology (i.e., dominant, bankfull, and effective discharges), effective discharge is the only one that can be computed directly. The effective discharge has morphological significance since it is the discharge that transports the bulk of the sediment.

The effective discharge represents the single flow increment that is responsible for transporting the most sediment over some time period. However, there is a range of flows on either side of the effective discharge that also carry a significant portion of the total annual sediment load.

Biedenharn and Thorne (1994) used a graphical relationship between the cumulative percentage of sediment transported and the water discharge to define a range of effective discharges responsible for the majority of the sediment transport on the Lower Mississippi River. They found that approximately 70 percent of the total sediment was moved in a range of flows between 500,000 cfs and 1,200,000 cfs, which corresponds to the flow that is equaled or exceeded 40 percent of the time and 3 percent of the time, respectively. Thorne et al. (1996) used a similar approach to define the range of effective discharges on the Brahmaputra River.

A standard procedure should be used for the determination of the effective discharge to ensure that the results for different sites can be compared. To be practical, it must either be based on readily available gauging station data or require only limited additional information and computational procedures.

The basic components required for calculation of effective discharge are (1) flow duration data and (2) sediment load as a function of water discharge. The method most commonly adopted for determining the effective discharge is to calculate the total bed material sediment load (tons) transported by each flow increment over a period of time by multiplying the frequency of occurrence for the flow increment (number of days) by the sediment load (tons/day) transported by that flow level. The flow increment with the largest product is the effective discharge. Although this approach has the merit of simplicity, the accuracy of the estimate of the effective discharge is clearly dependent on the calculation procedure adopted.

Values of mean daily discharges are usually used to compute the flow duration curve, as discussed above and presented in Figure 7.1. However, on flashy streams, mean daily values can underestimate the influence of the high flows, and, therefore, it might be necessary to reduce the discharge averaging period from 24 hours (mean daily) to 1 hour, or perhaps 15 minutes.

A *sediment rating curve* must be developed to determine the effective discharge. (See the *Sediment Yield and Delivery* section in Chapter 8 for more details.) The bed material load should be used in the calculation of the effective discharge. This sediment load can be determined from measured data or computed using an appropriate sediment transport equation. If measured suspended sediment data are used, the wash load should be subtracted and only the suspended bed material portion of the suspended load used. If the bed load is a significant portion of the load, it should be calculated using an appropriate sediment transport function and added to the suspended bed material load to provide an estimate of the total bed material load. If bed load measurements are available, these data can be used.

Design Discharge and Ecological Function

Although a channel-forming or dominant discharge is important for design, it is often not sufficient for channel restoration initiatives. An assessment of a wider range of discharges might be necessary to ensure that the functional objectives of the project are met For example, a restoration initiative targeting low-flow habitat conditions must consider the physical conditions in the channel during low flows.

Determination of effective discharge using flow and sediment data is further discussed by Wolman and Miller (1960) and Carling (1988).

Determining Channel-Forming Discharge from Other Watershed Variables

When neither time nor resources permit field determination of bankfull discharge or data are unavailable to calculate the effective discharge, indirect methods based on *regional hydrologic analysis* may be used (Ponce 1989). In its simplest form, regional analysis entails regression techniques to develop empirical relationships applicable to homogeneous hydrologic regions. For example, some workers have used watershed areas as surrogates for discharge (Brookes 1987, Madej 1982, Newbury and Gaboury 1993). Regional relationships of drainage area with bankfull discharge can provide good starting points for selecting the channel-forming discharge.

Within hydrologically homogeneous regions where runoff varies with contributing area, runoff is proportional to watershed drainage area. Dunne and Leopold (1978) and Leopold (1994) developed average curves relating bankfull discharge to drainage area for widely separated regions of the United States. For example, relationships between bankfull discharge and drainage area for Brandywine Creek in Pennsylvania and the upper Green River basin in Wyoming are shown in the **Figure 7.6**.

Two important points are immediately apparent from Figure 7.6. First, humid regions that have sustained, widely distributed storms yield higher bankfull discharges per unit of drainage area than semiarid regions where storms of high intensity are usually localized. Second, bankfull discharge is correlated with drainage area, and the general relationship can be represented by functions of the form:

$$Q_{bf} = aA^{b}$$

where Q_{bf} is the bankfull discharge in cfs, A is the drainage area in square miles, and a and b are regression coefficients and exponents given in **Table 7.1**.

Establishing similar parametric relationships for other rivers of interest is useful because the upstream area draining into a stream corridor can be easily determined from either maps or digital terrain analysis tools. Once the area is determined, an estimate of the expected bankfull discharge for the corridor can be made from the above equation.

Regional Relationship Between Bankfull and Mean Annual Discharge

Because the mean annual flow for each stream gauge operated by the USGS is readily available, it is useful to establish regional relationships between bankfull and mean annual discharges so that one can be estimated whenever the other is available. This information can be compared to the bankfull discharge estimated for any given ungauged site within a U.S. region. ***The user is cautioned, however, that regional curve values have a high degree of error and can vary significantly for specific sites or reaches to be restored.***

Mean Annual Flow

Another frequently used surrogate for channel-forming discharge in empirical regression equations is the *mean annual flow*. The mean annual flow, Q_m, is equivalent to the constant discharge that would yield the same volume of water in a water year as the sum of all continuously measured discharges. Just as in the case of bankfull discharge, Q_m varies proportionally with drainage area within hydrologically homogeneous

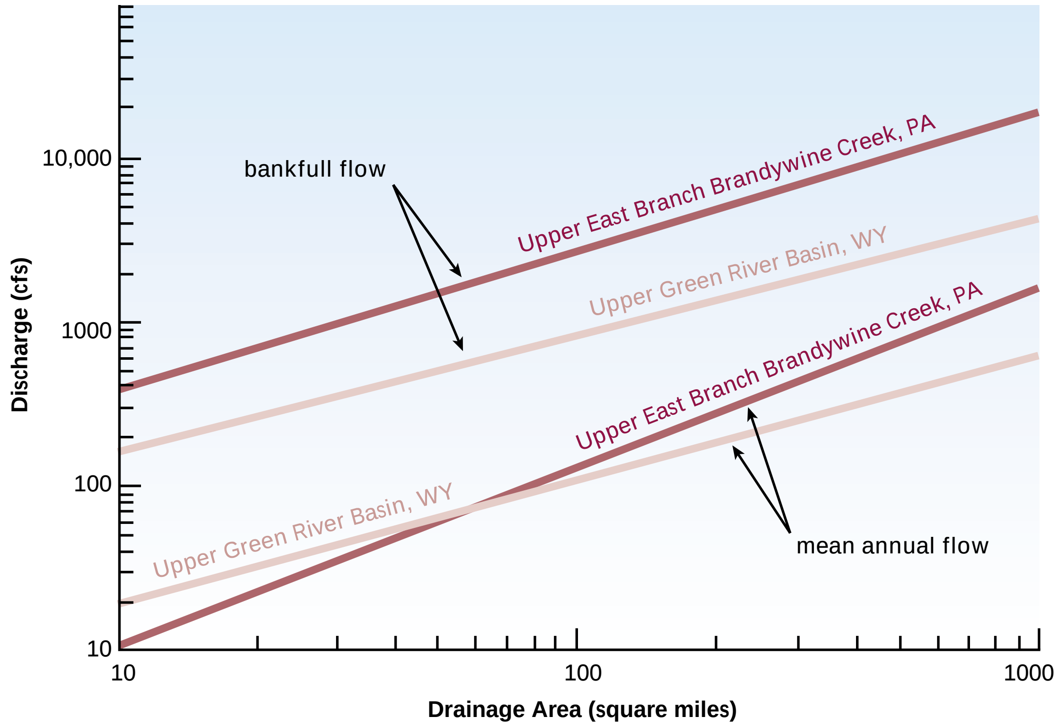


***Figure 7.6: Regional relationships for bankfull and mean annual discharge as a function of drainage area.** The mean annual flow is normally less than the bankfull flow.*
Source: Dunne and Leopold 1978.

Table 7.1: Functional parameters used in regional estimates of bankfull discharge. *In column a are regression coefficients and in column b are exponents that can be used in the bankfull discharge equation.*
Source: Dunne and Leopold 1978.

River Basin	a	b
Southeastern PA	61	0.82
Upper Salmon River, ID	36	0.68
Upper Green River, WY	28	0.69
San Francisco Bay Region, CA	53	0.93

$Q_{bf} = aA^b$

basins. Given that both Q_{bf} and Q_m exhibit a similar functional dependence on A, a consistent proportionality is to be expected between these discharge measures within the same region. In fact, Leopold (1994) gives the following average values of the ratio Q_{bf}/Q_m for three widely separated regions of the United States: 29.4 for 21 stations in the Coast Range of California, 7.1 for 20 stations in the Front Range of Colorado, and 8.3 for 13 stations in the Eastern United States.

Stage vs. Discharge Relationships

Surveys of stream channel cross sections are useful for analyzing channel form, function, and processes. Use of survey data to construct relationships among streamflow, channel geometry, and various hydraulic characteristics provides information that serves a variety of applications. Although stage-discharge curves often can be computed from such cross section data, users should be cautioned to verify their computations with direct discharge measurements whenever possible.

Information on stream channel geometry and hydraulic characteristics is useful for channel design, riparian area restoration, and instream structure placement. Ideally, once a channel-forming discharge is defined, the channel is designed to contain that flow and higher flows are allowed to spread over the floodplain. Such periodic flooding is extremely important for the formation of channel macrofeatures, such as point bars and meander bends, and for establishing certain kinds of riparian vegetation. A cross section analysis also may help in optimal design and placement of items such as culverts and fish habitat structures.

Additionally, knowledge of the relationships between discharge and channel geometry and hydraulics is useful for reconstructing the conditions associated with a particular flow rate. For example, in many channel stability analyses, it is customary to relate movement of bed materials to some measure of stream power or average bed shear stress. If the relationships between discharge and certain hydraulic variables (e.g., mean depth and water surface slope) are known, it is possible to estimate stream power and average bed shear as a function of discharge. A cross section analysis therefore makes it possible to estimate conditions of substrate movement at various levels of streamflow.

Continuity Equation

Discharge at a cross section is computed using the simplified form of the *continuity equation*:

$$Q = AV$$

where:

Q = discharge

A = cross sectional area of the flow

V = average velocity in the downstream direction

Computing the cross-sectional area is a geometry problem. The area of interest is bounded by the channel cross section and the water surface elevation (stage) (**Figure 7.7**). In addition to cross-sectional area, the top width, wetted perimeter, mean depth, and hydraulic radius are computed for selected stages (Figure 7.7).

Uniform flow equations may be used for estimating mean velocity as a function of cross section hydraulic parameters.

Manning's Equation

Manning's equation was developed for conditions of uniform flow in which the water surface profile and energy grade line are parallel to the streambed, and the area, hydraulic radius, and average depth remain constant throughout the reach. The energy grade line is a theoretical line whose elevation above the streambed is the sum of the water surface elevation and a term that represents the kinetic energy of the flow (Chow 1959). The slope of the energy grade line represents the rate at which energy is dissipated through turbulence and boundary friction. When the water surface slope and the energy grade line

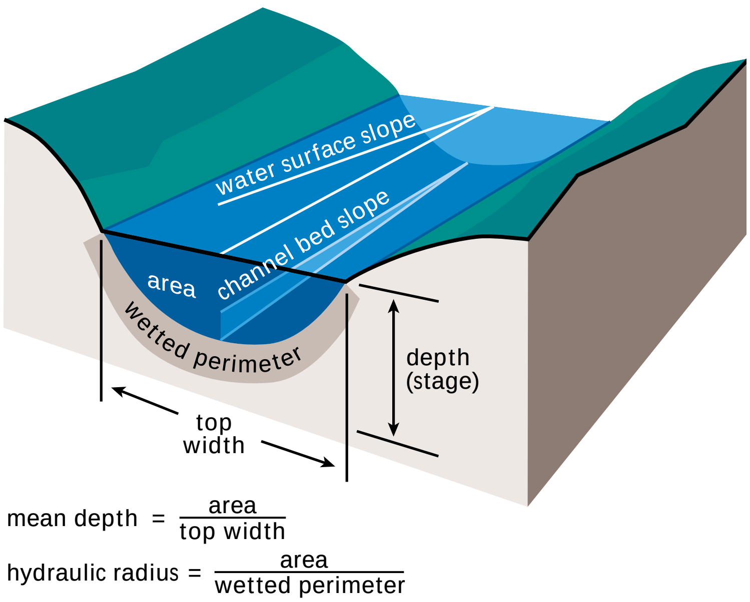


***Figure 7.7:* Hydraulic parameters.** *Streams have specific cross-sectional and longitudinal profile characteristics.*

parallel the streambed, the slope of the energy grade line is assumed to equal the water surface slope. When the slope of the energy grade line is known, various resistance formulas allow computing mean cross-sectional velocity.

The importance of Manning's equation in stream restoration is that it provides the basis for computing differences in flow velocities and elevations due to differences in hydraulic roughness. Note that the flow characteristics can be altered to meet the goals of the restoration either by direct intervention or by changing the vegetation and roughness of the stream. Manning's equation is also useful in determining bankfull discharge for bankfull stage.

Manning's equation is also used to calculate energy losses in natural channels with gradually varied flow. In this case, calculations proceed from one cross section to the next, and unique hydraulic parameters are calculated at each cross section. Computer models, such as HEC-2, perform these calculations and are widely used analytical tools.

Manning's equation for mean velocity, V (in feet per second or meters per second), is given as:

$$V = \frac{k}{n} R^{2/3} S^{1/2}$$

where:

k = 1.486 for English units (1 for metric units)

n = Manning's roughness coefficient

R = hydraulic radius (feet or meters)

S = energy slope (water surface slope).

Manning's roughness coefficient may be thought of as an index of the features of channel roughness that contribute to the dissipation of stream energy. **Table 7.2** shows a range of n values for various boundary materials and conditions.

Two methods are presented for estimating Manning's roughness coefficient for natural channels:

- Direct solution of Manning's equation for n.
- Comparison with computed n values for other channels.

Each method has its own limitations and advantages.

Direct Solution for Determining Manning's n

Even slightly nonuniform flow can be difficult to find in natural channels. The method of direct solution for Manning's n does not require perfectly uniform flow. Manning n values are computed for a reach in which multiple cross sections, water surface elevations, and at least one discharge have been measured. A series of water surface profiles are then computed with different n values, and the computed profile that matches the measured profile is deemed to have an n value that most nearly represents the roughness of that stream reach at the specific discharge.

Table 7.2: Manning roughness coefficients for various boundaries.
Source: Ven te Chow 1964.

Boundary	Manning Roughness, *n* Coefficient
Smooth concrete	0.012
Ordinary concrete lining	0.013
Vitrified clay	0.015
Shot concrete, untroweled, and earth channels in best condition	0.017
Straight unlined earth canals in good condition	0.020
Rivers and earth canals in fair condition—some growth	0.025
Winding natural streams and canals in poor condition—considerable moss growth	0.035
Mountain streams with rocky beds and rivers with variable sections and some vegetation along banks	0.040-0.050
Alluvial channels, sand bed, no vegetation	
1. Lower regime	
Ripples	0.017-0.028
Dunes	0.018-0.035
2. Washed-out dunes or transition	0.014-0.024
3. Upper regime	
Plane bed	0.011-0.015
Standing waves	0.012-0.016
Antidunes	0.012-0.020

Using Manning's n Measured at Other Channels

The second method for estimating n values involves comparing the reach to a similar reach for which Manning's n has already been computed. This procedure is probably the quickest and most commonly used for estimating Manning's n. It usually involves using values from a table or comparing the study reach with photographs of natural channels. Tables of Manning's n values for a variety of natural and artificial channels are common in the literature on hydrology (Chow 1959, Van Haveren 1986) (Table 7.2). Photographs of stream reaches with computed n values have been compiled by Chow (1959) and Barnes (1967). Estimates should be made for several stages, and the relationship between n and stage should be defined for the range of flows of interest.

When the roughness coefficient is estimated from table values, the chosen n value (n_b) is considered a base value that may need to be adjusted for additional resistance features. Several publications provide procedures for adjusting base values of n to account for channel irregularities, vegetation, obstructions, and sinuosity (Chow 1959, Benson and Dalrymple 1967, Arcement and Schneider 1984, Parsons and Hudson 1985).

The most common procedure uses the following formula, proposed by Cowan (1959) to estimate the value of n:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)\ m$$

where

n_b = base value of n for a straight, uniform, smooth channel in natural materials

n_1 = correction for the effect of surface irregularities

Uniform Flow

Under conditions of constant width, depth, area, and velocity, the water surface slope and energy grade line approach the slope of the streambed, producing a condition known as "uniform flow." One feature of uniform flow is that the streamlines are parallel and straight (Roberson and Crowe 1996). Perfectly uniform flow is rarely realized in natural channels, but the condition is approached in some reaches where the geometry of the channel cross section is relatively constant throughout the reach.

*Conditions that tend to disrupt uniform flow include bends in the stream course; changes in cross-sectional geometry; obstructions to flow caused by large roughness elements, such as channel bars, large boulders, and woody debris; or other features that cause convergence, divergence, acceleration, or deceleration of flow (**Figure 7.8**). Resistance equations may also be used to evaluate these nonuniform flow conditions (gradually varied flow); however, energy-transition considerations (backwater calculations) must then be factored into the analysis. This requires the use of multiple-transect models (e.g., HEC-2 and WSP2; HEC-2 is a water surface profile computer program developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center, in Davis, California; WSP2 is a similar program developed by the USDA Natural Resources Conservation Service.)*

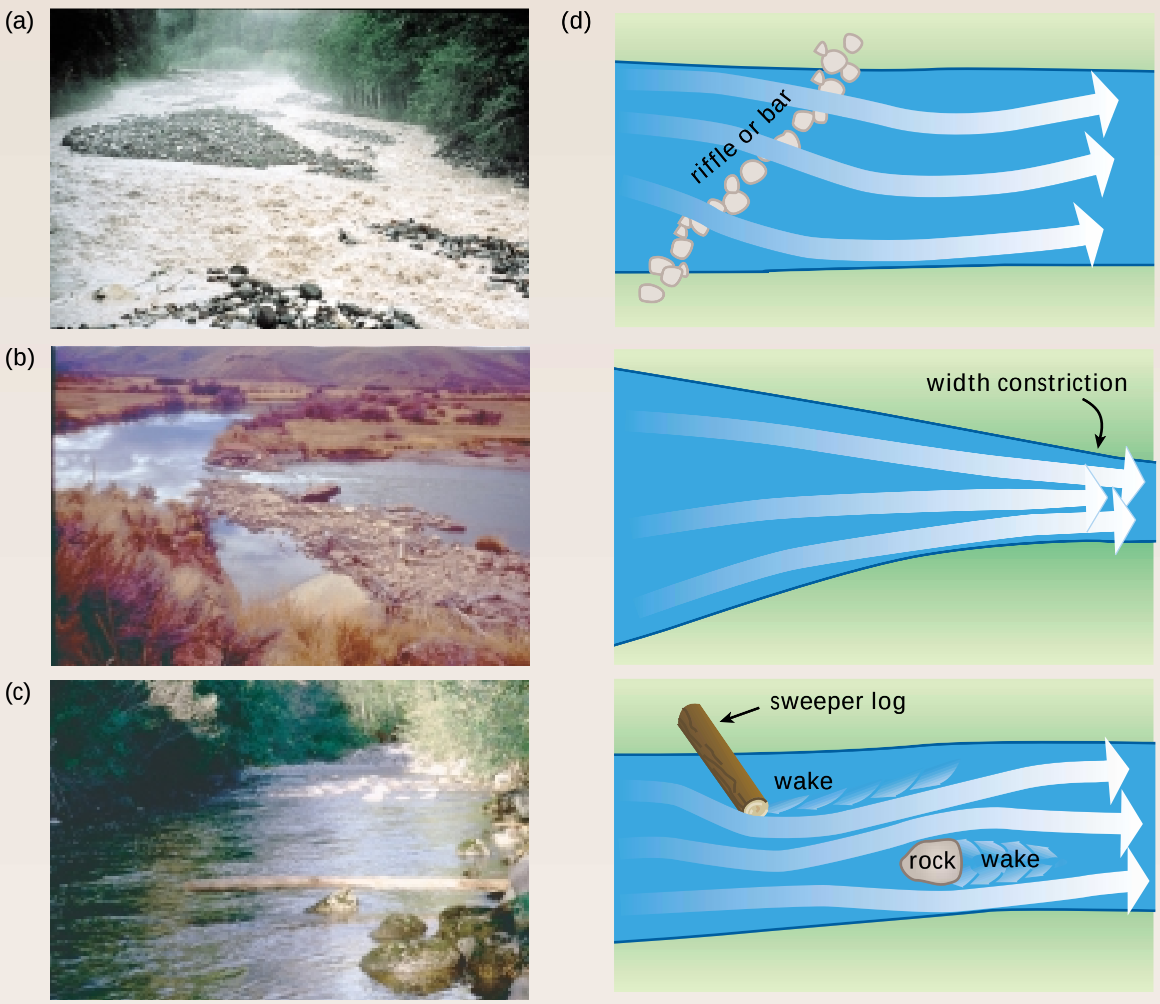


***Figure 7.8:* Streamflow paths for channels with constrictions or obstructions.**
(a) Riffle or bar, Nisqually, Washington.
Source: J. McShane.
(b) Stream width restriction.
(c) Sweeper log.
(d) Stream lines through a reach.

n_2 = correction for variations in cross section size and shape

n_3 = correction for obstructions

n_4 = correction for vegetation and flow conditions

m = correction for degree of channel meandering

Table 7.3 is taken from Aldridge and Garrett (1973) and may be used to estimate each of the above correction factors to produce a final estimated n.

Energy Equation

The *energy equation* is used to calculate changes in water-surface elevation between two relatively similar cross sections. A simplified version of this equation is:

$$z_1 + d_1 + V_1^2/2g = z_2 + d_2 + V_2^2/2g + h_e$$

where:

z = minimum elevation of streambed

d = maximum depth of flow

V = average velocity

g = acceleration of gravity

h_e = energy loss between the two sections

Subscript 1 indicates that the variable is at the upstream cross section, and subscript 2 indicates that the variable is at the downstream cross section.

This simplified equation is applicable when hydraulic conditions between the two cross sections are relatively similar (gradually varied flow) and the channel slope is small (less than 0.18).

Energy losses between the two cross sections occur due to channel boundary roughness and other factors described above. These roughnesses may be represented by a Manning's roughness coefficient, n, and then energy losses can be computed using the Manning equation.

Manning's n in Relation to Channel Bedforms

Just as Manning's n may vary significantly with changes in stage (water level), channel irregularities, obstructions, vegetation, sinuosity, and bed-material size distribution, n may also vary with bedforms in the channel. The hydraulics of sand and mobile-bed channels produce changes in bedforms as the velocity, stream power, and Froude number increase with discharge. The Froude number is a dimensionless number that represents the ratio of inertial forces to gravitational force. As velocity and stream power increase, bedforms evolve from ripples to dunes, to washed-out dunes, to plane bed, to antidunes, to chutes and pools. A stationary plane bed, ripples, and dunes occur when the Froude number (long wave equation) is less than 1 (subcritical flow); washed-out dunes occur at a Froude number equal to 1 (critical flow); and a plane bed in motion, antidunes, and chutes and pools occur at a Froude number greater than 1 (supercritical flow). Manning's n attains maximum values when dune bedforms are present, and minimum values when ripples and plane bedforms are present (Parsons and Hudson 1985).

$$h_e = L\,[Qn/kAR^{2/3}]^2$$

where:

L = distance between cross sections

Q = discharge

n = Manning's roughness coefficient

A = channel cross-sectional area

R = hydraulic radius (Area/wetted perimeter)

k = 1 (SI units)

k = 1.486 (ft-lb-sec units)

Computer models (such as HEC-2 and others) are available to perform these calculations for more complex cross-sectional shapes, including floodplains, and for cases where roughness varies laterally across the cross section (USACE 1991).

Table 7.3: "n" value adjustments.
Source: Aldridge and Garrett (1973).

	Channel Conditions	n Value Adjustment[1]	Example
Degree of irregularity (n_1)	Smooth	0.000	Compares to the smoothest channel attainable in a given bed material.
	Minor	0.001-0.005	Compares to carefully dredged channels in good condition but having slightly eroded or scoured side slopes.
	Moderate	0.006-0.010	Compares to dredged channels having moderate to considerable bed roughness and moderately sloughed or eroded side slopes.
	Severe	0.011-0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock.
Variation in channel cross section (n_2)	Gradual	0.000	Size and shape of channel cross sections change gradually.
	Alternating occasionally	0.001-0.005	Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side owing to changes in cross-sectional shape.
	Alternating frequently	0.010-0.015	Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.
Effect of obstruction (n_3)	Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cross-sectional area.
	Minor	0.005-0.015	Obstructions occupy less than 15 percent of the cross-sectional area and the spacing between obstructions is such that the sphere of influence around one obstruction does not extend to the sphere of influence around another obstruction. Smaller adjustments are used for curved smooth-surfaced objects than are used for sharp-edged angular objects.
	Appreciable	0.020-0.030	Obstructions occupy from 15 to 20 percent of the cross-sectional area or the space between obstructions is small enough to cause the effects of several obstructions to be additive, thereby blocking an equivalent part of a cross section.
	Severe	0.040-0.050	Obstructions occupy more than 50 percent of the cross-sectional area or the space between obstructions is small enough to cause turbulence across most of the cross section.
Amount of vegetation (n_4)	Small	0.002-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation.
	Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of the flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season, growing along the banks and no significant vegetation along the channel bottoms where the hydraulic radius exceeds 2 feet.
	Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 feet; bushy willows about 1 year old intergrown with some weeds along side slopes (all vegetation in full foliage) and no significant vegetation along channel bottoms where the hydraulic radius is greater than 2 feet.
	Very Large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foliage) or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full foliage).
Degree of meandering[1] (adjustment values apply to flow confined in the channel and do not apply where downvalley flow crosses meanders) (m)	Minor	1.00	Ratio of the channel length to valley length is 1.0 to 1.2.
	Appreciable	1.15	Ratio of the channel length to valley length is 1.2 to 1.5.
	Severe	1.30	Ratio of the channel length to valley length is greater than 1.5.

[1] Adjustments for degree of irregularity, variations in cross section, effect of obstructions, and vegetation are added to the base n value before multiplying by the adjustment for meander.

Backwater Effects

Straight channel reaches with perfectly uniform flow are rare in nature and, in most cases, may only be approached to varying degrees. If a reach with constant cross-sectional area and shape is not available, a slightly contracting reach is acceptable, provided there is no significant backwater effect from the constriction. Backwater occurs where the stage vs. discharge relationship is controlled by the geometry downstream of the area of interest (e.g., a high riffle controls conditions in the upstream pool at low flow). Manning's equation assumes uniform flow conditions. Manning's equation used with a single cross section, therefore, will not produce an accurate stage vs. discharge relationship in backwater areas. In addition, expanding reaches also should be avoided since there are additional energy losses associated with channel expansions. When no channel reaches are available that meet or approach the condition of uniform flow, it might be necessary to use multitransect models (e.g., HEC-2) to analyze cross section hydraulics. If there are elevation restrictions corresponding to given flows (e.g., flood control requirements), the water surface profile for the entire reach is needed and use of a multitransect (backwater) model is required.

Analyzing Composite and Compound Cross Sections

Natural channel cross sections are rarely perfectly uniform, and it may be necessary to analyze hydraulics for very irregular cross sections (compound channel). Streams frequently have overflow channels on one or both sides that carry water only during unusually high flows. Overflow channels and overbank areas, which may also carry out-of-bank flows at various flood stages, usually have hydraulic properties significantly different from those of the main channel. These areas are usually treated as separate subchannels, and the discharge computed for each of these subsections is added to the main channel to compute total discharge. This procedure ignores lateral momentum losses, which could cause n values to be underestimated.

A composite cross section has roughness that varies laterally across the section, but the mean velocity can still be computed by a uniform flow equation without subdividing the section. For example, a stream may have heavily vegetated banks, a coarse cobble bed at its lowest elevations, and a sand bar vegetated with small annual willow sprouts.

A standard hydraulics text or reference (such as Chow 1959, Henderson 1986, USACE 1991, etc.) should be consulted for methods of computing a composite n value for varying conditions across a section and for varying depths of flow.

Reach Selection

The intended use of the cross section analysis plays a large role in locating the reach and cross sections. Cross sections can be located in either a short critical reach where hydraulic characteristics change or in a reach that is considered representative of some larger area. The reach most sensitive to change or most likely to meet (or fail to meet) some important condition may be considered a critical reach. A representative reach typifies a definable extent of the channel system and is used to describe that portion of the system (Parsons and Hudson 1985).

Once a reach has been selected, the channel cross sections should be measured at locations considered most suitable for meeting the uniform flow requirements of Manning's equation. The uniform flow requirement is approached by siting cross sections where channel width, depth, and cross-sectional flow area remain relatively constant within the reach, and the water surface slope and energy grade line approach the slope of the streambed. For this reason, marked changes in channel geometry and discontinuities in the flow (steps, falls, and hydraulic jumps) should be avoided. Generally, sections should be located where it appears the streamlines are parallel to the bank and each other within the selected reach. If uniform flow conditions cannot be met and backwater computations are required, defining cross sections located at changes in channel geometry is essential.

Field Procedures

The basic information to be collected in the reach selected for analysis is a survey of the channel cross sections and water surface slope, a measurement of bed-material particle size distribution, and a discharge measurement. The U.S. Forest Service has produced an illustrated guide to field techniques for stream channel reference sites (Harrelson et al. 1994) that is a good reference for conducting field surveys.

Standard Step Backwater Computation

Many computer programs (e.g., HEC-2) are available to compute water surface profiles. The standard step method of Chow (1959, p. 265) can be used to determine the water surface elevation (depth) at the upstream end of the reach by iterative approximations. This method uses trial water surface elevations to determine the elevation that satisfies the energy and Manning equations written for the end sections of the reach. In using this method, cross sections should be selected so that velocities increase or decrease continuously throughout the reach (USACE 1991).

Survey of Cross Section and Water Surface Slope

The cross section is established perpendicular to the flow line, and the points across the section are surveyed relative to a known or arbitrarily established benchmark elevation. The distance/elevation paired data associated with each point on the section may be obtained by sag tape, rod-and-level survey, hydrographic surveys, or other methods.

Water surface slope is also required for a cross section analysis. The survey of water surface slope is somewhat more complicated than the cross section survey in that the slope of the water surface at the location of the section (e.g., pool, run, or riffle) must be distinguished from the more constant slope of the entire reach. (See Grant et al. 1990 for a detailed discussion on recognition and characteristics of channel units.) Water surface slope in individual channel reaches may vary significantly with changes in stage and discharge.

For this reason, when water surface slopes are surveyed in the field, the low-water slope may be approximated by the change in elevation over the individual channel unit where the cross section is located, approximately 1 to 5 channel widths in length, while the high-water slope is obtained by measuring the change in elevation over a much longer reach of channel, usually at least 15 to 20 channel widths in length.

Bed Material Particle Size Distribution

Computing mean velocity with resistance equations based on relative roughness, such as the ones suggested by Thorne and Zevenbergen (1985), requires an evaluation of the particle size distribution of the bed material of the stream. For streams with no significant channel armor and bed material finer than medium gravel, bed material samplers developed by the Federal Interagency Sedimentation Project (FISP 1986) may be used to obtain a representative sample of the streambed, which is then passed through a set of standard sieves to determine percent by weight of particles of various sizes. The cumulative percent of material finer than a given size may then be determined.

Particle size data are usually reported in terms of d_i, where i represents some nominal percentile of the distribution and d_i represents the particle size, usually expressed in millimeters, at which i percent of the total sample by weight is finer. For example, 84 percent of the total sample would be finer than the d_{84} particle size. For additional guidance on bed material sampling in sand-bed streams, refer to Ashmore et al. (1988).

For estimating velocity in steep mountain rivers with substrate much coarser than the medium-gravel limitation of FISP samplers, a *pebble count*, in which at least 100 bed material particles are manually collected from the streambed and measured, is used to measure surface particle size (Wolman 1954). At each sample point along a cross section, a particle is retrieved from the bed, and the intermediate axis (not the longest or shortest axis) is measured. The measurements are tabulated as to number of particles occurring within predetermined size intervals, and the percentage of the total number in each interval is then determined. Again, the percentage in each interval is accumulated to give a particle size distribution, and the particle size data are reported as described above. Additional guidance for bed material sampling in coarse-bed streams is provided in Yuzyk (1986). If an armor layer or pavement is present, standard techniques may be employed to characterize bed sediments, as described by Hey and Thorne (1986).

Discharge Measurement

If several discharge measurements can be made over a wide range of flows, relationships among stage, discharge, and other hydraulic parameters may be developed directly. If only one discharge measurement is obtained, it likely will occur during low water and will be useful for defining the lower end of the rating table. If two measurements can be made, it is desirable to have a low-water measurement and a high-water measurement to define both ends of the rating table and to establish the relationship between Manning's n and stage. If high water cannot be measured directly, it may be necessary to estimate the high-water n (see the discussion earlier in the chapter).

The Bureau of Reclamation *Water Measurement Manual* (USDI-BOR 1997) is an excellent source of information for measuring channel and stream discharge (**Figure 7.9**). Buchanan and Somers (1969) and Rantz et al. (1982) also provide in-depth discussions of discharge measurement techniques. When equipment is functioning properly and standard procedures are followed correctly, it is possible to measure streamflow to within 5 percent of the true value. The USGS considers a “good” measurement of discharge to account for plus or minus 5 percent and an “excellent” discharge measurement to be within plus or minus 3 percent of the true value.

Figure 7.9: Station measuring discharge. *Permanent stations provide measurements for a wide range of flow, but the necessary measurements can be made in other ways.* Source: C. Zabawa.

7.B Geomorphic Processes

In planning a project along a river or stream, awareness of the fundamentals of fluvial geomorphology and channel processes allows the investigator to see the relationship between form and process in the landscape. The detailed study of the fluvial geomorphic processes in a channel system is often referred to as a *geomorphic assessment*. The geomorphic assessment provides the process-based framework to define past and present watershed dynamics, develop integrated solutions, and assess the consequences of restoration activities. A geomorphic assessment generally includes data collection, field investigations, and channel stability assessments. It forms the foundation for analysis and design and is therefore an essential first step in the design process, whether planning the treatment of a single reach or attempting to develop a comprehensive plan for an entire watershed.

Stream Classification

The use of any *stream classification* system is an attempt to simplify what are complex relationships between streams and their watersheds.

Although classification can be used as a communications tool and as part of the overall restoration planning process, the use of a classification system is not required to assess, analyze, and design stream restoration initiatives. The design of a restoration does, however, require site-specific engineering analyses and biological criteria, which are covered in more detail in Chapter 8.

Restoration designs range from simple to complex, depending on whether “no action,” only management techniques, direct manipulation, or combinations of these approaches are used. Complete stream corridor restoration designs require an interdisciplinary approach as discussed in Chapter 4. A poorly designed restoration might be difficult to repair and can lead to more extensive problems.

More recent attempts to develop a comprehensive stream classification system have focused on morphological forms and processes of channels and valley bottoms, and drainage networks. Classification systems might be categorized as systems based on sediment transport processes and systems based on channel response to perturbation.

Stream classification methods are related to fundamental variables and processes that form streams. Streams are classified as either alluvial or non-alluvial. An *alluvial stream* is free to adjust its dimensions, such as width, depth, and slope, in response to changes in watershed sediment discharge. The bed and banks of an alluvial stream are composed of material transported by the river under present flow conditions. Conversely, a *non-alluvial* river, like a bedrock-controlled channel, is not free to adjust. Other conditions, such as a high mountain stream flowing in very coarse glacially deposited materials or streams which are significantly controlled by fallen timber, would suggest a non-alluvial system.

Streams may also be classified as either perennial, intermittent, or ephemeral, as discussed in Chapter 1. A perennial stream is one that has flow at all times. An intermittent stream has the potential for continued flow, but at times the entire flow is absorbed by the bed material. This may be seasonal in nature. An ephemeral stream has flow only following a rainfall event. When carrying flow, intermittent and ephemeral streams both have characteristics very similar to those of perennial streams.

Advantages of Stream Classification Systems

The following are some advantages of stream classification systems:

- Classification systems promote communication among persons trained in different resource disciplines.
- They also enable extrapolation of inventory data collected on a few channels of each stream class to a much larger number of channels over a broader geographical area.
- Classification helps the restoration practitioner consider the landscape context and determine the expected range of variability for parameters related to channel size, shape, and pattern and composition of bed and bank materials.
- Stream classification also enables the practitioner to interpret the channel-forming or dominant processes active at the site, providing a base on which to begin the process of designing restoration.
- Classified reference reaches can be used as the stable or desired form of the restoration.
- A classification system is also very useful in providing an important cross-check to verify if the selected design values for width/depth ratio, sinuosity, etc., are within a reasonable range for the stream type being restored.

Limitations of Stream Classification Systems

All stream classification systems have limitations that are inherent to their approaches, data requirements, and range of applicabilities. They should be used cautiously and only for establishing some of the baseline conditions on which to base initial restoration planning. Standard design techniques should never be replaced by stream classification alone.

Some limitations of classification systems are as follows:

- Determination of bankfull or channel-forming flow depth may be difficult or inaccurate. Field indicators are often subtle or missing and are not valid if the stream is not stable and alluvial.
- The dynamic condition of the stream is not indicated in most classification systems. The knowledge of whether the stream is stable, aggrading, or degrading or is approaching a critical geomorphic threshold is important for a successful restoration initiative.
- River response to a perturbation or restoration action is normally not determined from the classification system alone.
- Biological health of a stream is usually not directly determined through a stream classification system.
- A classification system alone should not be used for determining the type, location, and purpose of restoration activities. These are determined through the planning steps in Part II and the design process in Chapter 8.

When the results of stream classification will be used for planning or design, the field data collection should be performed or directed by persons with experience and training in hydrology, hydraulics, terrestrial and aquatic ecology, sediment transport, and river mechanics. Field data collected by personnel with only limited formal training may not be reliable, particularly in the field determination of bankfull indicators and the assessment of channel instability trends.

Stream Classification Systems

Stream Order

Designation of *stream order*, using the Strahler (1957) method, described in Chapter 1, is dependent on the scale of maps used to identify first-order streams. It is difficult to make direct comparisons of the morphological characteristics of two river basins obtained from topographic maps of different scales. However, the basic morphological relationships defined by Horton (1945) and Yang (1971) are valid for a given river basin regardless of maps used, as shown in the case study of the Rogue River Basin (Yang and Stall 1971, 1973).

Horton (1945) developed some basic empirical stream morphology relations, i.e., Horton's law of stream order, stream slope, and stream length. These show that the relationships between stream order, average stream length, and slope are straight lines on semilog paper.

Yang (1971) derived his theory of average stream fall based on an analogy with thermodynamic principles. The theory states that the ratio of average fall (change in bed elevation) between any two stream orders in a given river basin is unity. These theoretical results were supported by data from 14 river basins in the United States with an average fall ratio of 0.995. The Rogue River basin data were used by Yang and Stall (1973) to demonstrate the relationships between average stream length, slope, fall, and number of streams.

Stream order is used in the *River Continuum Concept* (Vannote et al. 1980), described in Chapter 1, to distinguish different levels of biological activity. However, stream order is of little help to planners and designers looking for clues to restore hydrologic and geomorphic functions to stream corridors.

Schumm

Other classification schemes combine morphological criteria with dominant modes of sediment transport. Schumm (1977) identified straight, meandering, and braided channels and related both channel pattern and stability to modes of sediment transport (**Figure 7.10**).

Schumm recognized relatively stable straight and meandering channels, with predominantly suspended sediment load and cohesive bank materials. On the other end of the spectrum are relatively unstable braided streams characterized by predominantly bedload sediment transport and wide, sandy channels with noncohesive bank materials. The intermediate condition is generally represented by meandering mixed-load channels.

Montgomery and Buffington

Schumm's classification system primarily applies to alluvial channels; Montgomery and Buffington (1993) have proposed a similar classification system for alluvial, colluvial, and bedrock streams in the Pacific Northwest that addresses channel response to sediment inputs throughout the drainage network. Montgomery and Buffington recognize six classes of alluvial channels—cascade, step-pool, plane-bed, riffle-pool, regime, and braided (**Figure 7.11**).

The stream types are differentiated on the basis of channel response to sediment inputs, with steeper channels (cascade and step-pool) maintaining their morphology while transmitting increased sediment loads, and low-gradient channels (regime and pool-riffle) responding to increased sediment through morphological adjustments. In general, steep channels act as sediment-delivery conduits connecting zones of sediment production with low-gradient response channels.

Rosgen Stream Classification System

One comprehensive stream classification system in common use is based on morphological characteristics described by Rosgen (1996) (**Figure 7.12**). The Rosgen system uses six morphological measurements for classifying a stream reach—entrenchment, width/depth ratio, sinuosity, number of channels, slope, and bedmaterial particle size. These criteria are used to define eight major stream classes with about 100 individual stream types.

Rosgen uses the bankfull discharge to represent the stream-forming discharge or channel-forming flow. Bankfull discharge is needed to use this classification system because all of the morphological relationships are related to this flow condition: width and depth of flow are measured at the bankfull elevation, for example.

Except for entrenchment and width/depth ratio (both of which depend on a determination of bankfull depth), the parameters used are relatively straightforward measurements. The problems in determining bankfull depth were discussed earlier in Chapter 1. The width/depth ratio is taken at bankfull stage and is the ratio of top width to mean depth for the bankfull channel. Sinuosity is the ratio of stream length to valley length or, alternatively, valley slope to stream slope. The bed material particle size used in the classification is the dominant bed surface particle size, determined in the field by a pebble-count procedure (Wolman 1954) or as modified for sand and smaller sizes. Stream slope is measured over a channel reach of at least 20 widths in length.

Entrenchment describes the relationship between a stream and its valley and is defined as the vertical containment of the stream and the degree to

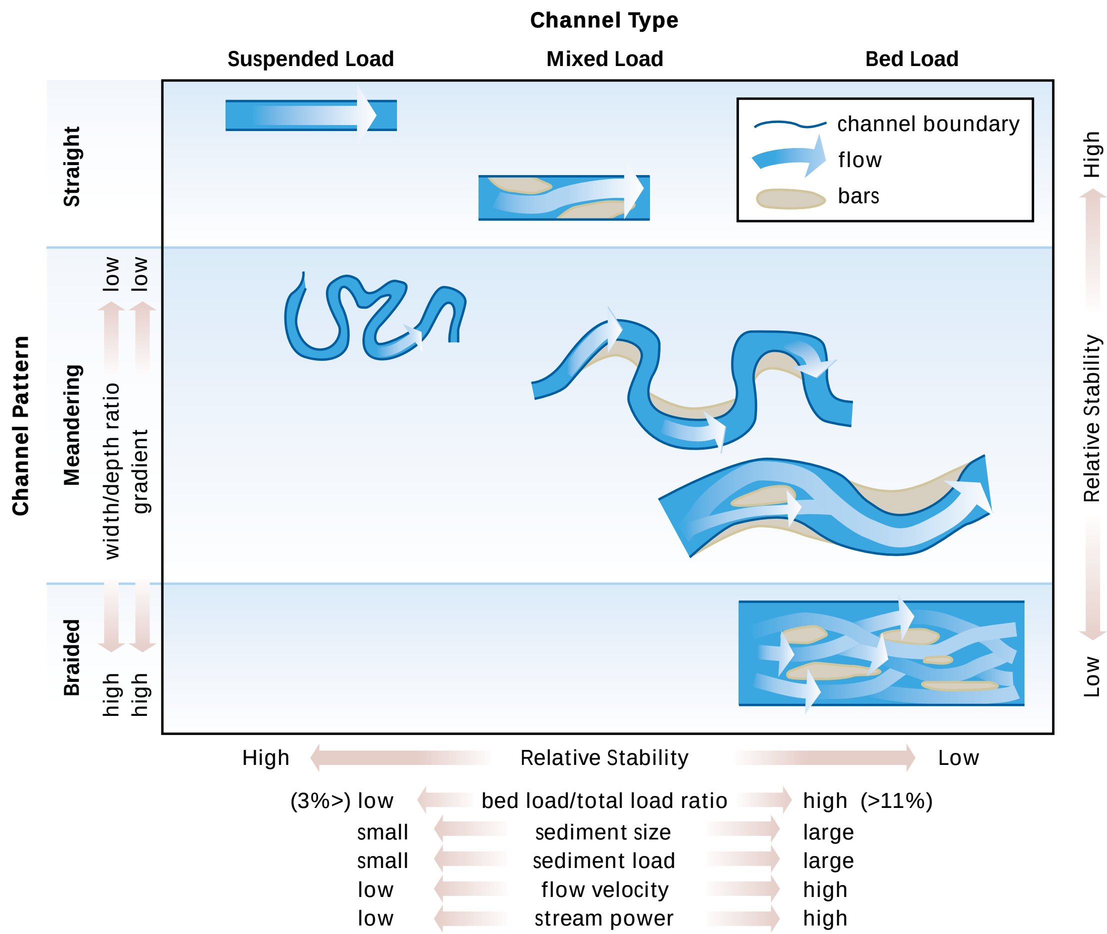


Figure 7.10: Classification of alluvial channels. *Schumm's classification system relates channel stability to kind of sediment load and channel type.*

Source: Schumm, The Fluvial System. © 1977. Reprinted by permission of John Wiley and Sons, Inc.

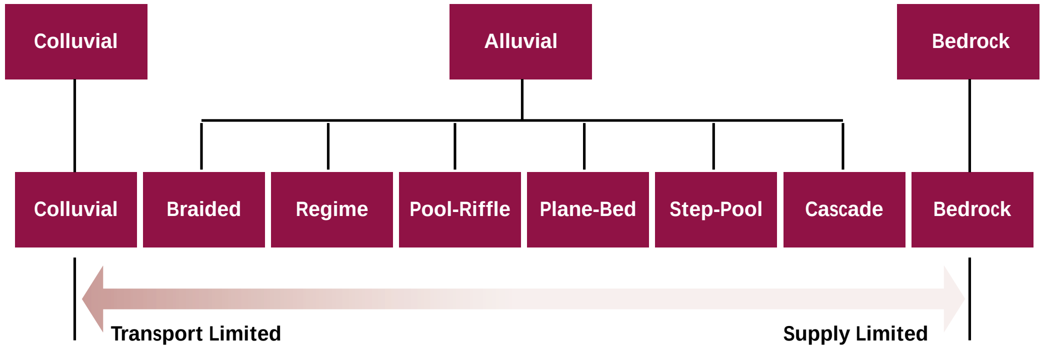
which it is incised in the valley floor. It is, therefore, a measure of how accessible a floodplain is to the stream. The entrenchment ratio used in the Rosgen classification system is the flood-prone width of the valley divided by the bankfull width of the channel. Flood-prone width is determined by doubling the maximum depth in the bankfull channel and measuring the width of the valley at that elevation. If the flood-prone width is greater than 2.2 times the bankfull width, the stream is considered to be slightly entrenched or confined and the stream has ready access to its floodplain. A stream is classified as entrenched if its flood-prone width is less than 1.4 times the bankfull width.

A sample worksheet for collecting data and classifying a stream using the Rosgen system is shown in **Figure 7.13**. A field book for collecting reference reach information is available (Leopold et al. 1997).

Channel Evolution Models

Conceptual *models of channel evolution* describe the sequence of changes a stream undergoes after certain kinds of disturbances. The changes can include increases or decreases in the width/depth ratio of the channel and also involve alterations in the floodplain. The sequence of changes is somewhat predictable, so it is important that the current stage of evolution be identified so appropriate actions can be planned.

Figure 7.11: Suggested stream classification system for Pacific Northwest. *Included are classifications for nonalluvial streams.*
Source: Montgomery and Buffington 1993.



	Braided	Regime	Pool-Riffle	Plane-Bed	Step-Pool	Cascade	Bedrock	Colluvial
Typical Bed Material	Variable	Sand	Gravel	Gravel, cobble	Cobble, boulder	Boulder	N/A	Variable
Bedform Pattern	Laterally oscillary	Multi-layered	Laterally oscillary	None	Vertically oscillary	None	•	Variable
Reach Type	Response	Response	Response	Response	Transport	Transport	Transport	Source
Dominant Roughness Elements	Bedforms (bars, pools)	Sinuosity, bedforms (dunes, ripples, bars) banks	Bedforms (bars, pools), grains, LWD, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, LWD, banks	Grains, banks	Boundaries (bed & banks)	Grains, LWD
Dominant Sediment Sources	Fluvial, bank failure, debris flow	Fluvial, bank failure, inactive channel	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Hillslope, debris flow
Sediment Storage Elements	Overbank, bedforms	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, inactive channel	Bedforms	Lee & stoss sides of flow obstructions	•	Bed
Typical Slope (m/m)	S < 0.03	S < 0.001	0.001 < S and S < 0.02	0.01 < S and S < 0.03	0.03 < S and S < 0.08	0.08 < S and S < 0.30	Variable	S > 0.20
Typical Confinement	Unconfined	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Pool Spacing (Channel Widths)	Variable	5 to 7	5 to 7	none	1 to 4	< 1	Variable	Variable

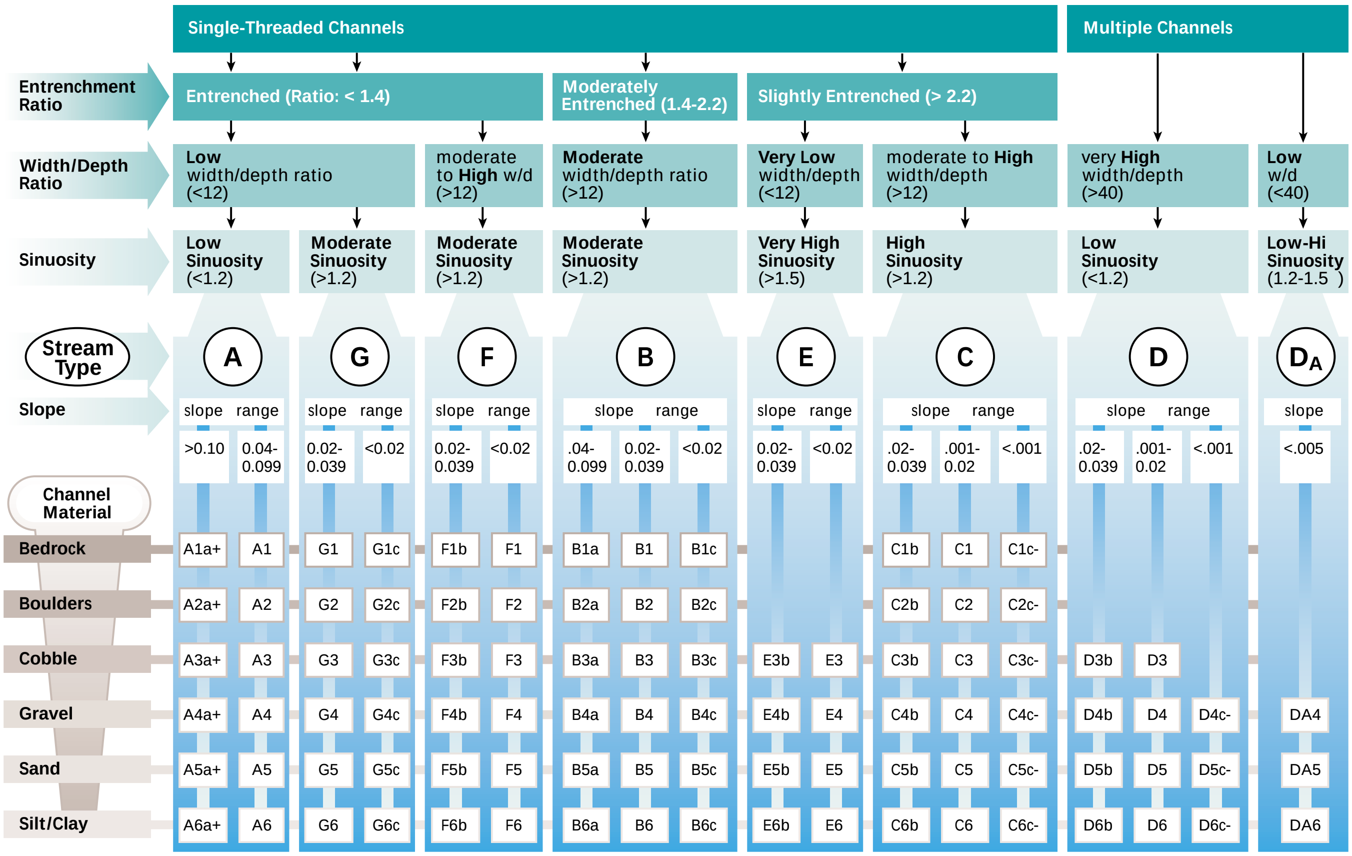


Figure 7.12: Rosgen's stream channel classification system (Level II). *This classification system includes a recognition of specific characteristics of channel morphology and the relationship between the stream and its floodplain.*
Source: Rosgen 1996. Published by permission of Wildland Hydrology.

Schumm et al. (1984), Harvey and Watson (1986), and Simon (1989) have proposed similar channel evolution models due to bank collapse based on a "space-for-time" substitution, whereby downstream conditions are interpreted as preceding (in time) the immediate location of interest and upstream conditions are interpreted as following (in time) the immediate location of interest. Thus, a reach in the middle of the watershed that previously looked like the channel upstream will evolve to look like the channel downstream.

Downs (1995) reviews a number of classification schemes for interpreting channel processes of lateral and vertical adjustment (i.e., aggradation, degradation, bend migration, and bar formation). When these adjustment processes are placed in a specific order of occurrence, a channel evolution model (CEM) is developed. Although a number of CEMs have been suggested, two models (Schumm et al. 1984 and Simon 1989, 1995) have gained wide acceptance as being generally applicable for channels with cohesive banks.

Both models begin with a predisturbance condition, in which the channel is well vegetated and has frequent interaction with its floodplain. Following a perturbation in the system (e.g., channelization or change in land use), degradation occurs, usually as a result of excess stream power in the disturbed reach. Channel degradation eventually leads to oversteepening of the banks, and when critical bank heights are exceeded, bank failures and mass wasting (the episodic

STREAM CLASSIFICATION WORKSHEET

Party:____________________ Date:_____________________
State:____________________ County:___________________
Stream: ____

Bankfull Measurements: Lat/Long ________________________
Width ______________ Depth _____________ W/D _____________

Sinuosity (Stream Length/Valley Length) or (Valley Slope/Channel Slope):
Strm. Length _________________ Valley Slope ________________________
Valley Length _________________ Channel Slope ______________________

Sinuosity $\frac{S_L}{V_L}$ ___________________ Sinuosity $\frac{V_S}{C_S}$ ________________________

Entrenchment Ratio (Floodprone Width/Bankfull Width):
Floodprone width is water level at 2x maximum depth in bankfull cross-section, or width of intermediate floodplain (10-50 yr. event)
Bankfull Width ________________ Floodprone Width __________________
Entrenchment Ratio __________________
Slight = 2.2+ Moderate + 1.41-2.2 Entrenched = 1.0-1.4

Dominant Channel Soils:
Bed Material ____________ Left Bank _____________ Right Bank _____________
Description of Soil Profiles (from base of bank to top)
Left: ____
Right: ____

Riparian Vegetation:
Left Bank: _____________________ Right Bank ________________________
% Total Area (Mass) L _______________ R ________________
% Total Ht w/Roots L ________________ R ________________
Ratio of Actual Bank Height to Bankfull Height __________________________

Bank Slope (Horizontal to Vertical): L __________________ R ___________________

STREAM TYPE _______________ Remarks ____________________________________

PEBBLE COUNT	Site________________________________															
Metric (mm)	English (inches)	Particle	Count	Tot #	% Tot	% Cum	Count	Tot #	% Tot	% Cum	Count	Tot #	% Tot	% Cum
<.062	<.002	Silt/Clay												
.062-0.25	.002-.01	Fine Sand												
0.25-.5	.01-.02	Med Sand												
.5-1.0	.02-.04	Coarse Sand												
1.0-2.0	.04-.08	Vy Coarse Sand												
2-8	.08-.32	Fine Gravel												
8-16	.32-.63	Med Gravel												
16-32	.63-1.26	Coarse Gravel												
32-64	1.26-2.51	Vy Coarse Gravel												
64-128	2.51-5.0	Small Cobbles												
128-256	5.0-10.1	Large Cobbles												
256-512	10.1-20.2	Sm Boulders												
512-1024	20.2-40.3	Med Boulders												
1024-2048	40.3-80.6	Lg Boulders												
2048-4096	80.6-161	Vy Lg Boulders												

Figure 7.13: Example of stream classification worksheet used with Rosgen methods.
Source: NRCS 1994 (worksheet) and Rosgen 1996 (pebble count). Published by permission of Wildland Hydrology.

downslope movement of soil and rock) lead to channel widening. As channel widening and mass wasting proceed upstream, an aggradation phase follows in which a new low-flow channel begins to form in the sediment deposits. Upper banks may continue to be unstable at this time. The final stage of evolution is the development of a channel within the deposited alluvium with dimensions and capacity similar to those of the predisturbance channel (Downs 1995). The new channel is usually lower than the predisturbance channel, and the old floodplain now functions primarily as a terrace.

Once streambanks become high, either by downcutting or by sediment deposition on the floodplain, they begin to fail due to a combination of erosion at the base of the banks and mass wasting. The channel continues to widen until flow depths do not reach the depths required to move the sloughed bank materials. Sloughed materials at the base of the banks may begin to be colonized by vegetation. This added roughness helps increase deposition at the base of the banks, and a new small-capacity channel begins to form between the stabilized sediment deposits. The final stage of channel evolution results in a new bankfull channel and active floodplain at a new lower elevation. The original floodplain has been abandoned due to channel incision or excessive sediment deposition and is now termed a terrace.

Schumm et al. (1984) applied the basic concepts of channel evolution to the problem of unstable channelized streams in Mississippi. Simon (1989) built on Schumm's work in a study of channelized streams in Tennessee. Simon's CEM consisted of six stages (**Figure 7.14**). Both models use the cross section, longitudinal profile, and geomorphic processes to distinguish stages of evolution. Both models were developed for landscapes dominated by streams with cohesive banks. However, the same physical processes of evolution can occur in streams with noncohesive banks but not necessarily in the same well-defined stages.

Table 7.4 and **Figure 7.15** show the processes at work in each of Simon's stages.

Advantages of Channel Evolution Models

CEMs are useful in stream corridor restoration in the following ways (Note: Stages are from Simon's 1989 six-stage CEM):

- CEMs help to establish the direction of current trends in disturbed or constructed channels. For example, if a reach of stream is classified as being in Stage IV of evolution (Figure 7.14), more stable reaches should occur downstream and unstable reaches should occur upstream. Once downcutting or incision occurs in a stream (Stage III), the headcut will advance upstream until it reaches a resistant soil layer, the drainage area becomes too small to generate erosive runoff, or the slope flattens to the point that the stream cannot generate enough energy to downcut. Stages IV to VI will follow the headcut upstream.
- CEMs can help to prioritize restoration activities if modification is planned. By stabilizing a reach of stream in early Stage III with grade control measures, the potential degradation of that reach and upstream reaches can be prevented. It also takes less intensive efforts to successfully restore stream reaches in Stages V and VI than to restore those in Stages III and IV.

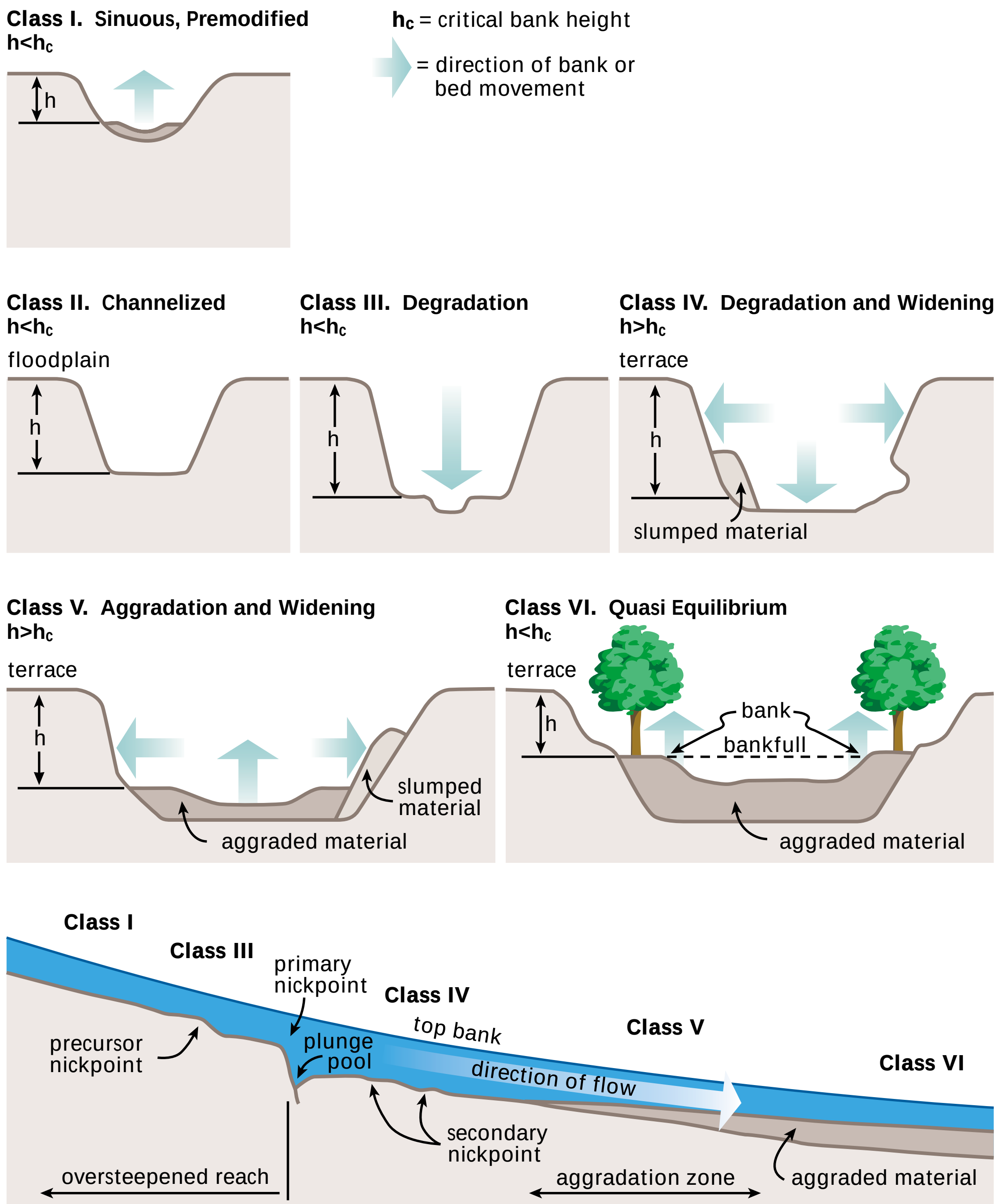


Figure 7.14: Channel evolution model. *A disturbed or unstable stream is in varying stages of disequilibrium along its length or profile. A channel evolution model theoretically may help predict future upstream or downstream changes in habitat and stream morphology.*
Source: Simon 1989, USACE 1990.

- CEMs can help match solutions to the problems. Downcutting in Stage III occurs due to the greater capacity of the stream created by construction, or earlier incision, in Stage II. The downcutting in Stage III requires treatments such as grade control aimed at modifying the factors causing the bottom instability. Bank stability problems are dominant in Stages IV and V, so the approaches to stabilization required are different from those for Stage III. Stages I and VI typically require only maintenance activities.

Table 7.4: Dominant hillslope and instream processes, characteristic cross section shape and bedforms, and condition of vegetation in the various stages of channel evolution.
Source: Simon 1989.

Class		Dominant Processes		Characteristic Forms	Geobotanical Evidence
No.	Name	Fluvial	Hillslope		
I	Premodified	Sediment transport - mild aggradation; basal erosion on outside bends; deposition on inside bends.		Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering.	Vegetated banks to flow line.
II	Constructed			Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank.	Removal of vegetation.
III	Degradation	Degradation; basal erosion on banks.	Pop-out failures.	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.	Riparian vegetation high relative to flow line and may lean toward channel.
IV	Threshold	Degradation; basal erosion on banks.	Slab, rotational and pop-out failures.	Large scallops and bank retreat; vertical face and upper-bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank.	Riparian vegetation high relative to flow line and may lean toward channel.
V	Aggradation	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks.	Slab, rotational and pop-out failures; low-angle slides of previously failed material.	Large scallops and bank retreat; vertical face, upper bank, and slough line; flattening of bank angles; flow line low relative to top bank; development of new floodplain.	Tilted and fallen riparian vegetation; reestablishing vegetation on slough line; deposition of material above root collars of slough line vegetation.
VI	Restabilization	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends deposition of flood-plain and bank surfaces.	Low-angle slides; some pop-out failures near flow line.	Stable, alternate channel bars; convex-short vertical face on top bank; flattening of bank angles; development of new floodplain; flow line high relative to top bank.	Reestablishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough-line and upper-bank vegetation; some vegetation establishing on bars.

- CEMs can help provide goals or models for restoration. Reaches of streams in Stages I and VI are graded streams, and their profile, form, and pattern can be used as models for restoring unstable reaches.

Limitations of Channel Evolution Models

The chief limitations in using CEMs for stream restoration are as follows:

- Future changes in base level elevations and watershed water and sediment yield are not considered when predicting channel response.
- Multiple adjustments by the stream simultaneously are difficult to predict.

Applications of Geomorphic Analysis

Stream classification systems and channel evolution models may be used together in resource inventories and analysis to characterize and group streams. Although many classification systems are based on morphological parameters, and channel evolution models are based on adjustment processes, the two approaches to stream characterization complement each other. Both indicate the present condition of a stream reach under investigation, but characterization of additional reaches upstream and downstream of the investigation area can provide an understanding of the overall trend of the stream.

Stream classification systems and channel evolution models also provide in-

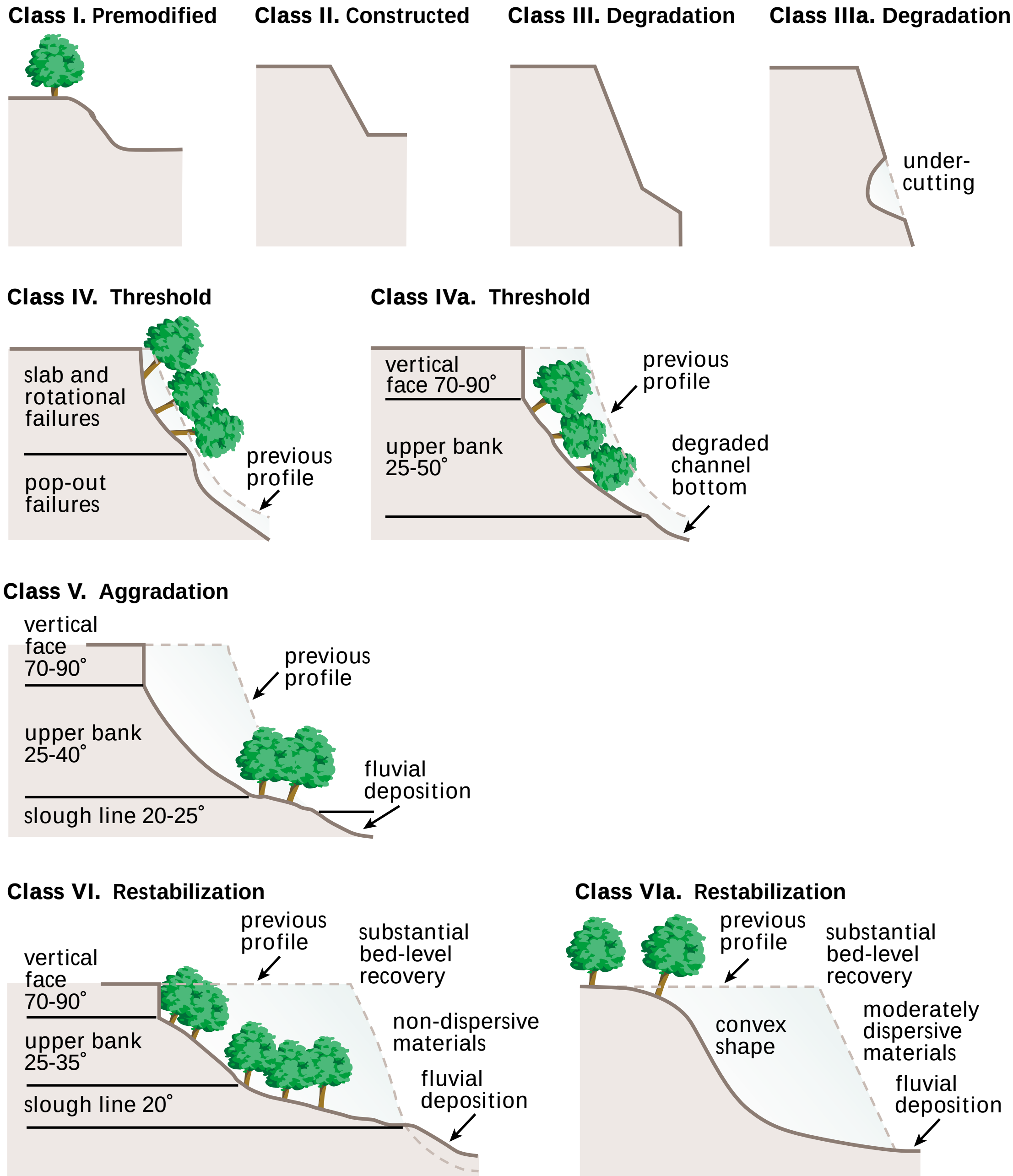


Figure 7.15: Simon's channel evolution stages related to streambank shape. *The cross-sectional shape of the streambank may be a good indicator of its evolutionary stage.*
Source: Simon 1989. Published by permission of the American Water Resources Association.

sights as to the type of stability problems occurring within the stream corridor and potential opportunities for restoration. Gullied stream channels are downcutting, so grade stabilization is required before time and money are spent on bank stabilization or floodplain restoration. Similarly, incised channels with lateral instabilities are in the initial stages of widening, a process that often must be accommodated before equilibrium conditions can be attained. Although most argue that channel widening must be accommodated to restore incised channels, in some cases not allowing the stream to widen might be preferred, depending on the value and priority placed on adjacent land use and structures within the corridor.

On the other hand, incised streams that have widened enough for a new inner channel and floodplain to begin forming are excellent candidates for vegetation management since these streams are already tending toward renewed stability and establishing riparian vegetation can accelerate the process.

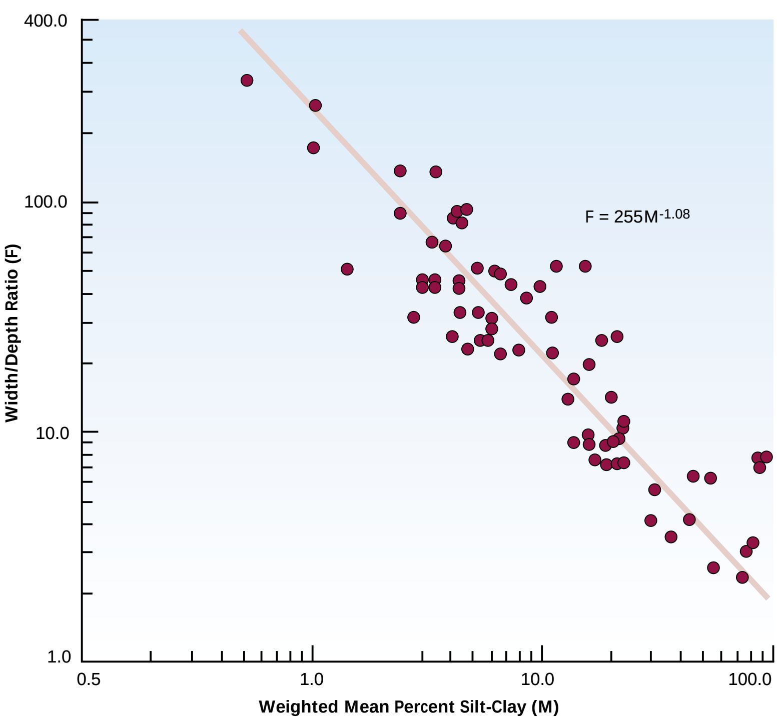


Figure 7.16: Schumm's F versus M relationship. *Data for aggrading streams generally plot above or to the right of the line. Degrading or incising streams plot below the line.*
Source: Schumm 1960.

Both the stream classification and the stage of channel evolution inventories can serve as the foundation for assessing systemwide stability. Channel width/depth ratio (F) at mean annual discharge and the percent of silt and clay in the channel boundary (M) are useful diagnostics for determining systemwide adjustments. These variables can be plotted on Schumm's (1960) curve of width/depth ratio versus percent silt-clay ($F = 255M^{-1.08}$) to assess stability (**Figure 7.16**). Schumm's width/depth ratio is the top width of the bankfull channel and the deepest depth in the bankfull channel cross section. The term "M" is defined by the relationship

$$M = [(S_c\, W) + (S_b\, 2D)] / (W + 2D)$$

where

S_c = percentage of silt and clay in the bed material

S_b = percentage of silt and clay in the bank material

W = channel width

D = channel depth

Data from aggrading streams generally plot above the line of best fit, whereas data for degrading streams plot below the line. Schumm's graph could also be used as a guide in selecting an appropriate width/depth ratio for an incised or recently disturbed channel.

Finally, classification systems and evolution models can help guide the selection of restoration treatments. As mentioned above, there is little opportunity for successfully establishing streambank vegetation in streams with vertical and horizontal instability. The banks of such streams are subject to deep-seated slope failures that are not usually prevented even by mature woody vegetation. Conversely, establishing and managing perennial grasses and woody vegetation is critical to protecting streams that are already functioning properly.

Proper Functioning Condition (PFC)

The Bureau of Land Management (BLM) has developed guidelines and procedures to rapidly assess whether a stream riparian area is functioning properly in terms of its hydrology, landform/soils, channel characteristics, and vegetation (Prichard et al. 1993, rev. 1995). This assessment, commonly called PFC, is useful as a baseline analysis of stream condition and physical function, and it can also be useful in watershed analysis.

It is essential to do a thorough analysis of the stream corridor and watershed conditions prior to development of restoration plans and selection of restoration approaches to be used. There are many cases where selection of the wrong approach has led to complete failure of stream restoration efforts and the waste of costs of restoration. In many cases, particularly in wildland situations, restoration through natural processes and control of land uses is the preferred and most cost-effective method. If hydrologic conditions are rapidly changing in a drainage, no restoration might be the wisest course until equilibrium is restored.

Identifying streams and drainages where riparian areas along streams are not in proper functioning condition, and those at risk of losing function, is an important first step in restoration analysis. Physical conditions in riparian zones are excellent indicators of what is happening in a stream or the drainage above.

With the results of PFC analysis, it is possible to begin to determine stream corridor and watershed restoration needs and priorities. PFC results may also be used to identify where gathering more detailed information is needed and where additional data are not needed.

PFC is a methodology for assessing the physical functioning of a riparian-wetland area. It provides information critical to determining the “health” of a riparian ecosystem. PFC considers both abiotic and biotic components as they relate to the physical functioning of riparian areas, but it does not consider the biotic component as it relates to habitat requirements. For habitat analysis, other techniques must be employed.

The PFC procedure is currently a standard baseline assessment for stream/riparian surveys for the BLM, and PFC is beginning to be used by the U.S. Forest Service in the West. This technique is not a substitute for inventory or monitoring protocols designed to yield detailed information on the habitat or populations of plants or animals dependent on the riparian-stream ecosystem.

PFC is a useful tool for watershed analysis. Although the assessment is conducted on a stream reach basis, the ratings can be aggregated and analyzed at the watershed scale. PFC, along with other watershed and habitat condition information, provides a good picture of watershed “health” and causal factors affecting watershed “health.” Use of PFC will help to identify watershed-scale problems and suggest management remedies.

The following are definitions of proper function as set forth in TR 1737-9:

- *Proper Functioning Condition*—Riparian-wetland areas are functioning properly when adequate vegetation, landform, or large woody debris is present to:

1. Dissipate stream energy associated with high waterflows, thereby reducing erosion and improving water quality.
2. Filter sediment, capture bedload, and aid floodplain development.
3. Improve floodwater retention and ground water storage.
4. Develop root masses that stabilize streambanks against cutting action.
5. Develop diverse ponding and channel characteristics to provide the habitat and the water depth, duration, and temperature necessary for fish production, waterfowl breeding, and other uses.
6. Support greater biodiversity.

- *Functional-at Risk*—Riparian-wetland areas that are in functional condition, but an existing soil, water, or vegetation attribute makes them susceptible to degradation.
- *Nonfunctional*—Riparian-wetland areas that clearly are not providing adequate vegetation, landform, or large debris to dissipate stream energy associated with high flow and thus are not reducing erosion, improving water quality, or performing other functions as listed above under the definition of proper function. The absence of certain physical attributes, such as absence of a floodplain where one should be, is an indicator of nonfunctioning conditions.

Assessing functionality with the PFC technique involves procedures for determining a riparian-wetland area's capability and potential, and comparing that potential with current conditions.

Although the PFC procedure defines streams without floodplains (when a floodplain would normally be present) as nonfunctional, many streams that lose their floodplains through incision or encroachment still retain ecological functions. The importance of a floodplain needs to be assessed in view of the site-specific aquatic and riparian community.

When using the PFC technique, it is important not to equate "proper function" with "desired condition." Proper function is intended to describe the state in which the stream channel and associated riparian areas are in a relatively stable and self-sustaining condition. Properly functioning streams can be expected to withstand intermediate flood events (e.g., 25- to 30-year flood events) without substantial damage to existing values. However, proper functioning condition will often develop well before riparian succession provides shrub habitat for nesting birds. Put another way, proper functioning condition is a prerequisite to a variety of desired conditions.

Although based on sound science, the PFC field technique is not quantitative. An advantage of this approach is that it is less time-consuming than other techniques because measurements are not required. The procedure is performed by an interdisciplinary team and involves completing a checklist evaluating 17 factors dealing with hydrology, vegetation, and erosional/depositional characteristics. Training in the technique is required, but the technique is not difficult to learn. With training, the functional determinations resulting from surveys are reproducible to a high degree.

Other advantages of the PFC technique are that it provides an easy-to-understand "language" for discussing stream conditions with a variety of agencies and publics, PFC training is readily available, and there is growing interagency acceptance of the technique.

Hydraulic Geometry: Streams in Cross Section

Stream corridor restoration initiatives frequently involve partial or total reconstruction of channels that have been severely degraded. Channel reconstruction design requires criteria for channel size and alignment. The following material presents an overview of *hydraulic geometry theory* and provides some sample hydraulic geometry relationships for relating bankfull dimensions to bankfull discharge. Correlations between certain planform dimensions (e.g., meander characteristics) of stable alluvial stream channels to bankfull discharge and channel width also are discussed.

Hydraulic geometry theory is based on the concept that a river system tends to develop in a way that produces an approximate equilibrium between the channel and the in-flowing water and sediment (Leopold and Maddock 1953). The theory typically relates an independent or driving variable, such as drainage area or discharge, to dependent variables such as width, depth, slope, and velocity. Hydraulic geometry relations are sometimes stratified according to bed material size or other factors. These relationships are empirically derived, and their development requires a relatively large amount of data.

Figure 7.17 presents hydraulic geometry relations based on the mean annual discharge rather than the bankfull discharge. Similar hydraulic geometry relationships can be determined for a watershed of interest by measuring channel parameters at numerous cross sections and plotting them against a discharge. Such plots can be used with care for planning and preliminary design. The use of hydraulic geometry relationships alone for final design is not recommended.

Careful attention to defining stable channel conditions, channel-forming discharge, and streambed and bank characteristics are required in the data collection effort. The primary role of discharge in determining channel cross sections has been clearly demonstrated, but there is a lack of consensus about which secondary factors such as sediment loads, bank materials, and vegetation are significant, particularly with respect to width. Hydraulic geometry relationships that do not explicitly consider sediment transport are applicable mainly to channels with relatively low bed-material loads (USACE 1994).

Hydraulic geometry relations can be developed for a specific river, watershed, or for streams with similar physiographic characteristics. Data scatter is expected about the developed curves even in the same river reach. The more dissimilar the stream and watershed characteristics are, the greater the expected data scatter is. It is important to recognize that this scatter represents a valid range of stable channel configurations due to variables such as geology, vegetation, land use, sediment load and gradation, and runoff characteristics.

Figures 7.18 and 7.19 show hydraulic geometry curves developed for the upper Salmon River watershed in Idaho (Emmett 1975). The scatter of data for stable reaches in the watershed indicates that for a drainage area of 10 square miles, the bankfull discharge could reasonably range from 100 to 250 cfs and the bankfull width could reasonably range from 10 to 35 feet. These relations were developed for a relatively homogeneous watershed, yet there is still quite a bit of natural variation in the data. This illustrates the importance of viewing the data used to develop any curve (not just the curve itself), along with statistical parameters such as R^2 values and confidence limits. (Refer to a text on statistics for additional information.)

Given the natural variation related to stream and watershed characteristics, the preferred source of data for a hydraulic geometry relationship would be the restoration initiative reach. This choice may be untenable due to channel instability. The second preferred choice is the project watershed, although care must be taken to ensure that data are acquired for portions of the watershed with physiographic conditions similar to those of the project reach.

Statistically, channel-forming discharge is a more reliable independent variable for hydraulic geometry relations than drainage area. This is because the magnitude of the channel forming discharge is the driving force that creates the observed channel geometry, and drainage

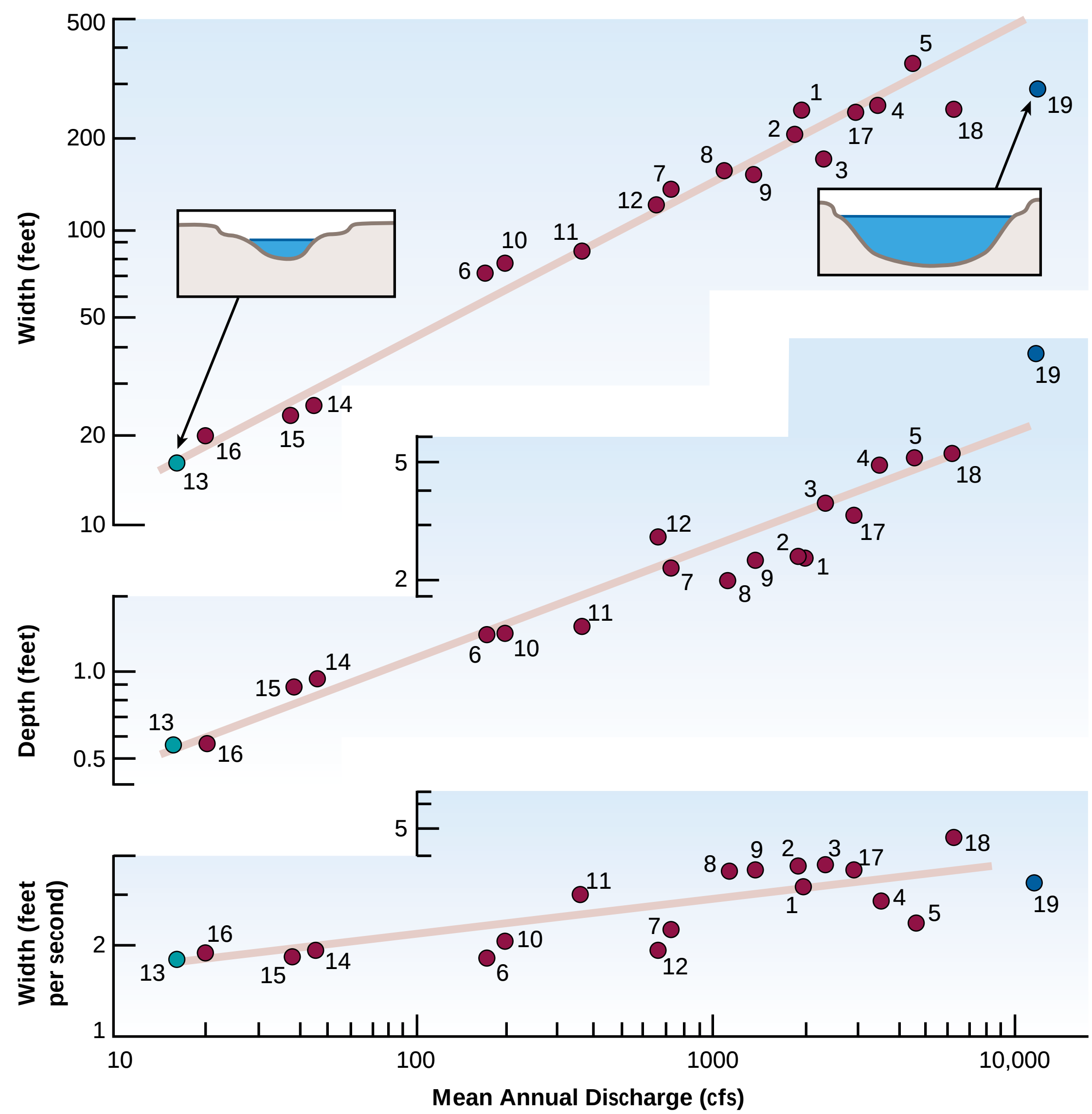


Figure 7.17: Channel morphology related to average annual discharge. *Width, depth, and velocity in relation to mean annual discharge as discharge increases downstream on 19 rivers in Wyoming and Montana.*
Source: Leopold and Maddock 1953.

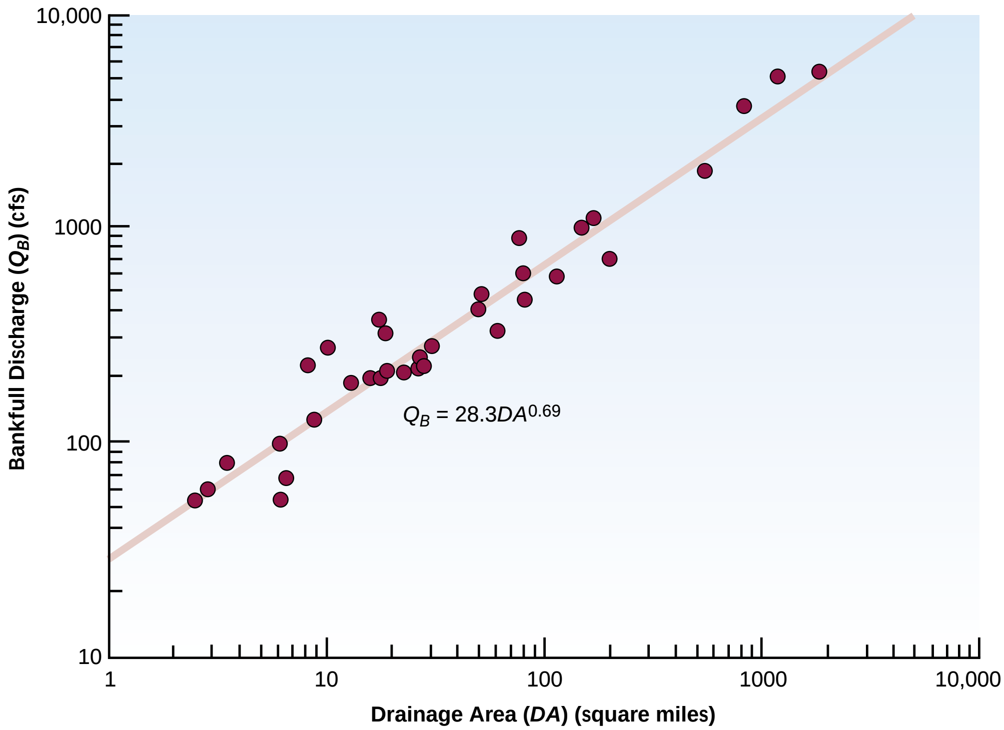


Figure 7.18: Bankfull discharge versus drainage area—Upper Salmon River area. *Curves based on measured data such as this can be valuable tools for designing restorations (Emmett 1975).*

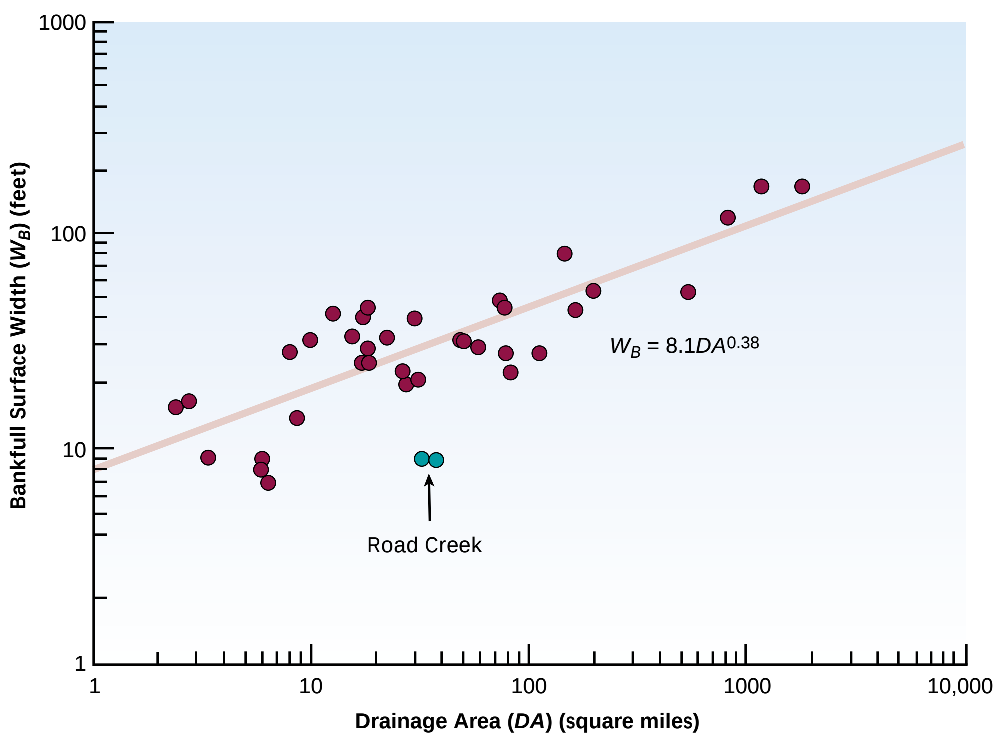


Figure 7.19: Bankfull surface width versus drainage area—Upper Salmon River area. *Local variations in bankfull width may be significant. Road Creek widths are narrower because of lower precipitation.*

Regime Theory and Hydraulic Geometry

Regime theory was developed about a century ago by British engineers working on irrigation canals in what is now India and Pakistan. Canals that required little maintenance were said to be "in regime," meaning that they conveyed the imposed water and sediment loads in a state of dynamic equilibrium, with width, depth, and slope varying about some long-term average. These engineers developed empirical formulas linking low-maintenance canal geometry and design discharge by fitting data from relatively straight canals carrying near-constant discharges (Blench 1957, 1969; Simons and Albertson 1963). Since few streams will be restored to look and act as canals, the regime relationships are not presented here.

About 50 years later, hydraulic geometry formulas similar to regime relationships were developed by geomorphologists studying stable, natural rivers. These rivers, of course, were not straight and had varying discharges. A sample of these hydraulic geometry relationship is presented in the table on the following page. In general, these formulas take the form:

$$w = k_1 Q^{k_2} D_{50}^{k_3}$$

$$D = k_4 Q^{k_5} D_{50}^{k_6}$$

$$S = k_7 Q^{k_8} D_{50}^{k_9}$$

where w and D are reach average width and depth in feet, S is the reach average slope, D_{50} is the median bed sediment size in millimeters, and Q is the bankfull discharge in cubic feet per second. These formulas are most reliable for width, less reliable for depth, and least reliable for slope.

area is merely a surrogate for discharge. Typically, channel-forming discharge correlates best with channel width. Correlations with depth are somewhat less reliable. Correlations with slope and velocity are the least reliable.

Hydraulic Geometry and Stability Assessment

The use of hydraulic geometry relations to assess the stability of a given channel reach requires two things. First, the watershed and stream channel characteristics of the reach in question must be the same as (or similar to) the data set used to develop the hydraulic geometry relations. Second, the reasonable scatter of the data in the hydraulic geometry relations must be known. If the data for a specific reach fall outside the reasonable scatter of data for stable reaches in a similar watershed, there is reason to believe that the reach in question may be unstable. This is only an indicator, since variability in other factors (geology, land use, vegetation, etc.) may cause a given reach to plot high or low on a curve. For instance, in Figure 7.17, the data points from the Road Creek subbasin plot well below the line (narrower bankfull surface width) because the precipitation in this subbasin is lower. These reaches are not unstable; they have developed smaller channel widths in response to lower discharges (as one would expect).

In summary, the use of hydraulic geometry relations requires that the actual data be plotted and the statistical coefficients known. Hydraulic geometry relations can be used as a preliminary guide to indicate stability or instability in stream reaches, but these indications should be checked using other techniques due to the wide natural variability of the data (see Chapter 8 for more information on assessment of channel stability).

Regional Curves

Dunne and Leopold (1978) looked at similar relationships from numerous watersheds and published *regional curves* relating bankfull channel dimensions to drainage area (**Figure 7.20**). Using these curves, the width and depth of the bankfull channel can be approximated once the drainage area of a watershed within one of these regions is known. Obviously, more curves such as these are needed for regions that experience different topographic, geologic, and hydrologic regimes; therefore, additional regional relationships should be developed for specific areas of interest. Several hydraulic geometry formulas are presented in **Table 7.5**.

Regional curves should be used only as indicators to help identify the channel geometry at a restoration initiative site

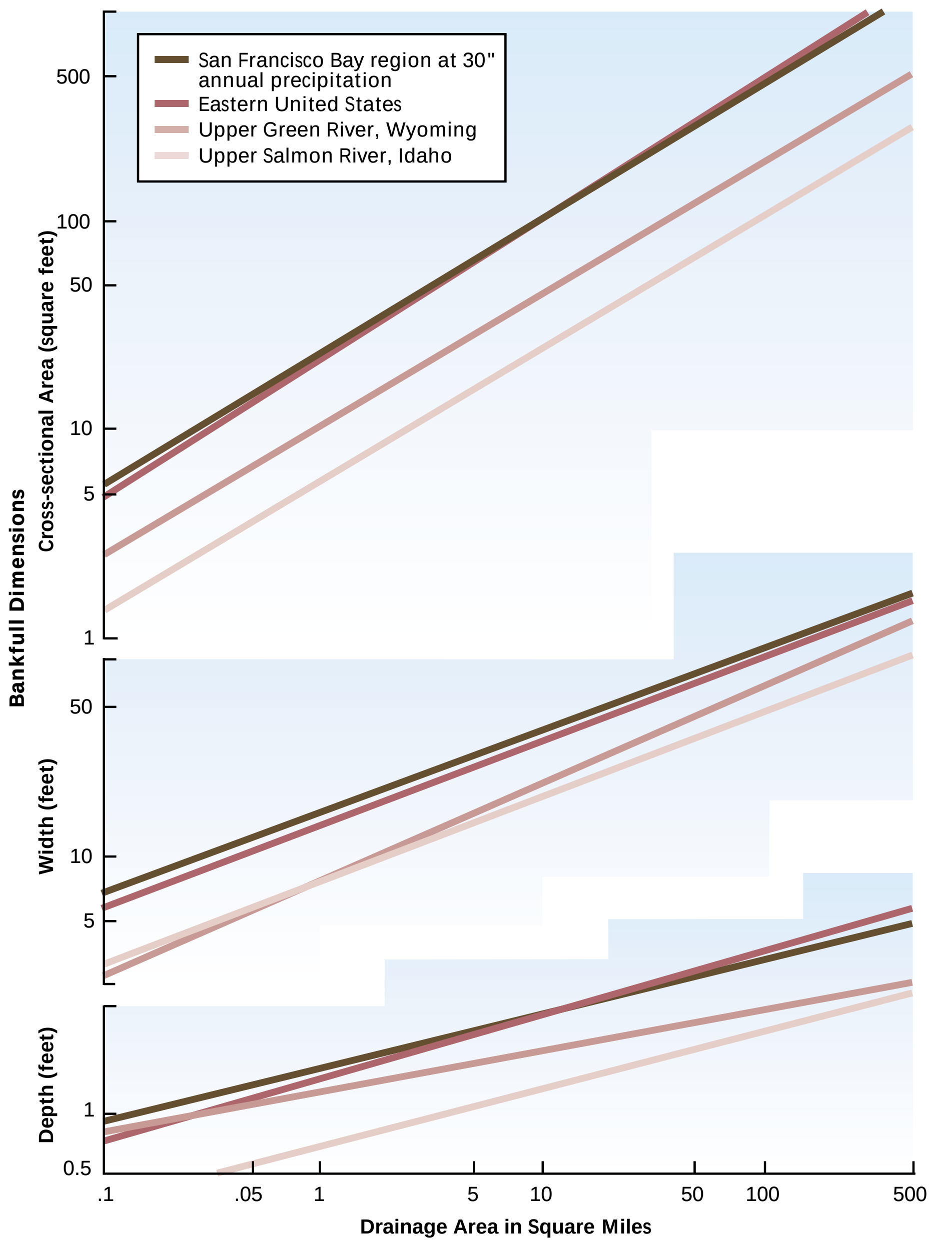


Figure 7.20: Regional curves for bankfull channel dimensions versus drainage area. *Curves showing channel dimensions relating to drainage area for a region of the country can be useful in determining departure from "normal" conditions. The use of such curves must be tempered with an understanding of the limitations of the specific data that produced the curves.*
Source: Dunne and Leopold 1978.

Table 7.5: Limits of data sets used to derive regime formulas.
Source: Hey 1988, 1990.

Reference	Data Source	Median Bed Material Size (mm)	Banks	Discharge (ft^3/s)	Sediment Concentration (ppm)	Slope	Bedforms
Lacey 1958	Indian canals	0.1 to 0.4	Cohesive to slightly cohesive	100 to 10,000	< 500		
Blench 1969	Indian canals	0.1 to 0.6	Cohesive	1 to 100,000	< 30[1]	Not specified	Ripples to dunes
Simons and Albertson 1963	U.S. and Indian canals	0.318 to 0.465	Sand	100 to 400	< 500	.000135 to .000388	Ripples to dunes
		0.06 to 0.46	Cohesive	5 to 88,300	< 500	.000059 to .00034	Ripples to dunes
		Cohesive, 0.029 to 0.36	Cohesive	137 to 510	< 500	.000063 to .000114	Plane
Nixon 1959	U.K. rivers	gravel		700 to 18,050	Not measured		
Kellerhals 1967	U.S., Canadian, and Swiss rivers of low sinuousity, and lab	7 to 265	Noncohesive	1.1 to 70,600	Negligible	.00017 to .0131	Plane
Bray 1982	Sinuous Canadian rivers	1.9 to 145		194 to 138,400	" Mobile" bed	.00022 to .015	
Parker 1982	Single channel Canadian rivers		Little cohesion	353 to 211,900			
Hey and Thorne 1986	Meandering U.K. rivers	14 to 176		138 to 14,970	Q_s computed to range up to 114	.0011 to .021	

[1] Blench (1969) provides adjustment factors for sediment concentrations between 30 and 100 ppm.

because of the large degree of natural variation in most data sets. Published hydraulic geometry relationships usually are based on stable, single-thread alluvial channels. Channel geometry-discharge relationships are more complex for multithread channels.

Exponents and coefficients for hydraulic geometry formulas are usually determined from data sets for a specific stream or watershed. The relatively small range of variation of the exponents k_2, k_5, and k_8 is impressive, considering the wide range of situations represented. Extremes for the data sets used to generate the hydraulic geometry formulas are given in **Tables 7.6 and 7.7**. Because formula coefficients vary, applying a given set of hydraulic geometry relationships should be limited to channels similar to the calibration sites. This principle severely limits applying the Lacey, Blench, and Simons and Albertson formulas in channel restoration work since these curves were developed using canal data. Additionally, hydraulic geometry relationships developed for pristine or largely undeveloped watersheds should not be applied to urban watersheds.

As shown in Table 7.5, hydraulic geometry relationships for gravel-bed rivers are far more numerous than those for sand-bed rivers. Gravel-bed relationships have been adjusted for bank soil characteristics and vegetation, whereas sand-bed formulas have been modified to include bank silt-clay content (Schumm 1977). Parker (1982) argues in favor of regime-type relationships based on dimensionless variables. Accordingly, the original form of the Parker formula was based on dimensionless variables.

Table 7.6: Coefficients for selected hydraulic geometry formulas.

Author	Year	Data	Domain	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
Nixon	1959	U.K. rivers	Gravel-bed rivers		0.5		0.545	0.33		$1.258n^{2b}$	-0.11	
Leopold et al.	1964	Midwestern U.S.		1.65	0.5			0.4			-0.49	
		Ephemeral streams in semiarid U.S.			0.5			0.3			-0.95	
Kellerhals	1967	Field (U.S., Canada, and Switzerland) and laboratory	Gravel-bed rivers with paved beds and small bed material concentration	1.8	0.5		0.33	0.4	-0.12^a	0.00062	-0.4	0.92^a
Schumm	1977	U.S. (Great Plains) and Australia (Riverine Plains of New South Wales)	Sand-bed rivers with properties shown in Table 6	$37k_1*$	0.38		$0.6k_4*$	0.29	-0.12^a	$0.01136k_7*$	-0.32	
Bray	1982	Canadian rivers	Gravel-bed rivers	3.1	0.53	-0.07	0.304	0.33	-0.03	0.00033	-0.33	0.59
Parker	1982	Single-channel Alberta rivers	Gravel-bed rivers, banks with little cohesion	6.06	0.444	-0.11	0.161	0.401	-0.0025	0.00127	-0.394	0.985
Hay and Thorne	1986	U.K. rivers	Gravel-bed rivers with:									
			Grassy banks with no trees or shrubs	2.39	0.5		0.41	0.37	-0.11	$0.00296k_7**$	-0.43	-0.09
			1-5% tree/ shrub cover	1.84	0.5		0.41	0.37	-0.11	$0.00296k_7**$	-0.43	-0.09
			Greater than 5-50% tree/ shrub cover	1.51	0.5		0.41	0.37	-0.11	$0.00296k_7**$	-0.43	-0.09
			Greater than 50% shrub cover or incised flood plain	1.29	0.5		0.41	0.37	-0.11	$0.00296k_7**$	-0.43	-0.09

[a] Bed material size in Kellerhals' equation is D_{90}.
[b] n = Manning n.
k_1* = $M^{-0.39}$, where M is the percent of bank materials finer than 0.074 mm. The discharge used in this equation is mean annual rather than bankfull.
k_4* = $M^{0.432}$, where M is the percent of bank materials finer than 0.074 mm. The discharge used in this equation is mean annual rather than bankfull.
k_7* = $M^{-0.36}$, where M is the percent of bank materials finer than 0.074 mm. The discharge used in this equation is mean annual rather than bankfull.
k_7** = $D_{54}^{0.84} Q_x^{0.10}$, where Q_x = bed material transport rate in kg s^{-1} at water discharge Q, and D_{54} refers to bed material and is in mm.

Planform and Meander Geometry: Stream Channel Patterns

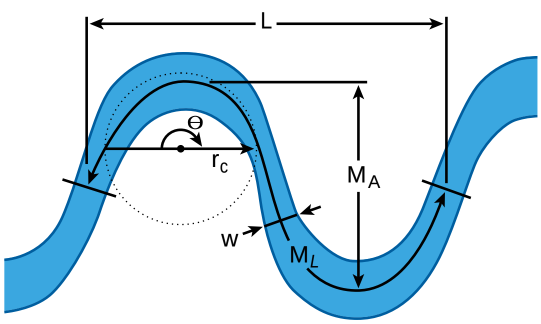
Meander geometry variables are shown in **Figure 7.21**. Channel planform parameters may be measured in the field or from aerial photographs and may be compared with published relationships, such as those identified in the box. Developing regional relationships or coefficients specific to the site of interest is, however, preferable to using published relationships that may span wide ranges in value. **Figure 7.22** shows some planform geometry relations by Leopold (1994). Meander geometries that do not fall within the range of predicted relationships may indicate stream instability and deserve attention in restoration design.

*Table 7.7: **Meander geometry equations.***
Source: Williams 1986.

Equation Number	Equation	Applicable Range
Interrelations between meander features		
2	$L_m = 1.25L_b$	$18.0 \le L_b \le 43{,}600$ ft
3	$L_m = 1.63B$	$12.1 \le B \le 44{,}900$ ft
4	$L_m = 4.53R_c$	$8.5 \le R_c \le 11{,}800$ ft
5	$L_b = 0.8L_m$	$26 \le L_m \le 54{,}100$ ft
6	$L_b = 1.29B$	$12.1 \le B \le 32{,}800$ ft
7	$L_b = 3.77R_c$	$8.5 \le R_c \le 11{,}800$ ft
8	$B = 0.61L_m$	$26 \le L_m \le 76{,}100$ ft
9	$B = 0.78L_b$	$18.0 \le L_b \le 43{,}600$ ft
10	$B = 2.88R_c$	$8.5 \le R_c \le 11{,}800$ ft
11	$R_c = 0.22L_m$	$33 \le L_m \le 54{,}100$ ft
12	$R_c = 0.26L_b$	$22.3 \le L_b \le 43{,}600$ ft
13	$R_c = 0.35B$	$16 \le B \le 32{,}800$ ft
Relations of channel size to meander features		
14	$A = 0.0094L_m^{1.53}$	$33 \le L_m \le 76{,}100$ ft
15	$A = 0.0149L_b^{1.53}$	$20 \le L_b \le 43{,}600$ ft
16	$A = 0.021B^{1.53}$	$16 \le B \le 38{,}100$ ft
17	$A = 0.117R_c^{1.53}$	$7 \le R_c \le 11{,}800$ ft
18	$W = 0.019L_m^{0.89}$	$26 \le L_m \le 76{,}100$ ft
19	$W = 0.026L_b^{0.89}$	$16 \le L_b \le 43{,}600$ ft
20	$W = 0.031B^{0.89}$	$10 \le B \le 44{,}900$ ft
21	$W = 0.81R_c^{0.89}$	$8.5 \le R_c \le 11{,}800$ ft
22	$D = 0.040L_m^{0.66}$	$33 \le L_m \le 76{,}100$ ft
23	$D = 0.054L_b^{0.66}$	$23 \le L_b \le 43{,}600$ ft
24	$D = 0.055B^{0.66}$	$16 \le B \le 38{,}100$ ft
25	$D = 0.127R_c^{0.66}$	$8.5 \le R_c \le 11{,}800$ ft

Equation Number	Equation	Applicable Range
Relations of meander features to channel size		
26	$L_m = 21A^{0.65}$	$0.43 \le A \le 225{,}000$ ft
27	$L_b = 15A^{0.65}$	$0.43 \le A \le 225{,}000$ ft
28	$B = 13A^{0.65}$	$0.43 \le A \le 225{,}000$ ft
29	$R_c = 4.1A^{0.65}$	$0.43 \le A \le 225{,}000$ ft
30	$L_m = 6.5W^{1.12}$	$4.9 \le W \le 13{,}000$ ft
31	$L_b = 4.4W^{1.12}$	$4.9 \le W \le 7{,}000$ ft
32	$B = 3.7W^{1.12}$	$4.9 \le W \le 13{,}000$ ft
33	$R_c = 1.3W^{1.12}$	$4.9 \le W \le 7{,}000$ ft
34	$L_m = 129D^{1.52}$	$0.10 \le D \le 59$ ft
35	$L_b = 86D^{1.52}$	$0.10 \le D \le 57.7$ ft
36	$B = 80D^{1.52}$	$0.10 \le D \le 59$ ft
37	$R_c = 23D^{1.52}$	$0.10 \le D \le 57.7$ ft
Relations between channel width, channel depth, and channel sinuosity		
38	$W = 12.5D^{1.45}$	$0.10 \le D \le 59$ ft
39	$D = 0.17W^{0.89}$	$4.92 \le W \le 13{,}000$ ft
40	$W = 73D^{1.23}K^{-2.35}$	$0.10 \le D \le 59$ ft and $1.20 \le K \le 2.60$
41	$D = 0.15w^{0.50}K^{1.48}$	$4.9 \le W \le 13{,}000$ ft and $1.20 \le K \le 2.60$

Derived empirical equations for river-meander and channel-size features.
A = bankfull cross-sectional area.
W = bankfull width.
D = bankfull mean depth.
L_m = meander wavelength.
L_b = along-channel bend length.
B = meander belt width.
R_c = loop radius of curvature.
K = channel sinuosity.



L meander wavelength
M_L meander arc length
w average width at bankfull discharge
M_A meander amplitude
r_c radius of curvature
Θ arc angle

Figure 7.21: Meander geometry variables.
Adapted from Williams 1986.

Stream System Dynamics

Stream management and restoration require knowledge of the complex interactions between watershed and stream processes, boundary sediments, and bank and floodplain vegetation. Identifying the causes of channel instability or potential instability and having knowledge of the magnitude and distribution of channel adjustment processes are important for the following:

- Estimating future channel changes.
- Developing appropriate mitigation measures.
- Protecting the stream corridor.

Meander Geometry Formulas

Reviews of meander geometry formulas are provided by Nunnally and Shields (1985, Table 3) and Chitale (1973). Ackers and Charlton (1970) developed a typical formula that relates meander wavelength and bankfull discharge, Q (cfs), using laboratory data and checking against field data from a wide range of stream sizes:

$$L = 38Q^{0.467}$$

There is considerable scatter about this regression line; examination of the plotted data is recommended. Other formulas, such as this one by Schumm (1977), also incorporate bed sediment size or the fraction of silt-clay in the channel perimeter:

$$L = 1890Q_m^{0.34} / M^{0.74}$$

where Q_m is average discharge (cfs) and M is the percentage of silt-clay in the perimeter of the channel. These types of relationships are most powerful when developed from regional data sets with conditions that are typical of the area being restored. Radius of curvature, r_c, is generally between 1.5 and 4.5 times the channel width, w, and more commonly between 2w and 3w, while meander amplitude is 0.5 to 1.5 times the meander wavelength, L (USACE 1994). Empirical (Apmann 1972, Nanson and Hickin 1983) and analytical (Begin 1981) results indicate that lateral migration rates are greatest for bends with radii of curvature between 2w and 4w.

Adjustment processes that affect entire fluvial systems often include channel incision (lowering of the channel bed with time), aggradation (raising of the channel bed with time), planform geometry changes, channel widening or narrowing, and changes in the magnitude and type of sediment loads. These processes differ from localized processes, such as scour and fill, which can be limited in magnitude and extent.

In contrast, the processes of channel incision and aggradation can affect long reaches of a stream or whole stream systems. Long-term adjustment processes, such as incision, aggradation, and channel widening, can exacerbate local scour problems. Whether streambed erosion occurs due to local scour or channel incision, sufficient bed level lowering can lead to bank instability and to changes in channel planform.

It is often difficult to differentiate between local and systemwide processes without extending the investigation upstream and downstream of the site in question. This is because channels migrate over time and space and so may affect previously undisturbed reaches. For example, erosion at a logjam initially may be attributed to the deflection of flows caused by the woody debris blocking the channel. However, the appearance of large amounts of woody debris may indicate upstream channel degradation related to instability of larger scope.

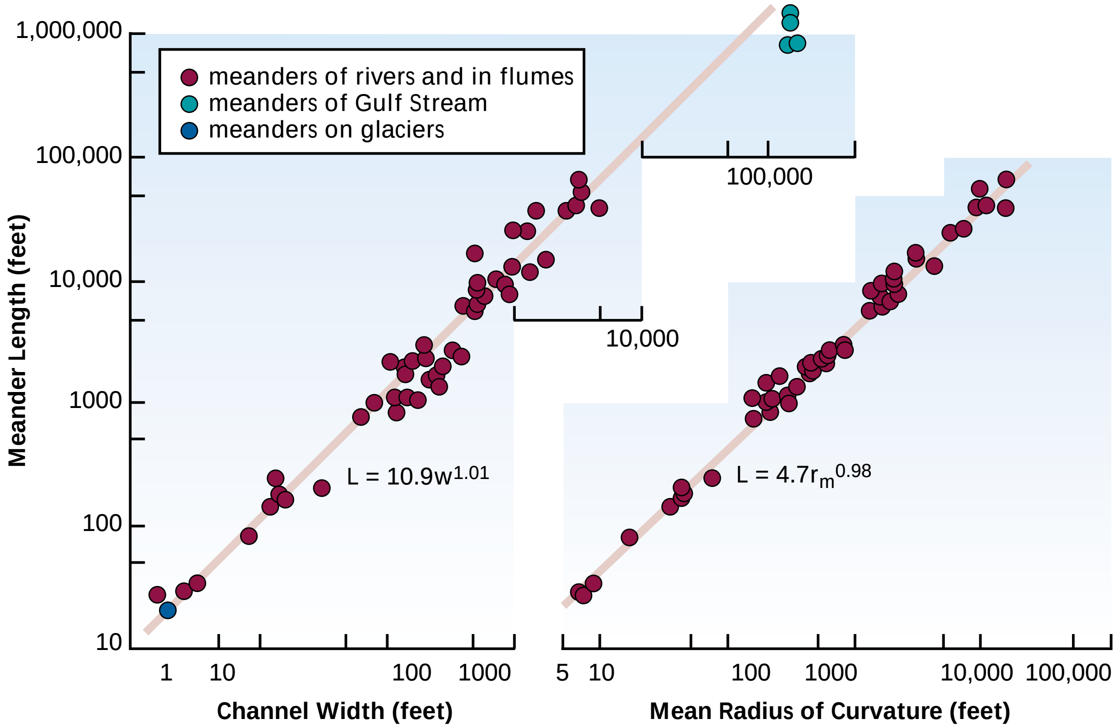


Figure 7.22: Planform geometry relationships. *Meander geometries that do not plot close to the predicted relationship may indicate stream instability.*
Source: Leopold 1994.

Figure 7.23: Bank instability. *Determining if instability is localized or systemwide is imperative to establish a correct path of action.*

Determining Stream Instability: Is It Local or Systemwide?

Stage of channel evolution is the primary diagnostic variable for differentiating between local and systemwide channel stability problems in a disturbed stream or constructed channel. During basinwide adjustments, stage of channel evolution usually varies systematically with distance upstream. Downstream sites might be characterized by aggradation and the waning stages of widening, whereas upstream sites might be characterized (in progressive upstream order) by widening and mild degradation, then degradation, and if the investigation is extended far enough upstream, the stable, predisturbed condition (**Figure 7.23**). This sequence of stages can be used to reveal systemwide instabilities. Stream classification can be applied in a similar manner to natural streams. The sequence of stream types can reveal systemwide instabilities.

Restoration measures often fail, not as the result of inadequate structural design, but rather because of the failure of the designers to incorporate the existing and future channel morphology into the design. For this reason, it is important for the designer to have some general understanding of stream processes to ensure that the selected restoration measures will work in harmony with the existing and future river conditions. This will allow the designer to assess whether the conditions at a particular site are due to local instability processes or are the result of some systemwide instability that may be affecting the entire watershed.

Systemwide Instability

The equilibrium of a stream system can be disrupted by various factors. Once this occurs, the stream will attempt to regain equilibrium by making adjustments in the dependent variables. These adjustments in the context of physical processes are generally reflected in aggradation, degradation, or changes in planform characteristics (meander wavelength, sinuosity, etc.). Depending on the magnitude of the change and the basin characteristics (bed and bank materials, hydrology, geologic or manmade controls, sediment sources, etc.), these adjustments can propagate throughout the entire watershed and even into neighboring systems. For this reason, this type of disruption of the equilibrium condition is referred to as system instability. If system instability is occurring or expected to occur, it is imperative that the restoration initiative address these problems before any bank stabilization or instream habitat development is considered.

Local Instability

Local instability refers to erosion and deposition processes that are not symptomatic of a disequilibrium condition in the watershed (i.e., system instability). Perhaps the most common form of local instability is bank erosion along the concave bank in a meander bend that is occurring as part of the natural meander process. Local instability can also occur in isolated locations as the result of channel constriction, flow obstructions (ice, debris, structures, etc.), or geotechnical instability. Local instability problems are amenable to local bank protection. Local instability can also exist in channels where severe system instability exists. In these situations, the local instability problems will probably be accelerated due to the system instability, and a more comprehensive treatment plan will be necessary.

Caution must be exercised if only local treatments on one site are implemented. If the upstream reach is stable and the downstream reach is unstable, a systemwide problem may again be indicated. The instability may continue moving upstream unless the root cause of the instability at the watershed level is removed or channel stabilization at and downstream of the site is implemented.

Local channel instabilities often can be attributed to redirection of flow caused by debris, structures, or the approach angle from upstream. During moderate and high flows, obstructions often result in vortices and secondary-flow cells that accelerate impacts on channel boundaries, causing local bed scour, erosion of bank toes, and ultimately bank failures. A general constriction of the channel cross section from debris accumulation or a bridge causes a backwater condition upstream, with acceleration of the flow and scour through the constriction.

Bed Stability

In unstable channels, the relationship between bed elevation and time (years)

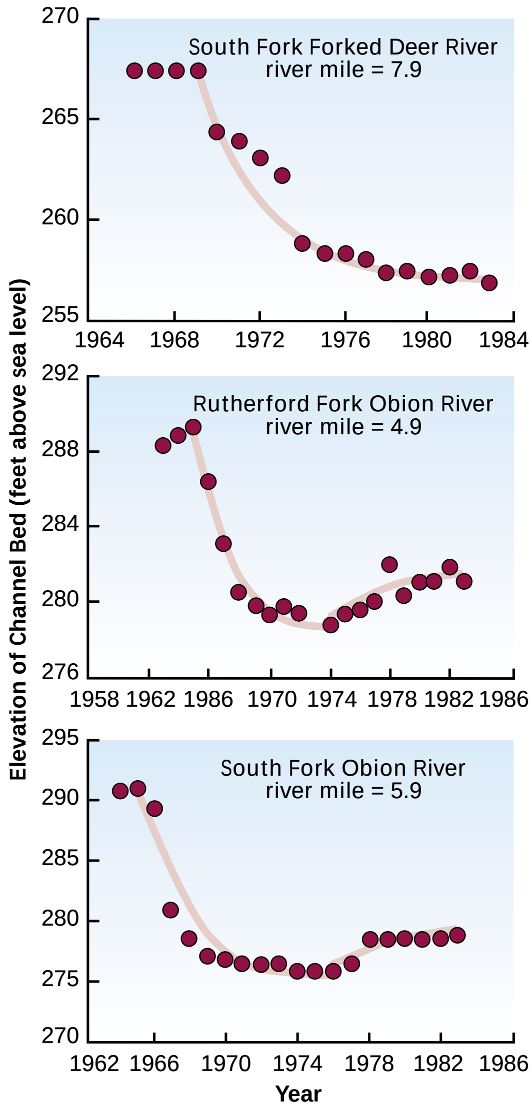


Figure 7.24: Changes in bed elevations over time. *Plotting river bed elevations at a point along the river over time can indicate whether a major phase of channel incision is ongoing or has passed.*

can be described by nonlinear functions, where change in response to a disturbance occurs rapidly at first and then slows and becomes asymptotic with time (**Figure 7.24**). Plotting bed elevations against time permits evaluating bed-level adjustment and indicates whether a major phase of channel incision has passed or is ongoing. Various mathematical forms of this function have been used to characterize bed-level adjustment at a site and to predict future bed elevations. This method also can provide valuable information on trends of channel stability at gauged locations where abundant data from discharge measurements are available.

Specific Gauge Analysis

Perhaps one of the most useful tools available to the river engineer or geomorphologist for assessing the historical stability of a river system is the specific gauge record. A specific gauge record is a graph of stage for a specific discharge at a particular stream gauging location plotted against time (Blench 1969). A channel is considered to be in equilibrium if the specific gauge record shows no consistent increasing or decreasing trends over time, while an increasing or decreasing trend is indicative of an aggradational or degradational condition, respectively. An example of a specific gauge record is shown in **Figure 7.25.**

The first step in a specific gauge analysis is to establish the stage vs. discharge relationship at the gauge for the period of record being analyzed. A rating curve is developed for each year in the period of record. A regression curve is then fitted to the data and plotted on the scatter plot. Once the rating curves have been developed, the discharges to be used in the specific gauge record must be selected. This selection depends largely on the objectives of the study. It is usually advisable to select discharges that encompass the entire range of observed flows. A plot is then developed showing the stage for the given flow plotted against time.

Specific gauge records are an excellent tool for assessing the historical stability at a specific location. However, specific gauge records indicate only the conditions in the vicinity of the particular gauging station and do not necessarily reflect river response farther upstream or downstream of the gauge. Therefore, even though the specific gauge record is one of the most valuable tools used by river engineers, it should be coupled with other assessment techniques to

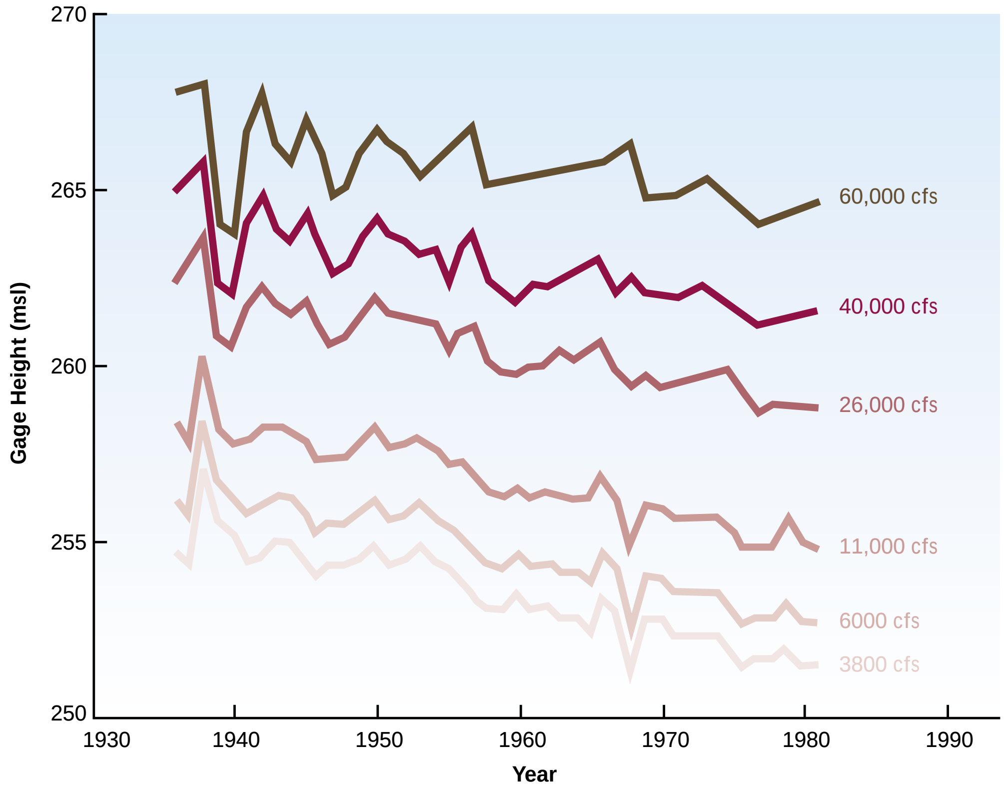


Figure 7.25: Specific gauge plot for Red River at Index, Arkansas. *Select discharges from the gauge data that represent the range of flows.* Source: Biedenharn et al. 1997.

assess reach conditions or to make predictions about the ultimate response on a river.

Comparative Surveys and Mapping

One of the best methods for directly assessing channel changes is to compare channel surveys (thalweg and cross section).

Thalweg surveys are taken along the channel at the lowest point in the cross section. Comparison of several thalweg surveys taken at different points in time allows the engineer or geomorphologist to chart the change in the bed elevation through time (**Figure 7.26**).

Certain limitations should be considered when comparing surveys on a river system. When comparing thalweg profiles, it is often difficult, especially on larger streams, to determine any distinct trends of aggradation or degradation if there are large scour holes, particularly in bendways. The existence of very deep local scour holes may completely obscure temporal variations in the thalweg. This problem can sometimes be overcome by eliminating the pool sections and focusing only on the crossing locations, thereby allowing aggradational or degradational trends to be more easily observed.

Although thalweg profiles are a useful tool, it must be recognized that they reflect only the behavior of the channel bed and do not provide information about the channel as a whole. For this reason it is usually advisable to study changes in the cross-sectional geometry. Cross-sectional geometry refers to width, depth, area, wetted perimeter, hydraulic radius, and channel conveyance at a specific cross section.

If channel cross sections are surveyed at permanent monumented range locations, the cross-sectional geometry at different times can be compared

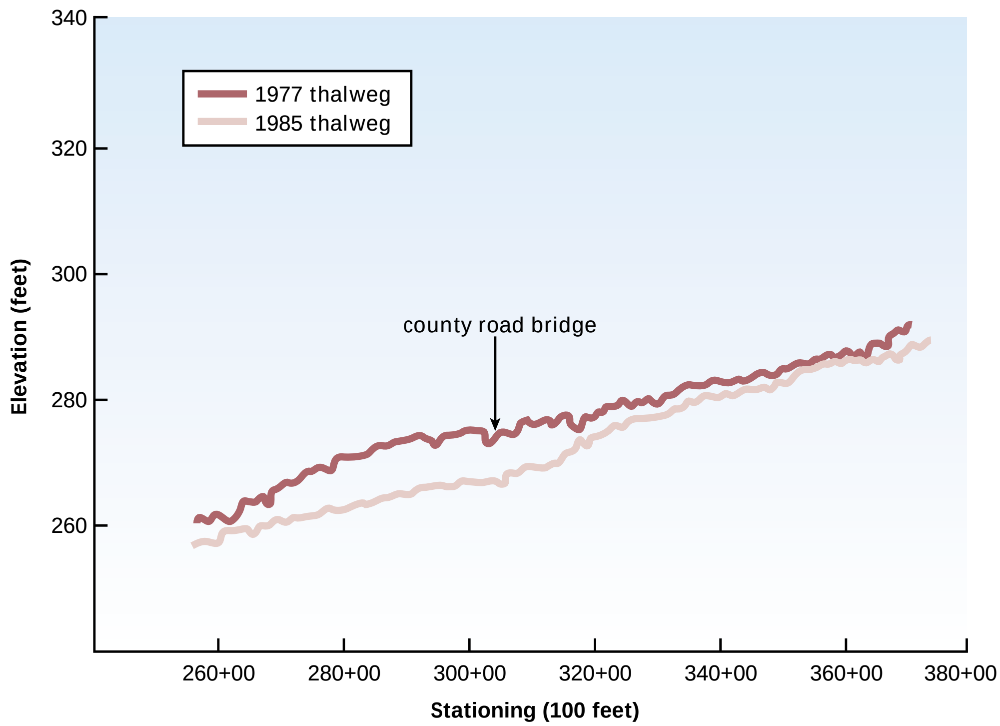


***Figure 7.26**: Comparative thalweg profiles.*
Changes in bed elevation over the length of a stream can indicate areas of transition and reaches where more information is needed.
Source: Biedenharn et al., USACE 1997.

directly. The cross section plots for each range at the various times can be overlaid and compared. It is seldom the case, however, that the cross sections are located in the exact same place year after year. Because of these problems, it is often advisable to compare reach-average values of the cross-sectional geometry parameters. This requires the study area to be divided into distinct reaches based on geomorphic characteristics. Next, the cross-sectional parameters are calculated at each cross section and then averaged for the entire reach. Then the reach-average values can be compared for each survey. Cross-sectional variability between bends (pools) and crossings (riffles) can obscure temporal trends, so it is often preferable to use only cross sections from crossing reaches when analyzing long-term trends of channel change.

Comparison of time-sequential maps can provide insight into the planform instability of the channel. Rates and magnitude of channel migration (bank caving), locations of natural and man-made cutoffs, and spatial and temporal changes in channel width and planform geometry can be determined from maps. With these types of data, channel response to imposed conditions can be documented and used to substantiate predictions of future channel response to a proposed alteration. Planform data can be obtained from aerial photos, maps, or field investigations.

Regression Functions for Degradation

Two mathematical functions have been used to describe bed level adjustments with time. Both may be used to predict channel response to a disturbance, subject to the caution statements below. The first is a power function (Simon 1989a):

$$E = a\, t^{b}$$

where E = elevation of the channel bed, in feet; a = coefficient, determined by regression, representing the premodified elevation of the channel bed, in feet; t = time since beginning of adjustment process, in years, where t_0 = 1.0 (year prior to onset of the adjustment process); and b = dimensionless exponent, determined by regression and indicative of the nonlinear rate of channel bed change (negative for degradation and positive for aggradation).

The second function is a dimensionless form of an exponential equation (Simon 1992):

$$z / z_0 = a + b\, e^{(-k\,t)}$$

where

z = the elevation of the channel bed (at time t)

z_0 = the elevation of the channel bed at t_0

a = the dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z/z_0) when the equation becomes asymptotic, a>1 = aggradation, a<1 = degradation

b = the dimensionless coefficient, determined by regression and equal to the total change in the dimensionless elevation (z/z_0) when the equation becomes asymptotic

k = the coefficient determined by regression, indicative of the rate of change on the channel bed per unit time

t = the time since the year prior to the onset of the adjustment process, in years (t_0=0)

Future elevations of the channel bed can, therefore, be estimated by fitting the equations to bed elevations and by solving for the period of interest. Either equation provides acceptable results, depending on the statistical significance of the fitted relation. Statistical significance of the fitted curves improves with additional data. Degradation and aggradation curves for the same site are fit separately. For degrading sites, the equations will provide projected minimum channel elevations when the value of t becomes large and, by subtracting this result from the floodplain elevation, projected maximum bank heights. A range of bed adjustment trends can be estimated by using different starting dates in the equations when the initial timing of bed level change is unknown. Use of the equations, however, may be limited in some areas because of a lack of survey data.

Regression Functions for Aggradation

Once the minimum bed elevation has been obtained, that elevation can be used as the starting elevation at a new t_0 for the secondary aggradation phase that occurs during channel widening (see discussion of channel evolution above). Secondary aggradation occurs at a site after degradation reduces channel gradient and stream power to such an extent that sediment loads delivered from degrading reaches upstream can no longer be transported (Simon 1989a). Coefficient values for Simon's power function for estimating secondary aggradation can be obtained either from interpolating existing data or from estimating their values as about 60 percent less than the corresponding value obtained for the degradation phase.

The variation of the regression coefficients a and b with longitudinal distance along the channel can be used as an empirical model of bed level adjustment providing there are data from enough sites. Examples using both equations are provided for the Obion River system, West Tennessee (**Figure 7.27**). Estimates of bed-level change with time for unsurveyed sites can be obtained using interpolated coefficient a values and t_0. For channels downstream from dams without significant tributary sediment inputs, the shape of the a-value curve would be similar but inverted; maximum amounts of degradation (minimum a values) occur immediately downstream of the dam and attenuate nonlinearly with distance farther downstream.

Caution: If one of the above mathematical functions is used to predict future bed elevations, the assumption is made that no new disturbances have occurred to trigger a new phase of channel change. Downstream channelization, construction of a reservoir, formation of a large woody debris jam that blocks the channel, or even a major flood are examples of disturbances that can trigger a new period of rapid change.

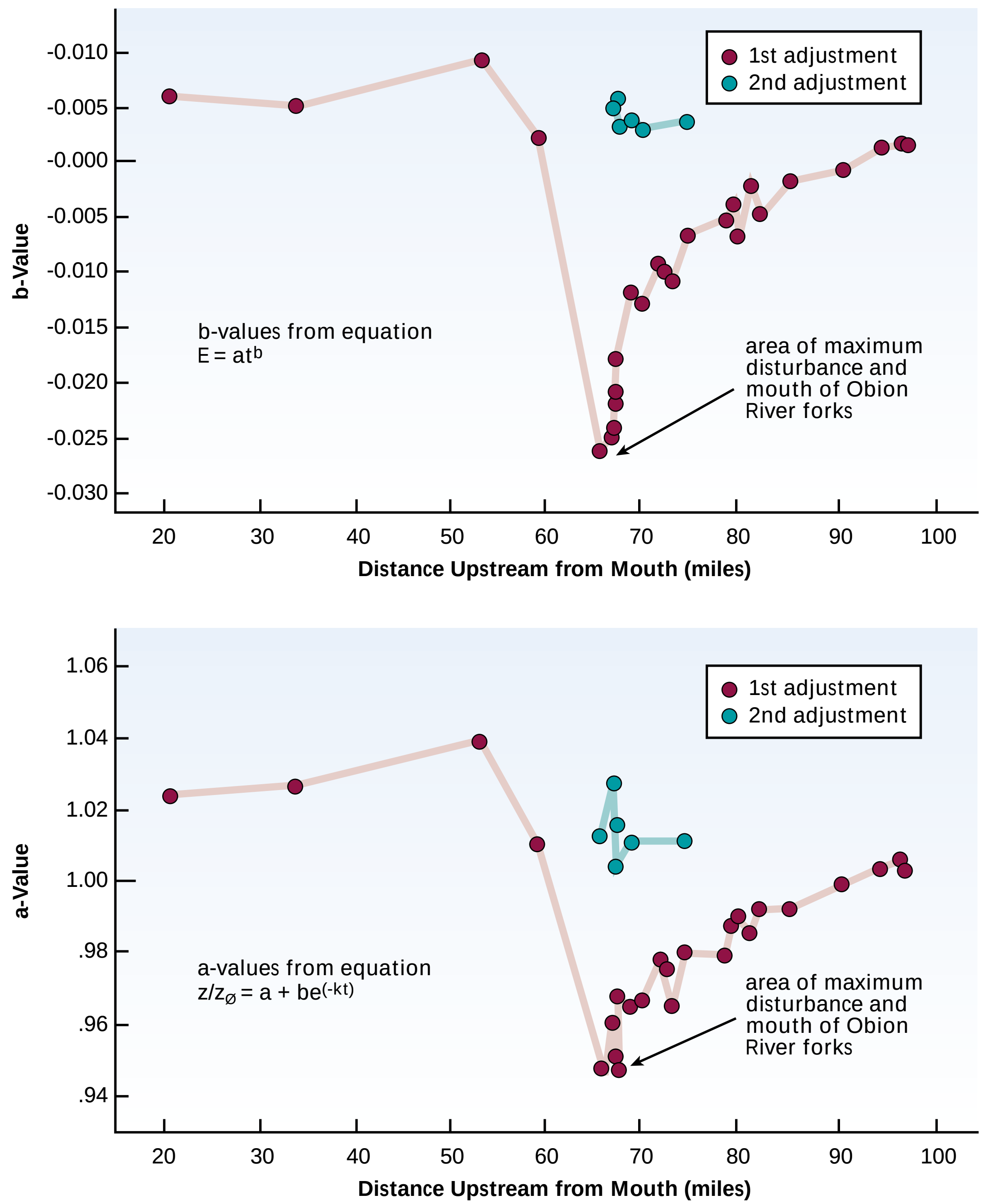


Figure 7.27: Coefficient a and b values for regression functions for estimating bed level adjustment versus longitudinal distance along stream. *Future bed elevations can be estimated by using empirical equations.*

Source: Simon 1989, 1992.

The investigator is cautioned that the use of regression functions to compute aggradation and degradation is an empirical approach that might be appropriate for providing insight into the degradational and aggradational processes during the initial planning phases of a project. However, this procedure does not consider the balance between supply and transport of water and sediment and, therefore, is not acceptable for the detailed design of restoration features.

Sediment Transport Processes

This document does not provide comprehensive coverage of sedimentation processes and analyses critical to stream restoration. These processes include erosion, entrainment, transport, deposition, and compaction. Refer to standard texts and reference on sediment, including Vanoni (1975), Simons and Senturk (1977), Chang (1988), Richards (1982), and USACE (1989a).

Numerical Analyses and Models to Predict Aggradation and Degradation

Numerical analyses and models such as HEC-6 are used to predict aggradation and degradation (incision) in stream channels, as discussed in Chapter 8.

Bank Stability

Streambanks can be eroded by moving water removing soil particles or by collapse. Collapse or mass failure occurs when the strength of bank materials is too low to resist gravity forces. Banks that are collapsing or about to collapse are referred to as being geotechnically unstable (**Figure 7.28**). The physical properties of bank materials should be described to aid characterization of potential stability problems and identification of dominant mechanisms of bank instability.

The level of intensity of geotechnical investigations varies in planning and design. During planning, enough information must be collected to determine the feasibility of alternatives being considered. For example, qualitative descriptions of bank stratigraphy obtained during planning may be all that is required for identifying dominant modes of failure in a study reach. Thorne (1992) describes stream reconnaissance procedures particularly for recording streambank data.

Qualitative Assessment of Bank Stability

Natural streambanks frequently are composed of distinct layers reflecting the depositional history of the bank materials. Each individual sediment layer can have physical properties quite different from those of other layers. The bank profile therefore will respond according to the physical properties of each layer. Since the stability of stream-

Figure 7.28: Bank erosion by undercutting.
Removal of toe slope support leads to instability requiring geotechnical solutions.

banks with respect to failures due to gravity depends on the geometry of the bank profile and the physical properties of the bank materials, dominant failure mechanisms tend to be closely associated with characteristic stratigraphy or succession of layers (**Figure 7.29**).

A steep bank consisting of uniform layers of cohesive or cemented soils generally develops tension cracks at the top of the bank parallel to the bank alignment. Slab failures occur when the weight of the soil exceeds the strength of the grain-to-grain contacts within the soil. As clay content or cementing agent decreases, the slope of the bank decreases; vertical failure planes become more flat and planar failure surfaces develop. Rotational failures occur when the bank soils are predominantly cohesive. Block-type failures occur when a weak soil layer is eroded away and the layers above the weak layer lose structural support.

The gravity failure processes described in Figure 7.29 usually occur after the banks have been saturated due to precipitation or high stream stages. The water adds weight to the soil and reduces grain-to-grain contacts and cohesion forces while increasing the pore pressure. Pore pressure occurs when soil water in the pore spaces is under pressure from overlying soil and water. Pore pressure therefore is internal to the soil mass. When a stream is full, the flowing

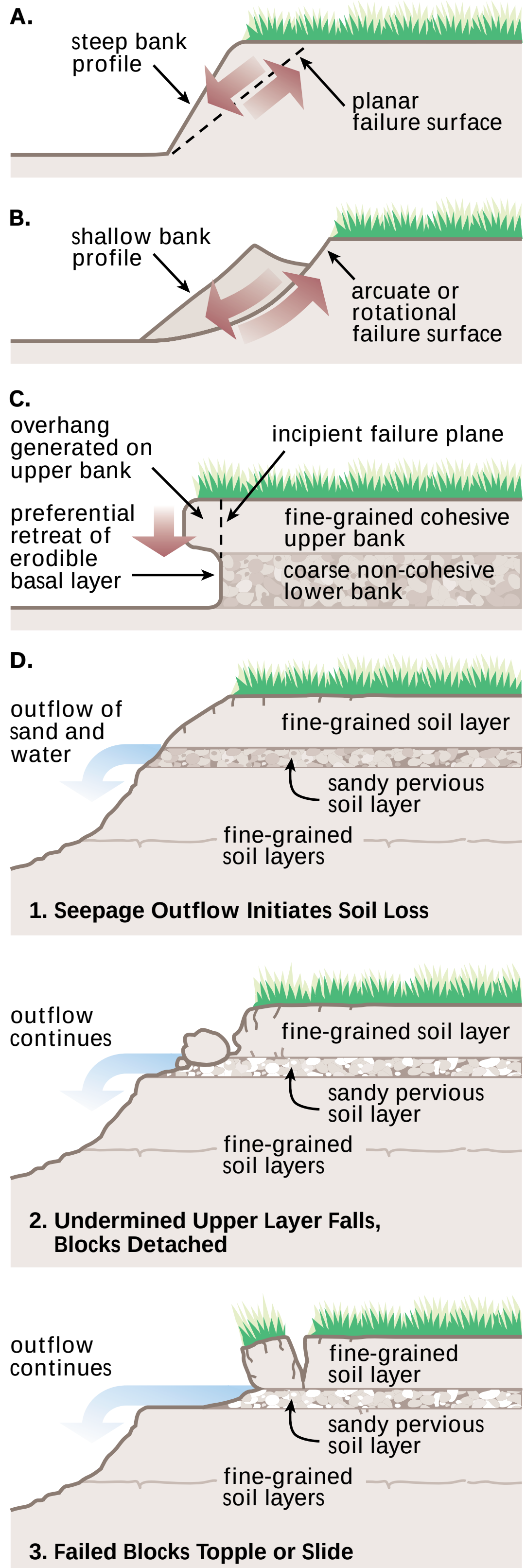


***Figure 7.29**: **Relationship of dominant bank failure mechanisms and associated stratigraphics.** (a) Uniform bank undergoing planar type failure (b) Uniform shallow bank undergoing rotational type failure (c) Cohesive upper bank, noncohesive lower bank leads to cantilever type failure mechanism (d) Complex bank stratigraphy may lead to piping or sapping type failures.*

Source: Hagerty 1991. In *Journal of Hydraulic Engineering.* Vol. 117 Number 8. Reproduced by permission of ASCE.

water provides some support to the streambanks. When the stream level drops, the internal pore pressure pushes out from within and increases the potential for bank failure.

The last situation described in Figure 7.29 involves ground water sapping or piping. Sapping or piping is the erosion of soil particles beneath the surface by flowing ground water. Dirty or sediment-laden seepage from a streambank indicates ground water sapping or piping is occurring. Soil layers above the areas of ground water piping eventually will collapse after enough soil particles have been removed from the support layer.

Quantitative Assessment of Bank Stability

When restoration design requires more quantitative information on soil properties, additional detailed data need to be collected (**Figure 7.30**). Values of cohesion, friction angle, and unit weight of the bank material need to be quantified. Because of spatial variability, careful sampling and testing programs are required to minimize the amount of data required to correctly characterize the average physical properties of individual layers or to determine a bulk average statistic for an entire bank.

Care must be taken to characterize soil properties not only at the time of measurement but also for the "worst case" conditions at which failure is expected (Thorne et al. 1981). Unit weight, cohesion, and friction angle vary as a function of moisture content. It usually is not possible to directly measure bank materials under worst-case conditions, due to the hazardous nature of unstable sites under such conditions. A qualified geotechnical or soil mechanics engineer should estimate these operational strength parameters.

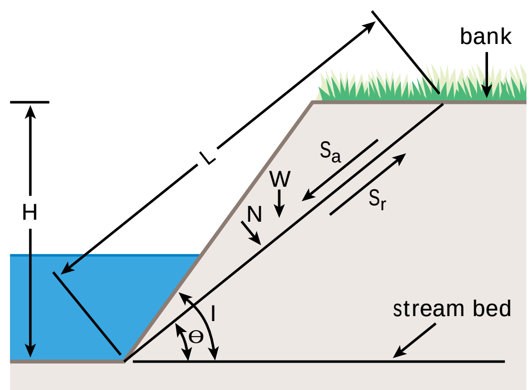
Quantitative analysis of bank instabilities is considered in terms of force and resistance. The shear strength of the bank material represents the resistance of the boundary to erosion by gravity. Shear strength is composed of cohesive strength and frictional strength. For the case of a planar failure of unit length, the Coulomb equation is applicable

$$S_r = c + (N - \mu) \tan \phi$$

where S_r = shear strength, in pounds per square foot; c = cohesion, in pounds per square foot; N = normal stress, in pounds per square foot; μ = pore pressure, in pounds per square foot; and ϕ = friction angle, in degrees.Also:

$$N = W \cos \theta$$

where W = weight of the failure block, in pounds per square foot; and θ = angle of the failure plane, in degrees.



Explanation

H = bank height
L = failure plane length
c = cohesion
ϕ = friction angle
γ = bulk unit weight
W = weight of failure block
(c, ϕ, γ, W: soil properties)
I = bank angle
S_a = Wsinθ (driving force)
S_r = cL + Ntanϕ (resisting force)
N = Wcosθ
θ = (0.5I = 0.5ϕ) (failure plane angle)

for the critical case $S_a = S_r$ and:

$$H_c = \frac{4c \sin I \cos \phi}{\gamma (1 - \cos [I - \phi])}$$

Figure 7.30: Forces acting on a channel bank assuming there is zero pore-water pressure. *Bank stability analyses relate strength of bank materials to bank height and angles, and to moisture conditions.*

The gravitational force acting on the bank is:

$$S_a = W \sin \theta$$

Factors that decrease the erosional resistance (S_r), such as excess pore pressure from saturation and the development of vertical tension cracks, favor bank instabilities. Similarly, increases in bank height (due to channel incision) and bank angle (due to undercutting) favor bank failure by increasing the gravitational force component. In contrast, vegetated banks generally are drier and provide improved bank drainage, which enhances bank stability. Plant roots provide tensile strength to the soil resulting in reinforced earth that resists mass failure, at least to the depth of roots (Yang 1996).

Bank Instability and Channel Widening

Channel widening is often caused by increases in bank height beyond the critical conditions of the bank material. Simon and Hupp (1992) show that there is a positive correlation between the amount of bed level lowering by degradation and amounts of channel widening. The adjustment of channel width by mass-wasting processes represents an important mechanism of channel adjustment and energy dissipation in alluvial streams, occurring at rates covering several orders of magnitude, up to hundreds of feet per year (Simon 1994).

Present and future bank stability may be analyzed using the following procedure:

- Measure the current channel geometry and shear strength of the channel banks.
- Estimate the future channel geometries and model worst-case pore pressure conditions and average shear strength characteristics.

For fine-grained soils, cohesion and friction angle data can be obtained from standard laboratory testing (triaxial shear or unconfined compression tests) or by in situ testing with a borehole shear test device (Handy and Fox 1967, Luttenegger and Hallberg 1981, Thorne et al. 1981, Simon and Hupp 1992). For coarse-grained, cohesionless soils, estimates of friction angles can be obtained from reference manuals. By combining these data with estimates of future bed elevations, relative bank stability can be assessed using bank stability charts.

Bank Stability Charts

To produce bank stability charts such as the one following, a stability number (N_s) representing a simplification of the bank (slope) stability equations is used. The stability number is a function of the bank-material friction angle (ϕ) and the bank angle (i) and is obtained from a stability chart developed by Chen (1975) (**Figure 7.31**) or from Lohnes and Handy (1968):

$$N_s = (4 \sin i \cos \phi) / [1 - \cos (i - \phi)]$$

The critical bank height H_c, where driving force S_a = resisting force S_r for a given shear strength and bank geometry is then calculated (Carson and Kirkby 1972):

$$H_c = N_s (c / \gamma)$$

where c =cohesion, in pounds per square foot, and γ = bulk unit weight of soil in pounds per cubic foot.

Equations are solved for a range of bank angles using average or ambient soil moisture conditions to produce the upper line “Ambient field conditions, unsaturated.” Critical bank height for worst-case conditions (saturated banks and rapid decline in river stage) are obtained by solving the equations, assuming that ϕ and the frictional component of shear strength goes to 0.0 (Lutton

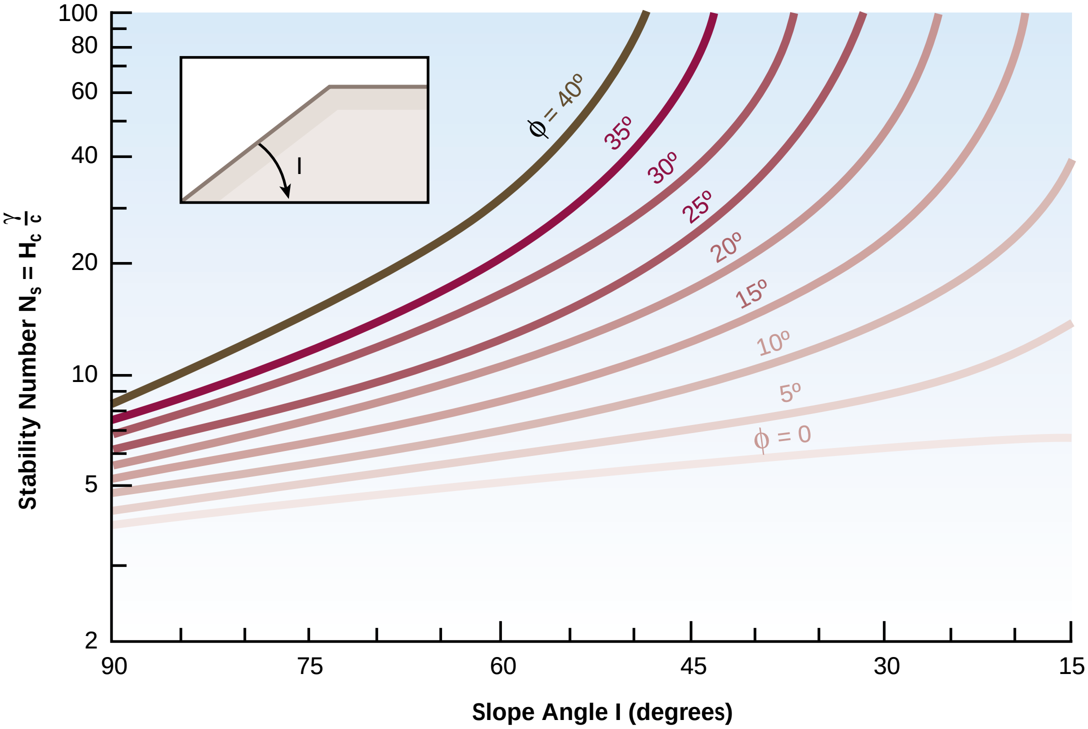


Figure 7.31: Stability number (N_s) as a function of bank angle (i) for a failure surface passing through the bank toe. *Critical bank height for worst-case condition can be computed.*
Source: Chen 1975.

1974) and by using a saturated bulk-unit weight. These results are represented by the lower line, "saturated conditions."

The frequency of bank failure for the three stability classes (unstable, at-risk, and stable) is subjective and is based primarily on empirical field data (**Figure 7.32**). An unstable channel bank can be expected to fail at least annually and possibly after each major stormflow in which the channel banks are saturated, assuming that there is at least one major stormflow in a given year. At-risk conditions translate to a bank failure every 2 to 5 years, again assuming that there is a major flow event to saturate the banks and to erode toe material. Stable banks by definition do not fail by mass wasting processes. However, channel banks on the outside of meander bends may experience erosion of the bank toe, leading to oversteepening of the bank profile and eventually to bank caving episodes.

Generalizations about critical bank heights (H_c) and angles can be made with knowledge of the variability in cohesive strengths. Five categories of mean cohesive strength of channel banks are identified in **Figure 7.33**. Critical bank heights above the mean low-water level and saturated conditions were used to construct the figure because bank failures typically occur during or after the recession of peak flows. The result is a nomograph giving critical bank heights for a range of bank angles and cohesive strengths that can be used to estimate stable bank configurations for worst-case conditions, such as saturation during rapid decline in river stage. For example, a saturated bank at an angle of 55 degrees and a

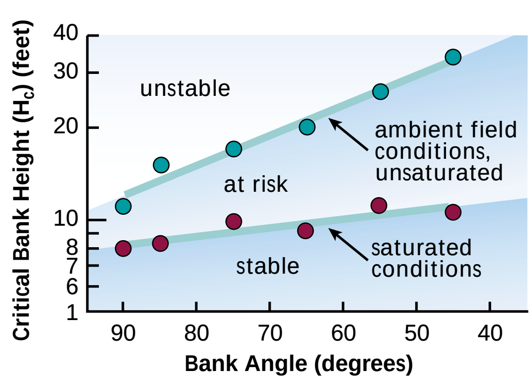


Figure 7.32: Example of a bank stability chart for estimating critical bank height (H_c). *Existing bank stability can be assessed, as well as potential stable design heights and slopes.*

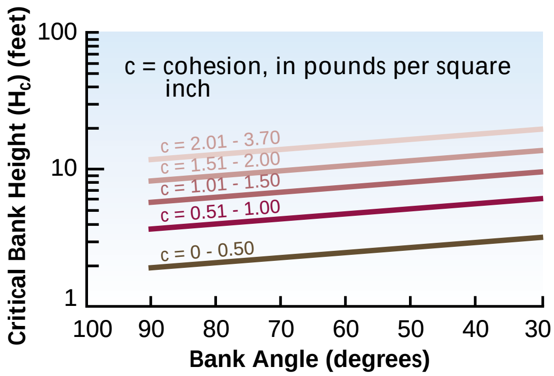


Figure 7.33: Critical bank-slope configurations for various ranges of cohesive strengths under saturated conditions. *Specific data on the cohesive strength of bank materials can be collected to determine stable configurations.*

cohesive strength of 1.75 pounds per square inch would be unstable when bank heights exceed about 10 feet.

Predictions of Bank Stability and Channel Width

Bank stability charts can be used to determine the following:

- The timing of the initiation of general bank instabilities (in the case of degradation and increasing bank heights).
- The timing of renewed bank stability (in the case of aggradation and decreasing bank heights).
- The bank height and angle needed for a stable bank configuration under a range of moisture conditions.

Estimates of future channel widening also can be made using measured channel-width data over a period of years and then fitting a nonlinear function to the data (**Figure 7.34**). Williams and Wolman (1984) used a dimensionless hyperbolic function of the following form to estimate channel widening downstream from dams:

$$(W_i / W_t) = j_1 + j_2 (1 / t)$$

where:

W_i = initial channel width, in feet

W_t = channel width at t years after W_1, in feet

t = time, in years

j_1 = intercept

j_2 = slope of the fitted straight line on a plot of W_i / W_t versus 1/t

Wilson and Turnipseed (1994) used a power function to describe widening after channelization and to estimate future channel widening in the loess area of northern Mississippi:

$$W = x\, t^d$$

where:

W = channel width, in feet

x = coefficient, determined by regression, indicative of the initial channel width

t = time, in years

d = coefficient, determined by regression, indicative of the rate of channel widening.

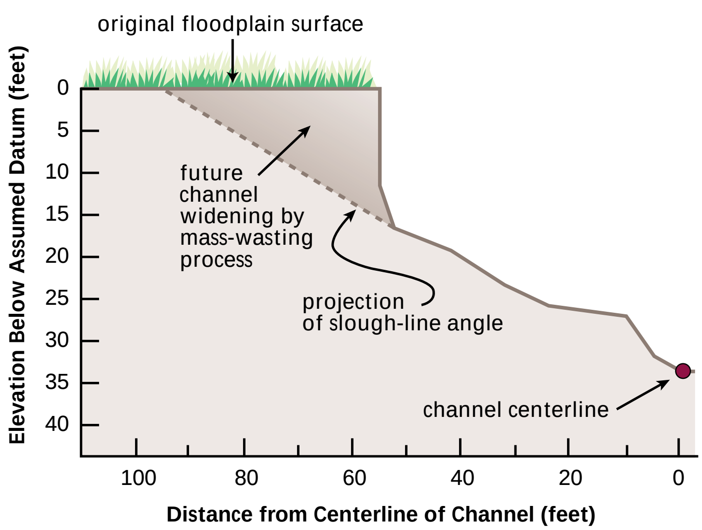


Figure 7.34: Method to estimate future channel widening (10–20 years) for one side of the channel. *The ultimate bank width can be predicted so that the future stream morphology can be visualized.*

7.C Chemical Characteristics

Assessing water chemistry in a stream restoration initiative can be one of the ways to determine if the restoration was successful. A fundamental understanding of the chemistry of a given system is critical for developing appropriate data collection and analysis methods. Although data collection and analysis are interdependent, each has individual components. It is also critical to have a basic understanding of the hydrologic and water quality processes of interest before data collection and analysis begin. Averett and Schroder (1993) discuss some fundamental concepts used when determining a data collection and analysis program.

Data Collection

Constituent Selection

Hundreds of chemical compounds can be used to describe water quality. It is typically too expensive and too time-consuming to analyze every possible chemical of interest in a given system. In addition to selecting a particular constituent to sample, the analytical techniques used to determine the constituent also must be considered. Another consideration is the chemistry of the constituent; for example, whether the chemical is typically in the dissolved state or sorbed onto sediment makes a profound difference in the methods used for sampling and analysis, as well as the associated costs.

Often it is effective to use parameters that integrate or serve as indicators for a number of other variables. For instance, dissolved oxygen and temperature measurements integrate the net impact of many physical and chemical processes on a stream system, while soluble reactive phosphorus concentration is often taken as a readily available indicator of the potential for growth of attached algae. Averett and Schroder (1993) discuss additional factors involved in selecting constituents to sample.

Sampling Frequency

The needed frequency of sampling depends on both the constituent of interest and management objectives. For instance, a management goal of reducing average instream nutrient concentrations may require monitoring at regular intervals, whereas a goal of maintaining adequate dissolved oxygen (DO) during summer low flow and high temperature periods may require only targeted monitoring during critical conditions. In general, water quality constituents that are highly variable in space or time require more frequent monitoring to be adequately characterized.

In many cases, the concentration of a constituent depends on the flow condition. For example, concentrations of a hydrophobic pesticide, which sorbs strongly to particulate matter, are likely to be highest during scouring flows or erosion washoff events, whereas concentrations of a dissolved chemical that is loaded to the stream at relatively steady rates will exhibit highest concentrations in extremely low flows.

In fact, field sampling and water quality analyses are time-consuming and expensive, and schedule and budget constraints often determine the frequency of data collection. Such constraints make it even more important to design data collection efforts that maximize the value of the information obtained.

Statistical tools often are used to help determine the sampling frequency. Statistical techniques, such as simple random sampling, stratified random sampling, two-stage sampling, and systematic sampling, are described in Gilbert (1987) and Averett and Schroder (1993). Sanders et al. (1983) also describe methods of determining sampling frequency.

Site Selection

The selection of sampling sites is the third critical part of a sampling design. Most samples represent a point in space and provide direct information only on what is happening at that point. A key objective of site selection is to choose a site that gives information that is representative of conditions throughout a particular reach of stream. Because most hydrologic systems are very complex, it is essential to have a fundamental understanding of the area of interest to make this determination.

External inputs, such as tributaries or irrigation return flow, as well as output, such as ground water recharge, can drastically change the water quality along the length of a stream. It is because of these processes that the hydrologic system must be understood to interpret the data from a particular site. For example, downstream from a significant lateral source of a load, the dissolved constituent(s) might be distributed uniformly in the stream channel. Particulate matter, however, typically is stratified. Therefore, the distribution of a constituent sorbed onto particulate matter is not evenly distributed. Averett and Schroder (1993) discuss different approaches to selecting sites to sample both surface water and ground water. Sanders et al. (1983) and Stednick (1991) also discuss site selection.

Finally, practical considerations are an important part of sample collection. Sites first must be accessible, preferably under a full range of potential flow and weather conditions. For this reason, sampling is often conducted at bridge crossings, taking into consideration the degree to which artificial channels at bridge crossings may influence sample results. Finally, where constituent loads and concentrations are of interest, it is important to align water quality sample sites with locations at which flow can be accurately gauged.

Sampling Techniques

This section provides a brief overview of water quality sampling and data collection techniques for stream restoration efforts. Many important issues can be treated only cursorily within the context of this document, but a number of references are available to provide the reader with more detailed guidance.

Key documents describing methods of water sample collection for chemical analysis are the U.S. Geological Survey (USGS) protocol for collecting and processing surface water samples for determining inorganic constituents in filtered water (Horwitz et al. 1994), the field guide for collecting and processing stream water samples for the National Water Quality Assessment program (Shelton 1994), and the field guide for collecting and processing samples of streambed sediment for analyzing trace elements and organic contaminants for the National Water Quality Assessment program (Shelton and Capel 1994). A standard reference document describing methods of sediment collection is the USGS *Techniques for Water-Resource Investigations*, *Field Methods for Measurement of Fluvial Sediment* (Guy and Norman 1982). The USGS is preparing a national field manual that describes techniques for collecting and processing water quality samples (Franceska Wilde, personal communication, 1997).

Sampling Protocols for Water and Sediment

Stream restoration monitoring may involve sampling both water and sediment quality. These samples may be collected by hand (manual samples), by using an automated sampler (automatic samples), as individual point-in-time samples (grab or discrete samples), or combined with other samples (composite samples). Samples collected and mixed in relation to the measured volume within or flow through a system are commonly termed volume- or flow-weighted composite samples, whereas equal-volume samples collected at regular vertical intervals through a portion or all of the water column may be mixed to provide a water column composite sample.

Manual Sampling and Grab Sampling

Samples collected by hand using various types of containers or devices to collect water or sediment from a receiving water or discharge often are termed grab samples. These samples can require little equipment and allow recording miscellaneous additional field observations during each sampling visit.

Manual sampling has several advantages. These approaches are generally uncomplicated and often inexpensive (particularly when labor is already available). Manual sampling is required for sampling some pollutants. For example, according to *Standard Methods* (APHA 1995), oil and grease, volatile compounds, and bacteria must be analyzed from samples collected using manual methods. (Oil, grease, and bacteria can adhere to hoses and jars used in automated sampling equipment, causing inaccurate results; volatile compounds can vaporize during automated sampling procedures or can be lost from poorly sealed sample containers; and bacteria populations can grow and community compositions change during sample storage.)

Disadvantages of grab sampling include the potential for personnel to be available around the clock to sample during storms and the potential for personnel to be exposed to hazardous conditions during sampling. Long-term sampling programs involving many sampling locations can be expensive in terms of labor costs.

Grab sampling is often used to collect discrete samples that are not combined with other samples. Grab samples can also be used to collect volume- or flow-weighted composite samples, where several discrete samples are combined by proportion to measured volume or flow rates; however, this type of sampling is often more easily accomplished using automated samplers and flow meters. Several examples of manual methods for flow weighting are presented in USEPA (1992a). Grab sampling also may be used to composite vertical water column or aerial composite samples of water or sediment from various kinds of water bodies.

Automatic Sampling

Automated samplers have been improved greatly in the last 10 years and now have features that are useful for many sampling purposes. Generally, such sampling devices require larger initial capital investments or the payment of rental fees, but they can reduce overall labor costs (especially for long-running sampling programs) and increase the reliability of flow-weighted compositing.

Some automatic samplers include an upper part consisting of a microprocessor-based controller, a pump assembly, and a filling mechanism, and a lower part containing a set of glass or plastic sample containers and a well that can be filled with ice to cool the collected samples. More expensive automatic samplers can include refrigeration equipment in place of the ice well; such devices, however, require a 120-volt power supply instead of a battery. Also, many automatic samplers can accept input signals from a flowmeter to activate the sampler and to initiate a flow-weighting compositing program. Some samplers can accept input from a rain gauge to activate a sampling program.

Most automatic samplers allow collecting multiple discrete samples or single or multiple composited samples. Also, samples can be split between sample bottles or can be composited into a single bottle. Samples can be collected on a predetermined time basis or in proportion to flow measurement signals sent to the sampler.

In spite of the obvious advantages of automated samplers, they have some disadvantages and limitations. Some pollutants cannot be sampled by automated equipment unless only qualitative results are desired. Although the cleaning sequence provided by most such samplers provide reasonably separate samples, there is some cross-contamination of the samples since water droplets usually remain in the tubing. Debris in the sampled receiving water can block the sampling line and prevent sample collection. If the sampling line is located in the vicinity of a flowmeter, debris caught on the sampling line can also lead to erroneous flow measurements.

While automatic samplers can reduce manpower needs during storm and runoff events, these devices must be checked for accuracy during these events and must be regularly tested and serviced. If no field checks are made during a storm event, data for the entire event may be lost. Thus, automatic samplers do not eliminate the need for field personnel, but they can reduce these needs and can produce flow-weighted composite samples that might be tedious or impossible using manual methods.

Discrete versus Composite Sampling

Flow rates, physical conditions, and chemical constituents in surface waters often vary continuously and simultaneously. This presents a difficulty when determining water volumes, pollutant concentrations, and masses of pollutants or their loads in the waste discharge flows and in receiving waters. Using automatic or continuously recording flowmeters allows obtaining reasonable and continuous flow rate measurements for these waters. Pollutant loads can then be computed by multiplying these flow volumes over the period of concern by the average pollutant concentration determined from the discrete or flow-composited samples. When manual (instantaneous) flow measurements are used, actual volume flows over time can be estimated only for loading calculations, adding additional uncertainty to loading estimates.

Analyzing constituents of concern in a single grab sample collection provides the minimum information at the minimum cost. Such an approach, however, could be appropriate where conditions are relatively stable; for example, during periods without rainfall or other potential causes of significant runoff and when the stream is well-mixed. Most often, the usual method is to collect a random or regular series of grab samples at predefined intervals during storm or runoff events.

When samples are collected often enough, such that concentration changes between samples are minimized, a clear pattern or time series for the pollutant's concentration dynamics can be obtained. When sampling intervals are spaced too far apart in relation to changes in the pollutant concentration, less clear understanding of these relationships is obtained. Mixing samples from adjacent sampling events or regions (compositing) requires fewer samples to be analyzed; for some assessments, this is a reasonable approach. Sample compositing provides a savings, especially related to costs for water quality analyses, but it also results in loss of information. For example, information on maximum and minimum concentrations during a runoff event is usually lost. But compositing many samples collected through multiple periods during the events can help ensure that the samples analyzed do not include only extreme conditions that are not entirely representative of the event.

Even though analytical results from composited samples rarely equal average conditions for the event, they can still be used, when a sufficient distribution of samples is included, to provide reasonably representative conditions for computing loading estimates. In some analyses, however, considerable errors can be made when using analytical results from composited samples in completing loading analyses. For example, when maximum pollutant concentrations accompany the maximum flow rates, yet concentrations in high and low flows are treated equally, true loadings can be underestimated.

Consequently, when relationships between flow and pollutant concentrations are unknown, it is often preferable initially to include in the monitoring plan at least three discrete or multiple composite sample collections: during the initial period of increasing flow, during the period of the peak or plateau flow, and during the period of declining flow.

The most useful method for sample compositing is to combine samples in relation to the flow volume occurring during study period intervals. There are two variations for accomplishing flow-weighted compositing:

1. Collect samples at equal time intervals at a volume proportional to the flow rate (e.g., collect 100 mL of sample for every 100 gallons of flow that passed during a 10-minute interval) or
2. Collect equal-volume samples at varying times proportional to the flow (e.g., collect a 100-mL sample for each 100 gallons of flow, irrespective of time).

The second method is preferable for estimating load accompanying wet weather flows, since it results in samples being collected most often when the flow rate is highest.

Another compositing method is time-composited sampling, where equal sample volumes are collected at equally spaced time intervals (e.g., collect 100 mL of sample every 10 minutes during the monitored event). This approach provides information on the average conditions at the sampling point during the sampling period. It should be used, for example, to determine the average toxic concentrations to which resident aquatic biota are exposed during the monitored event.

Field Analyses of Water Quality Samples

Concentrations of various water quality parameters may be monitored both in the field and in samples submitted to a laboratory (**Figure 7.35**). Some parameters, such as water temperature, must be obtained in the field. Parameters such as concentrations of specific synthetic organic chemicals require laboratory analysis. Other parameters, such as nu-

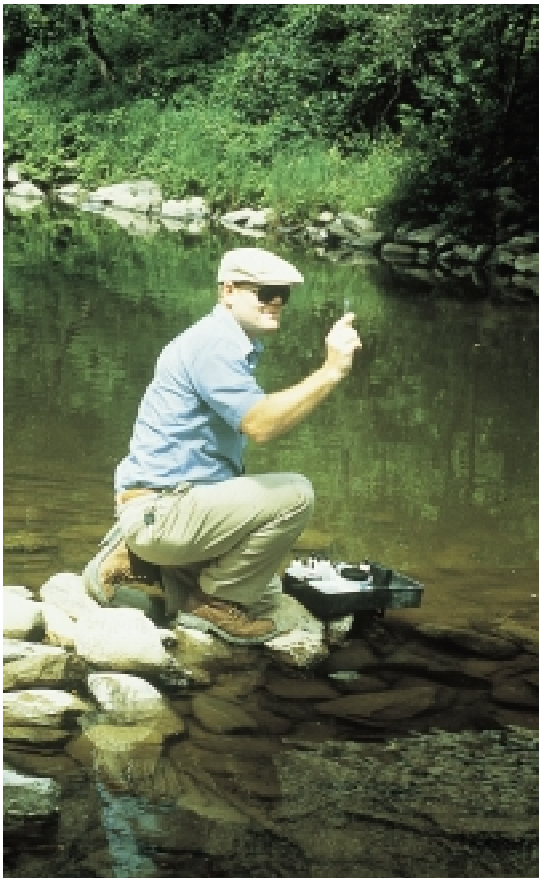


Figure 7.35: Field sampling. *Sampling can also be automated.*

trient concentrations, can be measured by both field and laboratory analytical methods. For chemical constituents, field measurements generally should be considered as qualitative screening values since rigorous quality control is not possible. In addition, samples collected for compliance with Clean Water Act requirements must be analyzed by a laboratory certified by the appropriate authority, either the state or the USEPA. The laboratories must use analytic techniques listed in the *Code of Federal Regulations* (CFR), Title 40, Part 136, "Guidelines Establishing Test Procedures for Analysis of Pollutants Under the Clean Water Act."

The balance of this subsection notes special considerations regarding those parameters typically sampled and analyzed in the field, including pH, temperature, and dissolved oxygen (DO).

pH

Levels of pH can change rapidly in samples after collection. Consequently, pH often is measured in the field using a hand-held pH electrode and meter. Electrodes are easily damaged and contaminated and must be calibrated with a standard solution before each use. During calibrations and when site measurements are conducted, field instruments should be at thermal equilibrium with the solutions being measured.

Temperature

Because water temperature changes rapidly after collection, it must be measured either in the field (using in situ probes) or immediately after collecting a grab sample. EPA Method 170.1 describes procedures for thermometric determination of water temperature. Smaller streams often experience wide diurnal variations in temperature, as well as pH and DO. Many streams also experience vertical and longitudinal variability in temperature from shading and flow velocity. Because of the effect of temperature on other water quality factors, such as dissolved oxygen concentration, temperatures always should be recorded when other field measurements are made.

Dissolved Oxygen

When multiple DO readings are required, a DO electrode and meter (EPA method 360.1) are typically used. To obtain accurate measurements, the Winkler titration method should be used to calibrate the meter before and after each day's use. Often it is valuable to recheck the calibration during days of intensive use, particularly when the measurements are of critical importance.

Oxygen electrodes are fragile and subject to contamination, and they need frequent maintenance. Membranes covering these probes must be replaced when bubbles form under the membrane, and the electrode should be kept full of fresh electrolyte solution. If the meter has temperature and salinity compensation controls, they should be used carefully, according to the manufacturer's instructions.

Water Quality Sample Preparation and Handling for Laboratory Analysis

Sample collection, preparation, preservation, and storage guidelines are designed to minimize altering sample constituents. Containers must be made of materials that will not interact with pollutants in the sample, and they should be cleaned in such a way that neither the container nor the cleaning agents interfere with sample analysis. Sometimes, sample constituents must be preserved before they degrade or transform prior to analysis. Also, specified holding times for the sample must not be exceeded. Standard procedures for collecting, preserving, and storing samples are presented in APHA (1995) and at 40 CFR Part 136. Useful material also is contained in the USEPA *NPDES Storm Water Sampling Guidance Document* (1992a).

Most commercial laboratories provide properly cleaned sampling containers with appropriate preservatives. The laboratories also usually indicate the maximum allowed holding periods for each analysis. Acceptable procedures for cleaning sample bottles, preserving their contents, and analyzing for appropriate chemicals are detailed in various methods manuals, including APHA (1995) and USEPA (1979a). Water samplers, sampling hoses, and sample storage bottles always should be made of materials compatible with the goals of the study. For example, when heavy metals are the concern, bottles should not have metal components that can contaminate the collected water samples. Similarly, when organic contaminants are the concern, bottles and caps should be made of materials not likely to leach into the sample.

Sample Preservation, Handling, and Storage

Sample preservation techniques and maximum holding times are presented in APHA (1995) and 40 CFR Part 136. Cooling samples to a temperature of 4 degrees Celsius (° C) is required for most water quality variables. To accomplish this, samples are usually placed in a cooler containing ice or an ice substitute. Many automated samplers have a well next to the sample bottles to hold either ice or ice substitutes. Some more expensive automated samplers have refrigeration equipment requiring a source of electricity. Other preservation techniques include pH adjustment and chemical fixation. When needed, pH adjustments are usually made using strong acids and bases, and extreme care should be exercised when handing these substances.

Bacterial analysis may be warranted, particularly where there are concerns regarding inputs of sewage and other wastes or fecal contamination. Bacterial samples have a short holding time and are not collected by automated sampler. Similarly, volatile compounds must be collected by grab sample, since they are lost through volatilization in automatic sampling equipment.

Sample Labeling

Samples should be labeled with waterproof labels. Enough information should be recorded to ensure that each sample label is unique. The information recorded on sample container labels also should be recorded in a sampling notebook kept by field personnel. The label typically includes the following information:

- Name of project.
- Location of monitoring.
- Specific sample location.
- Date and time of sample collection.
- Name or initials of sampler.
- Analysis to be performed.
- Sample ID number.
- Preservative used.
- Type of sample (grab, composite).

Sample Packaging and Shipping

It is sometimes necessary to ship samples to the laboratory. Holding times should be checked before shipment to ensure that they will not be exceeded. Although wastewater samples are not usually considered hazardous, some samples, such as those with extreme pH, require special procedures. If the sample is shipped through a common carrier or the U.S. Postal Service, it must comply with Department of Transportation Hazardous Material Regulations (49 CFR Parts 171-177). Air shipment of samples defined as hazardous may be covered by the requirements of the International Air Transport Association.

Samples should be sealed in leakproof bags and padded against breakage. Many samples must be packed with an ice substitute to maintain a temperature of 4 degrees C during shipment. Plastic or metal recreational coolers make ideal shipping containers because they protect and insulate the samples. Accompanying paperwork, such as the chain-of-custody documentation, should be sealed in a waterproof bag in the shipping container.

Chain of Custody

Chain-of-custody forms document each change in possession of a sample, starting at its collection and ending when it is analyzed. At each transfer of possession, both the relinquisher and the receiver of the samples are required to sign and date the form. The form and the procedure document possession of the samples and help prevent tampering. The container holding samples also can be sealed with a signed tape or seal to help ensure that samples are not compromised.

Copies of the chain-of-custody form should be retained by the sampler and by the laboratory. Contract laboratories often supply chain-of-custody forms with sample containers. The form is also useful for documenting which analyses will be performed on the samples. These forms typically contain the following information:

- Name of project and sampling locations.
- Date and time that each sample is collected.
- Names of sampling personnel.
- Sample identification names and numbers.
- Types of sample containers.
- Analyses performed on each sample.
- Additional comments on each sample.
- Names of all those transporting the samples.

Collecting and Handling Sediment Quality Samples

Sediments are sinks for a wide variety of materials. Nonpoint source discharges typically include large quantities of suspended material that settle out in sections of receiving waters having low water velocities. Nutrients, metals, and organic compounds can bind to suspended solids and settle to the bottom of a water body when flow velocity is insufficient to keep them in suspension. Contaminants bound to sediments may remain separated from the water column, or they may be resuspended in the water column.

Flood scouring, bioturbation (mixing by biological organisms), desorption, and biological uptake all promote the release of adsorbed pollutants. Organisms that live and feed in sediment are especially vulnerable to contaminants in sediments. Having entered the food chain, contaminants can pass to feeders at higher food (trophic) levels and can accumulate or concentrate in these organisms. Humans can ingest these contaminants by eating fish.

Sediment deposition also can physically alter benthic (bottom) habitats and affect habitat and reproductive potentials for many fish and invertebrates. Sediment sampling should allow all these impact potentials to be assessed.

Collection Techniques

Sediment samples are collected using hand- or winch-operated dredges. Although a wide variety of dredges are available, most operate in the following similar fashion:

1. The device is lowered or pushed through the water column by hand or winch.
2. The device is released to allow closure, either by the attached line or by a weighted messenger that is dropped down the line.
3. The scoops or jaws of the device close either by weight or spring action.
4. The device is retrieved to the surface.

Ideally, the device disturbs the bottom as little as possible and closes fully so that fine particles are not lost. Common benthic sampling devices include the Ponar, Eckman, Peterson, Orangepeel, and Van Veen dredges. When information is needed about how chemical depositions and accumulations have varied through time, sediment cores can be collected with a core sampling device. Very low density or very coarse sediments can be sampled by freeze coring. A thorough description of sediment samplers is included in Klemm et al. (1990).

Sediment sampling techniques are useful for two types of investigations related to stream assessments:
(1) chemical analysis of sediments and (2) investigation of benthic macroinvertebrate communities. In either type of investigation, sediments from reference stations should be sampled so that they can be compared with sediments in the affected receiving waters. Sediments used for chemical analyses should be removed from the dredge or core samples by scraping back the surface layers of the collected sediment and extracting sediments from the central mass of the collected sample. This helps to avoid possible contamination of the sample by the sample device. Sediment samples for toxicological and chemical examination should be collected following method E 1391 detailed in ASTM (1991). Sediments for benthic population analyses may be returned in total for cleaning and analysis or may receive a preliminary cleaning in the field using a No. 30 sieve.

Sediment Analyses

There are a variety of sediment analysis techniques, each designed with inherent assumptions about the behavior of sediments and sediment-bound contaminants. An overview of developing techniques is presented in Adams et al. (1992). EPA has evaluated 11 of the methods available for assessing sediment quality (USEPA 1989b). Some of the techniques may help to demonstrate attainment of narrative requirements of some water quality standards. Two of these common analyses are introduced briefly in the following paragraphs.

Bulk sediment analyses analyze the total concentration of contaminants that are either bound to sediments or present in pore water. Results are reported in milligrams or micrograms per kilogram of sediment material. This type of testing often serves as a screening analysis to classify dredged material. Results of bulk testing tend to overestimate the mass of contaminants that will be available for release or for biological uptake because a portion of the contaminants are not biologically available or likely to dissolve.

Elutriate testing estimates the amount of contaminants likely to be released from sediments when mixed with water. In an elutriate test, sediment is mixed with water and then agitated. The standard elutriate test for dredge material mixes four parts water from the receiving water body with one part sediment (USEPA 1990). After vigorous mixing, the sample is allowed to settle before the supernatant is filtered and analyzed for contaminants. This test was designed to estimate the amount of material likely to enter the dissolved phase during dredging; however, it is also useful as a screening test for determining whether further testing should be performed and as a tool for comparing sediments upstream and downstream of potential pollutant sources.

Data Management

All monitoring data should be organized and stored in a readily accessible form. The potentially voluminous and diverse nature of the data, and the variety of individuals who can be involved in collecting, recording, and entering data, can easily lead to the loss of data or the recording of erroneous data. Lost or erroneous data can severely damage the quality of monitoring programs. A sound and efficient data management program for a monitoring program should focus on preventing such problems. This requires that data be managed directly and separately from the activities that use them.

Data management systems include technical and managerial components. The technical components involve selecting appropriate computer equipment and software and designing the database, including data definition, data standardization, and a data dictionary. The managerial components include data entry, data validation and verification, data access, and methods for users to access the data.

To ensure the integrity of the database, it is imperative that data quality be controlled from the point of collection to the time the information is entered into the database. Field and laboratory personnel must carefully enter data into proper spaces on data sheets and avoid transposing numbers. To avoid transcription errors, entries into a database should be made from original data sheets or photocopies. As a preliminary screen for data quality, the database design should include automatic parameter range checking. Values outside the defined ranges should be flagged by the program and immediately corrected or included in a follow-up review of the entered data. For some parameters, it might be appropriate to include automatic checks to disallow duplicate values. Preliminary database files should be printed and verified against the original data to identify errors.

Additional data validation can include expert review of the verified data to identify possible suspicious values. Sometimes, consultation with the individuals responsible for collecting or entering original data is required to resolve problems. After all data are verified and validated, they can be merged into the monitoring program's master database. To prevent loss of data from computer failure, at least one set of duplicate (backup) database files should be maintained at a location other than where the master database is kept.

Quality Assurance and Quality Control (QA/QC)

Quality assurance (QA) is the management process to ensure the quality of data. In the case of monitoring projects, it is managing environmental data collection to ensure the collection of high-quality data. QA focuses on systems, policies, procedures, program structures, and delegation of responsibility that will result in high-quality data. Quality control (QC) is a group of specific procedures designed to meet defined data quality objectives. For example, equipment calibration and split samples are QC procedures. QA/QC procedures are essential to ensure that data collected in environmental monitoring programs are useful and reliable.

The following are specific QA plans required of environmental monitoring projects that receive funding from EPA:

- State and local governments receiving EPA assistance for environmental monitoring projects must complete a quality assurance program plan acceptable to the award official. Guidance for producing the program plan is contained in USEPA (1983d).
- Environmental monitoring projects that receive EPA funding must file a quality assurance project plan, or QAPP, (40 CFR 30.503), the purpose of which is to ensure quality of a specific project. The QAPP describes quality assurance practices designed to produce data of quality sufficient to meet project objectives. Guidance for producing the QAPP (formerly termed the QAPjP) is contained in USEPA (1983e). The plan must address the following items:
  - Title of project and names of principal investigators.
  - Table of contents.
  - Project description.
  - Project organization and QA/QC responsibility.
  - Quality assurance objectives and criteria for determining precision, accuracy, completeness, representativeness, and comparability of data.
  - Sampling procedures.
  - Sample custody.
  - Calibration procedures.
  - Analytical procedures.
  - Data reduction, validation, and reporting.
  - Internal quality control checks.
  - Performance and system audits.
  - Preventive maintenance procedures.
  - Specific routine procedures to assess data precision, accuracy, representativeness, and comparability.
  - Corrective action.
  - Quality assurance reports.

Sample and Analytical Quality Control

The following quality control techniques are useful in assessing sampling and analytic performance (see also USEPA 1979b, Horwitz et al. 1994):

- *Duplicate samples* are independent samples collected in such a manner that they are equally representative of the contaminants of interest. Duplicate samples, when analyzed by the same laboratory, provide precision information for the entire measurement system, including sample collection, homogeneity, handling, shipping, storage, preparation, and analysis.

- *Split samples* have been divided into two or more portions at some point in the measurement process. Split samples that are divided in the field yield results relating precision to handling, shipping, storage, preparation, and analysis. The split samples may be sent to different laboratories and subjected to the same measurement process to assess interlaboratory variation. Split samples serve an oversight function in assessing the analytical portion of the measurement system, whereas error due to sampling technique may be estimated by analyzing duplicate versions of the same sample.

- *Spiked samples* are those to which a known quantity of a substance is added. The results of spiking a sample in the field are usually expressed as percent recovery of the added material. Spiked samples provide a check of the accuracy of laboratory and analytic procedures.

Sampling accuracy can be estimated by evaluating the results obtained from blanks. The most suitable types of blanks for this appraisal are equipment, field, and trip blanks.

- *Equipment blanks* are samples obtained by running analyte-free water through sample collection equipment, such as a bailer, pump, or auger, after decontamination procedures are completed. These samples are used to determine whether variation is introduced by sampling equipment.

- *Field blanks* are made by transferring deionized water to a sample container at the sampling site. Field blanks test for contamination in the deionized water and contamination introduced through the sampling procedure. They differ from trip blanks, which remain unopened in the field.

- *Trip blanks* test for cross-contamination during transit of volatile constituents, such as many synthetic organic compounds and mercury. For each shipment of sample containers sent to the analytical laboratory, one container is filled with analyte-free water at the laboratory and is sealed. The blanks are transported to the site with the balance of the sample containers and remain unopened. Otherwise, they are handled in the same manner as the other samples. The trip blanks are returned to the laboratory with the samples and are analyzed for the volatile constituents.

Field Quality Assurance

Errors or a lack of standardization in field procedures can significantly decrease the reliability of environmental monitoring data. If required, a quality assurance project plan should be followed for field measurement procedures and equipment. If the QAPP is not formally required, a plan including similar material should be developed to ensure the quality of data collected. Standard operating procedures should be followed when available and should be developed when not.

It is important that quality procedures be followed and regularly examined. For example, field meters can provide erroneous values if they are not regularly calibrated and maintained. Reagent solutions and probe electrolyte solutions have expiration periods and should be refreshed periodically.

7.D Biological Characteristics

Nearly all analytical procedures for assessing the condition of biological resources can be used in stream corridor restoration. Such procedures differ, however, in their scale and focus and in the assumptions, knowledge, and effort required to apply them. These procedures can be grouped into two broad classes—synthetic measures of system condition and analyses based on how well the system satisfies the life history requirements of target species or species groups.

The most important difference between these classes is the logic of how they are applied in managing or restoring a stream corridor system. This chapter focuses on metrics of biological conditions and does not describe, for example, actual field methods for counting organisms.

Synthetic Measures of System Condition

Synthetic measures of system condition summarize some aspect of the structural or functional status of a system at a particular point in time. Complete measurement of the state of a stream corridor system, or even a complete census of all of the species present, is not feasible. Thus, good indicators of system condition are efficient in the sense that they summarize the health of the overall system without having to measure everything about the system.

Use of indicators of system condition in management or restoration depends completely on comparison to values of the indicator observed in other systems or at other times. Thus, the current value of an indicator for a degraded stream corridor can be compared to a previously measured preimpact value for the corridor, a desired future value for the corridor, a value observed at an "unimpacted" reference site, a range of values observed in other systems, or a normative value for that class of stream corridors in a stream classification system. However, the indicator itself and the analysis that establishes the value of the indicator provide no direct information about what has caused the system to have a particular value for the indicator.

Deciding what to change in the system to improve the value of the indicator depends on a temporal analysis in which observed changes in the indicator in one system are correlated with various management actions or on a spatial analysis in which values of the indicator in different systems are correlated with different values of likely controlling variables. In both cases, no more than a general empirical correlation between specific causal factors and the indicator variable is attempted. Thus, management or restoration based on synthetic measures of system condition relies heavily on iterative monitoring of the indicator variable and trial and error, or adaptive management, approaches. For example, an index of species composition based on the presence or absence of a set of sensitive species might be generally correlated with water quality, but the index itself provides no information on how water quality should be improved. However, the success of management actions in improving water quality could be tracked and evaluated through iterative measurement of the index.

Synthetic measures of system condition vary along a number of important dimensions that determine their applicability. In certain situations, single species might be good indicators of

Stream Visual Assessment Protocol

This is another assessment tool that provides a basic level of stream health evaluation. It is intended to be the first level in a four-part hierarchy of assessment protocols that facilitate planning stream restorations. Scores are assigned by the planners for the following:

- *Channel condition*
- *Hydrologic alteration*
- *Riparian zone width*
- *Bank stability*
- *Canopy cover*
- *Water appearance*
- *Nutrient enrichment*
- *Manure presence*
- *Salinity*
- *Barriers to fish movement*
- *Instream fish cover*
- *Pools*
- *Riffle quality*
- *Invertebrate habitat*
- *Macroinvertebrates observed*

The planning assessment concludes with narratives of the suspected causes of observed problems, as well as recommendations or further steps in the planning process (USDA-NRCS 1998).

some aspect of a stream corridor system; in others, community metrics, such as diversity, might be more suitable. Some indicators incorporate physical variables, and others do not. Measurements of processes and rates, such as primary productivity and channel meandering rates, are incorporated into some and not into others. Each of these dimensions must be evaluated relative to the objectives of the restoration effort to determine which, if any, indicator is most appropriate.

Indicator Species

Landres et al. (1988) define an indicator species as an organism whose characteristics (e.g., presence or absence, population density, dispersion, reproductive success) are used as an index of attributes too difficult, inconvenient, or expensive to measure for other species or environmental conditions of interest. Ecologists and management agencies have used aquatic and terrestrial indicator species for many years as assessment tools, the late 1970s and early 1980s being a peak interest period. During that time, Habitat Evaluation Procedures (HEP) were developed by the U.S. Fish and Wildlife Service, and the U.S. Forest Service's use of management indicator species was mandated by law with passage of the National Forest Management Act in 1976. Since that time, numerous authors have expressed concern about the ability of indicator species to meet the expectations expressed in the above definition. Most notably, Landres et al. (1988) critically evaluated the use of vertebrate species as ecological indicators and suggested that rigorous justification and evaluation are needed before the concept is used. The discussion of indicator species below is largely based on their paper.

The Good and Bad of Indicator Species

Indicator species have been used to predict environmental contamination, population trends, and habitat quality; however, their use in evaluating water quality is not covered in this section. The assumptions implicit in using indicators are that if the habitat is suitable for the indicator it is also suitable for other species (usually in a similar ecological guild) and that wildlife populations reflect habitat conditions. However, because each species has unique life requisites, the relationship between the indicator and its guild may not be completely reliable, although the literature is inconsistent in this regard (see Riparian Response Guilds subsection below). It is also difficult to include all the factors that might limit a population when selecting a group of species that an indicator is expected to represent. For example, similarities in breeding habitat between the indicator and its associates might appear to group species when in fact differences in predation rates, disease, or winter habitat actually limit populations.

Some management agencies use vertebrate indicators to track changes in habitat condition or to assess the influence of habitat alteration on selected species. Habitat suitability indices and other habitat models are often used for this purpose, though the metric chosen to measure a species' response to its habitat can influence the outcome of the investigation. As Van Horne (1983) pointed out, density and other abundance metrics may be misleading indicators of habitat quality. Use of diversity and other indices to estimate habitat quality also creates problems when the variation in measures yields an average value for an index that might not represent either extreme.

Selecting Indicators

Landres et al. (1988) suggest that if the decision is made to use indicators, then several factors are important to consider in the selection process:

- Sensitivity of the species to the environmental attribute being evaluated. When possible, data that suggest a cause-and-effect relationship are preferred to correlates (to ensure the indicator reflects the variable of interest and not a correlate).
- Indicator accurately and precisely responds to the measured effect. High variation statistically limits the ability to detect effects. Generalist species do not reflect change as well as more sensitive endemics. However, because specialists usually have lower populations, they might not be the best for cost-effective sampling. When the goal of monitoring is to evaluate on-site conditions, using indicators that occur only within the site makes sense. However, although permanent residents may better reflect local conditions, the goal of many riparian restoration efforts is to provide habitat for neotropical migratory birds. In this case, residents such as cardinals or woodpeckers might not serve as good indicators for migrating warblers.
- Size of the species home range. If possible, the home range should be larger than that of other species in the evaluation area. Management agencies often are forced to use high-profile game or threatened and endangered species as indicators. Game species are often poor indicators simply because their populations are highly influenced by hunting mortality, which can mask environmental effects. Species with low populations or restrictions on sampling methods, such as threatened and endangered species, are also poor indicators because they are difficult to sample adequately, often due to budget constraints. For example, Verner (1986) found that costs to detect a 10 percent change in a randomly sampled population of pileated woodpeckers would exceed a million dollars per year.
- Response of an indicator species to an environmental stressor cannot be expected to be consistent across varying geographic locations or habitats without corroborative research.

Riparian Response Guilds

Vertebrate response guilds as indicators of restoration success in riparian ecosystems may be a valuable monitoring tool but should be used with the same cautions presented above. Croonquist and Brooks (1991) evaluated the effects of anthropogenic disturbances on small mammals and birds along Pennsylvania waterways. They evaluated species in five different response guilds, including wetland dependency, trophic level, species status (endangered, recreational, native, exotic), habitat specificity, and seasonality (birds).

They found that community coefficient indices were better indicators than species richness. The habitat specificity and seasonality response guilds for birds were best able to distinguish those species sensitive to disturbance from those which were not affected or were benefited. Neotropical migrants and species with specific habitat requirements were the best predictors of disturbance. Edge and exotic species were greater in abundance in the disturbed habitats and might serve as good indicators there. Seasonality analysis showed migrant breeders were more common in undisturbed areas, which, as suggested by Verner (1984), indicates the ability of guild analysis to distinguish local impacts. Mammalian response guilds did not exhibit any significant sensitivity to disturbance and were considered unsuitable as indicators.

In contrast, Mannan et al. (1984) found that in only one of the five avian guilds tested was the density of birds consistent across managed and undisturbed forests. In other words, population response to restoration might not be consistent across different indicator guilds. Also, periodically monitoring restoration initiatives is necessary to document when, during the recovery stage, the more sensitive species outcompete generalists.

Aquatic Invertebrates

Aquatic invertebrates have been used as indicators of stream and riparian health for many years. Perhaps more than other taxa, they are closely tied to both aquatic and riparian habitat. Their life cycles usually include periods in and out of the water, with ties to riparian vegetation for feeding, pupation, emergence, mating, and egg laying (Erman 1991).

It is often important to look at the entire assemblage of aquatic invertebrates as an indicator group. Impacts to a stream often decrease diversity but might increase the abundance of some species, with the size of the first species to be affected often larger (Wallace and Gurtz 1986). In summary, a good indicator species should be low on the food chain to respond quickly, should have a narrow tolerance to change, and should be a native species (Erman 1991).

Diversity and Related Indices

Biological diversity refers to the number of species in an area or region and includes a measure of the variety of species in a community that takes into account the relative abundance of each species (Ricklefs 1990). When measuring diversity, it is important to clearly define the biological objectives, stating exactly what attributes of the system are of concern and why (Schroeder and Keller 1990). Different measures of diversity can be applied at various levels of complexity, to different taxonomic groups, and at distinct spatial scales. Several factors should be considered in using diversity as a measure of system condition for stream corridor restoration.

Levels of Complexity

Diversity can be measured at several levels of complexity—genetic, population/species, community/ecosystem, and landscape (Noss 1994). There is no single correct level of complexity to use because different scientific or management issues are focused on different levels (Meffe et al. 1994). The level of complexity chosen for a specific stream corridor restoration initiative should be determined based on careful consideration of the biological objectives of the project.

Subsets of Concern

Overall diversity within any given level of complexity may be of less concern than diversity of a particular subset of species or habitats. Measures of overall diversity include all of the elements of concern and do not provide information about the occurrence of specific elements. For example, measures of overall species diversity do not provide information about the presence of individual species or species groups of management concern.

Any important subsets of diversity should be described in the process of setting biological objectives. At the community level, subsets of species of interest might include native, endemic, locally rare or threatened, specific guilds (e.g., cavity users), or taxonomic groups (e.g., amphibians, breeding birds, macroinvertebrates). At the terrestrial landscape level, subsets of diversity could include forest types or seral stages (Noss 1994). Thus, for a specific stream corridor project, measurement of diversity may be limited to a target group of special concern. In this manner, comparison of diversity levels becomes more meaningful.

Spatial Scale

Diversity can be measured within the bounds of a single community, across community boundaries, or in large areas encompassing many communities. Diversity within a relatively homogeneous community is known as alpha diversity. Diversity between communities, described as the amount of differentiation along habitat gradients, is termed beta diversity. The total diversity across very large landscapes is gamma diversity. Noss and Harris (1986) note that management for alpha diversity may increase local species richness, while the regional landscape (gamma diversity) may become more homogeneous and less diverse overall. They recommend a goal of maintaining the regional species pool in an approximately natural relative abundance pattern. The specific size of the area of concern should be defined when diversity objectives are established.

Measures of Diversity

Magurran (1988) describes three main categories of diversity measures—richness indices, abundance models, and indices based on proportional abundance. Richness indices are measures of the number of species (or other element of diversity) in a specific sampling unit and are the most widely used indices (Magurran 1988). Abundance models account for the evenness (equitability) of distribution of species and fit various distributions to known models, such as the geometric series, log series, lognormal, or broken stick. Indices based on the proportional abundance of species combine both richness and evenness into a single index. A variety of such indices exist, the most common of which is the Shannon-Weaver diversity index (Krebs 1978):

$$H = -\Sigma p_i \log_e p_i$$

where

H = index of species diversity

S = number of species

p_i = proportion of total sample belonging to the i^{th} species

Results of most studies using diversity indices are relatively insensitive to the particular index used (Ricklefs 1979). For example, bird species diversity indices from 267 breeding bird censuses were highly correlated (r = 0.97) with simple counts of bird species richness (Tramer 1969). At the species level, a simple measure of richness is most often used in conservation biology studies because the many rare species that characterize most systems are generally of greater interest than the common species that dominate in diversity indices and because accurate population density estimates are often not available (Meffe et al. 1994).

Simple measures of species richness, however, are not sensitive to the actual species composition of an area. Similar richness values in two different areas may represent very different sets of species. The usefulness of these measures can be increased by considering specific subsets of species of most concern, as mentioned above. Magurran (1988) recommends going beyond the use of a single diversity measure and examining the shape of the species abundance distribution as well. Breeding bird census data from an 18-hectare (ha) riparian deciduous forest habitat in Ohio (Tramer 1996) can be used to illustrate these different methods of presentation **(Figure 7.36)**. Breeding bird species richness in this riparian habitat was 38.

Pielou (1993) recommends the use of three indices to adequately assess diversity in terrestrial systems:

- A measure of plant species diversity.
- A measure of habitat diversity.
- A measure of local rarity.

Other indices used to measure various aspects of diversity include vegetation measures, such as foliage height diversity (MacArthur and MacArthur 1961), and landscape measures, such as fractal dimension, fragmentation indices, and juxtaposition (Noss 1994).

Related Integrity Indices

Karr (1981) developed the Index of Biotic Integrity to assess the diversity and health of aquatic communities. This index is designed to assess the present status of the aquatic community using fish community parameters related to species composition, species richness, and ecological factors. Species composition and richness parameters may include the presence of intolerant species, the richness and composition of specific species groups (e.g., darters), or the proportion of specific groups (e.g., hybrid individuals). Ecological parameters may include the proportion of top carnivores, number of individuals, or proportion with disease or other anomalies. Key parameters are developed for the stream system of interest, and each parameter is assigned a rating. The overall rating of a stream is used to evaluate the quality of the aquatic biota.

Rapid Bioassessment

Rapid bioassessment techniques are most appropriate when restoration goals are nonspecific and broad, such as improving the overall aquatic community or establishing a more balanced and diverse community in the stream corridor. Bioassessment often refers to use of biotic indices or composite analyses, such as those used by Ohio EPA (1990), and rapid bioassessment protocols (RBP), such as those documented by Plafkin et al. (1989). Ohio

EPA evaluates biotic integrity by using an invertebrate community index (ICI) that emphasizes structural attributes of invertebrate communities and compares the sample community with a reference or control community. The ICI is based on 10 metrics that describe different taxonomic and pollution tolerance relationships within the macroinvertebrate community. The RBP established by USEPA (Plafkin et al. 1989) were developed to provide states with the technical information necessary for conducting cost-effective biological assessments. The RBP are divided into five sets of protocols (RBP I to V), three for macroinvertebrates and two for fish (**Table 7.8**).

Algae

Although not detailed by Plafkin et al. (1989), algal communities are useful for bioassessment. Algae generally have short life spans and rapid reproduction rates, making them useful for evaluating short-term impacts. Sampling impacts are minimal to resident biota, and collection requires little effort. Primary productivity of algae is affected by physical and chemical impairments. Algal communities are sensitive to some pollutants that might not visibly affect other aquatic communities. Algal communities can be examined for indicator species, diversity indices, taxa richness, community respiration, and colonization rates. A variety of nontaxonomic evaluations, such as biomass and chlorophyll, may be used and are summarized in Weitzel (1979). Rodgers et al. (1979) describe functional measurements of algal communities, such as primary productivity and community respiration, to evaluate the effects of nutrient enrichment.

Although collecting algae in streams requires little effort, identifying for metrics, such as diversity indices and taxa

Species Sequence	Species	Abundance in 18-ha Plot
1	American robin	18.5
2	House wren	13
3	Gray catbird	10.5
4	Song sparrow	9.5
5	Northern cardinal	7.5
6	Baltimore oriole	7
7	Warbling vireo	6
8	Wood thrush	4.5
9	Common grackle	4.5
10	Eastern wood-pewee	4
11	Red-eyed vireo	4
12	Indigo bunting	4
13	Red-winged blackbird	4
14	Mourning dove	3
15	Northern flicker	3
16	Blue jay	3
17	Tufted titmouse	3
18	White-breasted nuthatch	3
19	American redstart	3
20	Rose-breasted grosbeak	3
21	Downy woodpecker	2
22	Great crested flycatcher	2
23	Black-capped chickadee	2
24	Carolina wren	2
25	European starling	2
26	Yellow warbler	2
27	Brown-headed cowbird	2
28	American goldfinch	2
29	Wood duck	1
30	Ruby-throated hummingbird	1
31	Red-bellied woodpecker	1
32	Hairy woodpecker	1
33	Tree swallow	1
34	Blue-gray gnatcatcher	1
35	Prothonotary warbler	1
36	Common yellowthroat	1
37	Eastern phoebe	1
38	N. rough-winged swallow	1

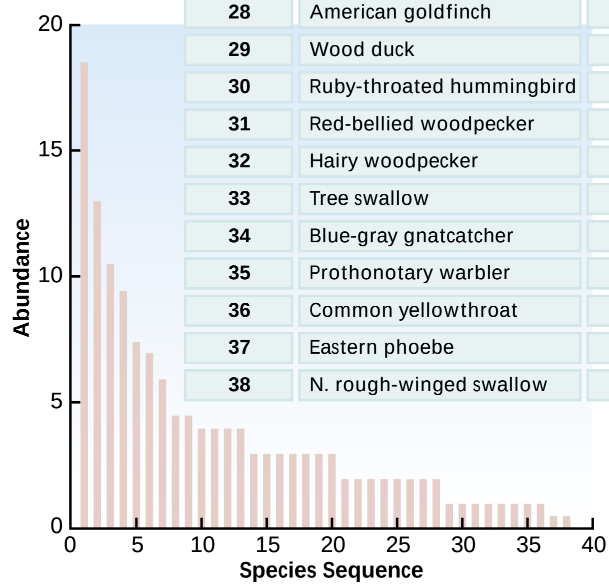


Figure 7.36: Breeding bird census data. *Species abundance curve in a riparian deciduous forest habitat.*
Source: Tramer 1996.

Table 7.8: Five tiers of the rapid bioassessment protocols. *RBPs are used to conduct cost-effective biological assessments.*
Source: Plafkin et al. 1989.

Level or Tier	Organism Group	Relative Level of Effort	Level of Taxonomy/ Where Performed	Level of Expertise Required
I	Benthic invertebrates	Low; 1-2 hr per site (no standardized sampling)	Order, family/field	One highly-trained biologist
II	Benthic invertebrates	Intermediate; 1.5-2.5 hr per site (all taxonomy performed in field)	Family/field	One highly-trained biologist and one technician
III	Benthic invertebrates	Most rigorous; 3-5 hr per site (2-3 hr of total are for lab taxonomy)	Genus or species/laboratory	One highly-trained biologist and one technician
IV	Fish	Low; 1-3 hr per site (no fieldwork involved)	Not applicable	One highly-trained biologist
V	Fish	Most rigorous; 2-7 hr per site (1-2 hr per site are for data analysis)	Species/field	One highly-trained biologist and 1-2 technicians

richness, may require considerable effort. A great deal of effort may be expended to document diurnal and seasonal variations in productivity.

Benthic Macroinvertebrates

The intent of the benthic rapid bioassessment is to evaluate overall biological condition, optimizing the use of the benthic community's capacity to reflect integrated environmental effects over time. Using benthic macroinvertebrates is advantageous for the following reasons:

- They are good indicators of localized conditions.
- They integrate the effects of short-term environmental variables.
- Degraded conditions are easily detected.
- Sampling is relatively easy.
- They provide food for many fish of commercial or recreational importance.
- Macroinvertebrates are generally abundant.
- Many states already have background data.

As indicated above, the RBP are divided into three sets of protocols (RBP I to III) for macroinvertebrates. RBP I is a "screening" or reconnaissance-level analysis used to discriminate obviously impaired and nonimpaired sites from potentially affected areas requiring further investigation. RBP II and III use a set of metrics based on taxon tolerance and community structure similar to the ICI used by the state of Ohio. Both are more labor-intensive than RBP I and incorporate field sampling. RBP II uses family-level taxonomy to determine the following set of metrics used in describing the biotic integrity of a stream:

- Taxa richness.
- Hilsenhoff biotic index (Hilsenhoff 1988).
- Ratio of scrapers to filtering collectors.
- Ratio of Ephemeroptera/Plecoptera/Trichoptera (EPT) and chironomid abundances.
- Percent contribution of dominant taxa.
- EPT index.
- Community similarity index.
- Ratio of shredders to total number of individuals.

RBP III further defines the level of biotic impairment and is essentially an intensified version of RBP II that uses species-level taxonomy. As with ICI, the RBP metrics for a site are compared to metrics from a control or reference site.

Fish

Hocutt (1981) states "perhaps the most compelling ecological factor is that structurally and functionally diverse fish communities both directly and indirectly provide evidence of water quality in that they incorporate all the local environmental perturbations into the stability of the communities themselves."

The advantages of using fish as bioindicators are as follows:

- They are good indicators of long-term effects and broad habitat conditions.
- Fish communities represent a variety of trophic levels.
- Fish are at the top of the aquatic food chain and are consumed by humans.
- Fish are relatively easy to collect and identify.
- Water quality standards are often characterized in terms of fisheries.
- Nearly one-third of the endangered vertebrate species and subspecies in the United States are fish.

The disadvantages of using fish as bioindicators are as follows:

- The cost.
- Statistical validity may be hard to attain.
- It is difficult to interpret findings.

Electrofishing is the most commonly used field technique. Each collecting station should be representative of the study reach and similar to other reaches sampled; effort between reaches should be equal. All fish species, not just game species, should be collected for the fish community assessment (**Figure 7.37**). Karr et al. (1986) used 12 biological metrics to assess biotic integrity using taxonomic and trophic composition and condition and abundance of fish. Although the Index of Biological Integrity (IBI) developed by Karr was designed for small midwestern streams, it has been modified for many regions of the country and for use in large rivers (see Plafkin et al. 1989).

Establishing a Standard of Comparison

With stream restoration activities, it is important to select a desired end condition for the proposed management action. A predetermined standard of comparison provides a benchmark against which to measure progress. For example, if the chosen diversity measure is native species richness, the standard of comparison might be the maximum expected native species richness for a defined geographic area and time period.

Figure 7.37: Fish samples. *Water quality standards are often characterized in terms of fisheries.*

Historical conditions in the region should be considered when establishing a standard of comparison. If current conditions in a stream corridor are degraded, it may be best to establish the standard at a period in the past that represented more natural or desired conditions. Knopf (1986) notes that for certain western streams, historical diversity might have been less than current due to changes in hydrology and encroachment of native and exotic riparian vegetation in the floodplain. Thus, it is important to agree on what conditions are desired prior to establishing the standard of comparison. In addition, the geographic location and size of the area should be considered. Patterns of diversity vary with geographic location, and larger areas are typically more diverse than smaller areas.

The IBI is scaled to a standard of comparison determined through either professional judgment or empirical data, and such indices have been developed for a variety of streams (Leonard and Orth 1986, Bramblett and Fausch 1991, Lyons et al. 1996).

Evaluating the Chosen Index

For a hypothetical stream restoration initiative, the following biological diversity objective might be developed. Assume that a primary concern in the area is conserving native amphibian species and that 30 native species of amphibians have been known to occur historically in the 386 m^2 watershed. The objective could be to manage the stream corridor to provide and maintain suitable habitat for the 30 native amphibian species.

Stream corridor restoration efforts must be directed toward those factors that can be managed to increase diversity to the desired level. Those factors might be the physical and structural features of the stream corridor or possibly the presence of an invasive species in the community. Knowledge of the important factors can be obtained from existing literature and from discussions with local and regional experts.

Diversity can be measured directly or predicted from other information. Direct measurement requires an actual inventory of the element of diversity, such as counting the amphibian species in the study area. The IBI requires sampling fish populations to determine the number and composition of fish species. Measures of the richness of a particular animal group require counts. Determining the number of species in a community is best accomplished with a long-term effort because there can be much variation over short periods. Variation can arise from observer differences, sampling design, or temporal variation in the presence of species.

Direct measures of diversity are most helpful when baseline information is available for comparing different sites. It is not possible, however, to directly measure certain attributes, such as species richness or the population level of various species, for various future conditions. For example, the IBI cannot be directly computed for a predicted stream corridor condition, following management action.

Predictions of diversity for various future conditions, such as with restoration or management, require the use of a predictive model. Assume the diversity objective for a stream corridor restoration effort is to maximize native amphibian species richness. Based on knowledge of the life history of the species, including requirements for habitat, water quality, or landscape configuration, a plan can be developed to restore a stream corridor to meet these needs. The plan could include a set of criteria or a model to describe the specific features that should be included to maximize amphibian richness. Examples of indirect methods to assess diversity include habitat models (Schroeder and Allen 1992, Adamus 1993) and cumulative impact assessment methods (Gosselink et al. 1990, Brooks et al. 1991).

Predicting diversity with a model is generally more rapid than directly measuring diversity. In addition, predictive methods provide a means to analyze alternative future conditions before implementing specific restoration plans. The reliability and accuracy of diversity models should be established before their use.

Classification Systems

Classification is an important component of many of the scientific disciplines relevant to stream corridors—hydrology, geomorphology, limnology, plant and animal ecology. **Table 7.9** lists some of the classification systems that might be useful in identifying and planning riverine restoration activities. It is not the intent of this section to exhaustively review all classification schemes or to present a single recommended classification system. Rather, we focus on some of the principal distinctions among classification systems and factors to consider in the use of classification systems for restoration planning, particularly in the use of a classification system as a measure of biological condition. It is likely that multiple systems will be useful in most actual riverine restoration programs.

The common goal of classification systems is to organize variation. Important dimensions in which riverine classification systems differ include the following:

- *Geographic domain*. The range of sites being classified varies from rivers of the world to local differences in the composition and characteristics of patches within one reach of a single river.
- *Variables considered*. Some classifications are restricted to abiotic vari-

Table 7.9: Selected riverine and riparian classification systems. *Classification systems are useful in characterizing biological conditions.*

Classification System	Subject	Geographic Domain	Citation
Riparian vegetation of Yampa, San Miguel/Dolores River Basins	Plant communities	Colorado	Kittel and Lederer (1993)
Riparian and scrubland communities of Arizona and New Mexico	Plant communities	Arizona and New Mexico	Szaro (1989)
Classification of Montana riparian and wetland sites	Plant communities	Montana	Hansen et al. (1995)
Integrated riparian evaluation guide	Hydrology, geomorphology, soils, vegetation	Intermountain	U.S. Forest Service (1992)
Streamflow cluster analysis	Hydrology with correlations to fish and invertebrates	National	Pott and Ward (1989)
River Continuum	Hydrology, stream order, water chemistry, aquatic communities	International, national	Vannote et al. (1980)
World-wide stream classification	Hydrology, water chemistry, substrate, vegetation	International	Pennak (1971)
Rosgen's river classification	Hydrology, geomorphology: stream and valley types	National	Rosgen (1996)
Hydrogeomorphic wetland classification	Hydrology, geomorphology, vegetation	National	Brinson (1993)
Recovery classes following channelization	Hydrology, geomorphology, vegetation	Tennessee	Hupp (1992)

ables of hydrology, geomorphology, and aquatic chemistry. Other community classifications are restricted to biotic variables of species composition and abundance of a limited number of taxa. Many classifications include both abiotic and biotic variables. Even purely abiotic classification systems are relevant to biological evaluations because of the important correlations (e.g., the whole concept of physical habitat) between abiotic structure and community composition.

- *Incorporation of temporal relations.* Some classifications focus on describing correlations and similarities across sites at one, perhaps idealized, point in time. Other classifications identify explicit temporal transitions among classes, for example, succession of biotic communities or evolution of geomorphic landforms.
- *Focus on structural variation or functional behavior.* Some classifications emphasize a parsimonious description of observed variation in the classification variables. Others use classification variables to identify types with different behaviors. For example, a vegetation classification can be based primarily on patterns of species co-occurrence, or it can be based on similarities in functional effect of vegetation on habitat value.
- *The extent to which management alternatives or human actions are explicitly considered as classification variables.* To the extent that these variables are part of the classification itself, the classification system can directly predict the result of a management action. For example, a vegetation classification based on grazing intensity would predict a change from one class of vegetation to another class based on a change in grazing management.

Use of Classification Systems in Restoring Biological Conditions

Restoration efforts may apply several national and regional classification systems to the riverine site or sites of interest because these are efficient ways to summarize basic site description and inventory information and they can facilitate the transference of existing information from other similar systems.

Most classification systems are generally weak at identifying causal mechanisms. To varying degrees, classification systems identify variables that efficiently describe existing conditions. Rarely do they provide unequivocal assurance about how variables actually cause the observed conditions. Planning efficient and effective restoration actions generally requires a much more mechanistic analysis of how changes in controllable variables will cause changes toward desired values of response variables. A second limitation is that application of a classification system does not substitute for goal setting or design. Comparison of the degraded system to an actual unimpacted reference site, to the ideal type in a classification system, or to a range of similar systems can provide a framework for articulating the desired state of the degraded system. However, the desired state of the system is a management objective that ultimately comes from outside the classification of system variability.

Analyses of Species Requirements

Analyses of species requirements involve explicit statements of how variables interact to determine habitat or how well a system provides for the life requisites of fish and wildlife species. Complete specification of relations between all relevant variables and all species in a stream corridor system is not possible. Thus, analyses based on species requirements focus on one or more target species or groups of species. In a simple case, this type of analysis may be based on an explicit statement of the physical factors that distinguish good habitat for a species (places where it is most likely to be found or where it best reproduces) from poor habitat (places where it is unlikely to be found or reproduces poorly). In more complicated cases, such approaches incorporate variables beyond those of purely physical habitat, including other species that provide food or biotic structure, other species as competitors or predators, or spatial or temporal patterns of resource availability.

Analyses based on species requirements differ from synthetic measures of system condition in that they explicitly incorporate relations between "causal" variables and desired biological attributes. Such analyses can be used directly to decide what restoration actions will achieve a desired result and to evaluate the likely consequences of a proposed restoration action. For example, an analysis using the habitat evaluation procedures might identify mast production (the accumulation of nuts from a productive fruiting season which serves as a food source for animals) as a factor limiting squirrel populations. If squirrels are a species of concern, at least some parts of the stream restoration effort should be directed toward increasing mast production. In practice, this logical power is often compromised by incomplete knowledge of the species habitat requirements.

The complexity of these methods varies along a number of important dimensions, including prediction of habitat suitability versus population numbers, analysis for a single place and single time versus a temporal sequence of spatially complex requirements, and analysis for a single target species versus a set of target species involving tradeoffs. Each of these dimensions must be carefully considered in selecting an analysis procedure appropriate to the problem at hand.

The Habitat Evaluation Procedures (HEP)

Habitat evaluation procedures (HEP) can be used for several different types of habitat studies, including impact assessment, mitigation, and habitat management. HEP provides information for two general types of habitat comparisons—the relative value of different areas at the same point in time and the relative value of the same area at different points in time. Potential changes in wildlife (both aquatic and terrestrial) habitat due to proposed projects are characterized by combining these two types of comparisons.

Basic Concepts

HEP is based on two fundamental ecological principles—habitat has a definable carrying capacity, or suitability, to support or produce wildlife populations (Fretwell and Lucas 1970), and the suitability of habitat for a given wildlife species can be estimated using measurements of vegetative, physical, and chemical traits of the habitat. The suitability of a habitat for a given species is described by a habitat suitability index (HSI) constrained between 0 (unsuitable habitat) and 1 (optimum habitat). HSI models have been developed and published by the U.S. Fish and Wildlife Service (Schamberger et al. 1982; Terrell and Carpenter, in press), and USFWS (1981) provides guidelines for use in developing HSI models for specific projects. HSI models can be developed for many of the previously described metrics, including species, guilds, and communities (Schroeder and Haire 1993).

The fundamental unit of measure in HEP is the Habitat Unit, computed as follows:

$$HU = AREA \times HSI$$

where HU is the number of habitat units (units of area), AREA is the areal extent of the habitat being described (units of area), and HSI is the index of suitability of the habitat (unitless). Conceptually, an HU integrates the quantity and quality of habitat into a single measure, and one HU is equivalent to one unit of optimal habitat.

Use of HEP to Assess Habitat Changes

HEP provides an assessment of the net change in the number of HUs attributable to a proposed future action, such as a stream restoration initiative. A HEP application is essentially a two-step process—calculating future HUs for a particular project alternative and calculating the net change as compared to a base condition.

The steps involved in using and applying HEP to a management project are outlined in detail in USFWS (1980a). However, some early planning decisions often are given little attention although they may be the most important part of a HEP study. These initial decisions include forming a study team, defining the study boundaries, setting study objectives, and selecting the evaluation species. The study team usually consists of individuals representing different agencies and viewpoints. One member of the team is generally from the lead project planning agency and other members are from resources agencies with an interest in the resources that would be affected.

One of the first tasks for the team is to delineate the study area boundaries. The study area boundaries should be drawn to include any areas of direct impact, such as a flood basin for a new reservoir, and any areas of secondary impact, such as a downstream river reach that might have an altered flow, increased turbidity, or warmer temperature, or riparian or upland areas subject to land use changes as a result of an increased demand on recreational lands. Areas such as an upstream spawning ground that are not contiguous to the primary impact site also might be affected and therefore should be included in the study area.

The team also must establish project objectives, an often neglected aspect of project planning. Objectives should state what is to be accomplished in the project and specify an endpoint to the project. An integral aspect of objective setting is selecting evaluation species, the specific wildlife resources of concern for which HUs will be computed in the HEP analysis. These are often individual species, but they do not have to be. Depending on project objectives, species' life stages (e.g., juvenile salmon), species' life requisites (e.g., spawning habitat), guilds (e.g., cavity-nesting birds), or communities (e.g., avian richness in riparian forests) can be used.

Instream Flow Incremental Methodology

The Instream Flow Incremental Methodology (IFIM) is an adaptive system composed of a library of models that are linked to describe the spatial and temporal habitat features of a given river. IFIM is described in Chapter 5 under *Supporting Analysis for Selecting Restoration Alternatives*.

Physical Habitat Simulation

The Physical Habitat Simulation (PHABSIM) model was designed by the U.S. Fish and Wildlife Service primarily for instream flow analysis (Bovee 1982). It represents the habitat evaluation component of a larger instream flow incremental methodology for incorporating fish habitat consideration into flow management, presented in Chapter 5. PHABSIM is a collection of computer programs that allows evaluation of available habitat within a study reach for various life stages of different fish species. The two basic components of the model are hydraulic simulation (based on field-measured cross-sectional data) and several standard hydraulic methods for predicting water surface elevations and velocities at unmeasured discharges (e.g., stage vs. discharge relations, Manning's equation, step-backwater computations). Habitat simulation integrates species and life-stage-specific habitat suitability curves for water depth, velocity, and substrate with the hydraulic data. Output is a plot of weighted usable area (WUA) against discharge for the species and life stages of interest. (**Figure 7.38**)

The stream hydraulic component predicts depths and water velocities at unobserved flows at specific locations on a cross section of a stream. Field measurements of depth, velocity, substrate material, and cover at specific sampling points on a cross section are taken at different observable flows. Hydraulic measurements, such as water surface elevations, also are collected during the field inventory. These data are used to calibrate the hydraulic simulation models. The models then are used to predict depths and velocities at flows different from those measured.

The habitat component weights each stream cell using indices that assign a relative value between 0 and 1 for each habitat attribute (depth, velocity, substrate material, cover), indicating how suitable that attribute is for the life stage under consideration. These attribute indices are usually termed habitat suitability indices and are developed from direct observations of the attributes used most often by a life stage, from expert opinion about what the life requisites are, or a combination. Various approaches are taken to factor assorted biases out of these suitability data, but they remain indices that are used as weights of suitability. In the last step of the habitat component, hydraulic estimates of depth and velocity at different flow levels are combined with the suitability values for those attributes to weight the area of each cell at the simulated flows. The weighted values for all cells are summed to produce the WUA.

There are many variations on the basic approach outlined above, with specific analyses tailored for different water management phenomena (such as hydropeaking and unique spawning habitat needs), or for special habitat needs (such as bottom velocity instead of mean column velocity) (Milhous et al. 1989). However, the fundamentals of hydraulic and habitat modeling remain the same, resulting in a WUA versus discharge function. This function should be combined with the appropriate hydrologic time series (water availability) to develop an idea of what life states might be affected by a loss or gain of available habitat and at what time of the year. Time series analysis plays this role and also factors in any physical and institutional constraints on water management so that alternatives can be evaluated (Milhous et al. 1990).

Several things must be remembered about PHABSIM. First, it provides an index to microhabitat availability; it is not a measure of the habitat actually used by aquatic organisms. It can be used only if the species under consideration exhibit documented preferences for depth, velocity, substrate material, cover, or other predictable microhabitat attributes in a specific environment of

REVERSE

Review Chapter 5's Supporting Analysis for Selecting Restoration Alternatives

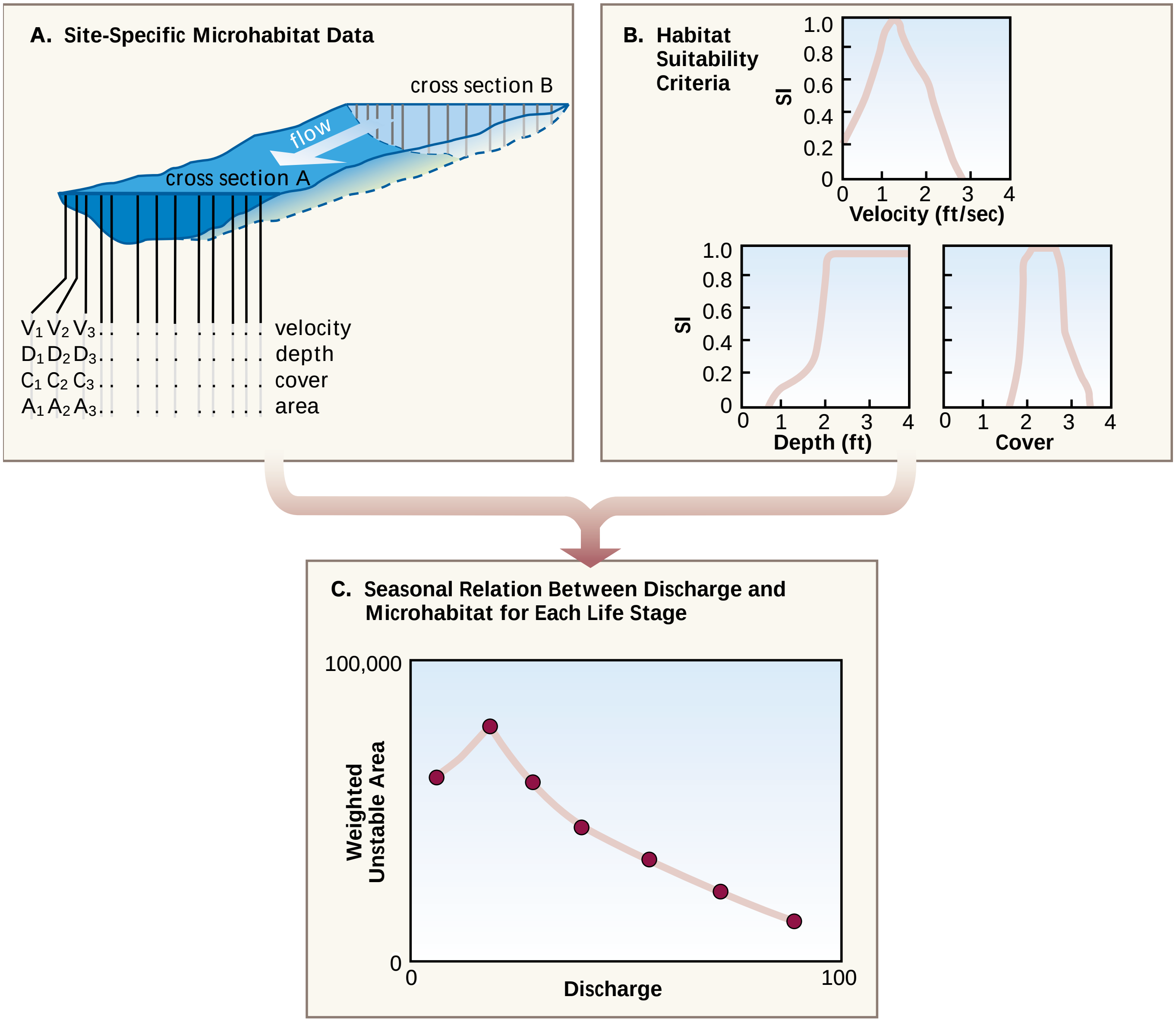


Figure 7.38: Conceptualization of how PHABSIM calculates habitat values as a function of discharge. *A. First, depth (Di), velocity (Vi), cover conditions (Ci), and area (Ai) are measured or simulated for a given discharge. B. Suitability index (SI) criteria are used to weight the area of each cell for the discharge. The habitat values for all cells in the study reach are summed to obtain a single habitat value for the discharge. C. The procedure is repeated for a range of discharges.*
Modified from Nestler et al. 1989.

competition and predation. The typical application of PHABSIM assumes relatively steady flow conditions such that depths and velocities are comparably stable within the chosen time step. PHABSIM does not predict the effects of flow on channel change. Finally, the field data and computer analysis requirements can be relatively large.

Two-dimensional Flow Modeling

Concern about the simplicity of the one-dimensional hydraulic models used in PHABSIM has led to current research interest in the use of more sophisticated two-dimensional hydraulic models to simulate physical conditions of depth and velocity for use in fish habitat analysis. A two-dimensional hydraulic model can be spatially adjusted to represent the scale of aquatic habitat and the variability of other field data. For example, the physical relationship between different aquatic habitat types is often a key parameter when considering fish habitat use. The spatial nature of two-dimensional flow modeling allows for the analysis of these relationships. The model can also consider the drying and wetting of intermittent stream channels.

Leclerc et al. (1995) used two-dimensional flow modeling to study the effect of a water diversion on the habitat of juvenile Atlantic salmon (*Salmo salar*) in the Moisie River in Quebec, Canada. Average model error was reduced when compared with traditional one-dimensional models. Output from the two-dimensional modeling was combined with habitat suitability indexes with finite element calculation techniques. Output from the analysis included maps displaying the spatial distribution of depth, velocity, and habitat suitability intervals.

Physical data collection for this modeling tool is intensive. Channel contour and bed material mapping is required along with discharge relationships and the upstream and downstream boundaries of each study reach. Velocity and water-surface measurements for various discharges are required for model calibration. Two-dimensional modeling does not address all of the issues related to hydrodynamics and flow modeling. Mobile bed systems and variability in Manning's coefficient are still problematic using this tool (Leclerc et al. 1995). Moderate to large rivers with a stable bedform are most suited to this methodology.

Riverine Community Habitat Assessment and Restoration Concept Model (RCHARC)

Another modeling approach to aquatic habitat restoration is the Riverine Community Habitat Assessment and Restoration (RCHARC) concept. This model is based on the assumption that aquatic habitat in a restored stream reach will best mimic natural conditions if the bivariate frequency distribution of depth and velocity in the subject channel is similar to a reference reach with good aquatic habitat. Study site and reference site data can be measured or calculated using a computer model. The similarity of the proposed design and reference reach is expressed with three-dimensional graphs and statistics (Nestler et al. 1993, Abt 1995). RCHARC has been used as the primary tool for environmental analysis on studies of flow management for the Missouri River and the Alabama-Coosa-Tallapoosa Apalachicola-Chattahoochee-Flint Basin.

Time Series Simulations

A relatively small number of applications have been made of time series simulations of fish population or individual fish responses to riverine habitat changes. Most of these have used PHABSIM to accomplish hydraulic model development and validation and hydraulic simulation, but some have substituted time-series simulations of individual or population responses for habitat suitability curve development and validation, and habitat suitability modeling. PHABSIM quantifies the relationship of hydraulic estimates (depth and velocity) and measurements (substrate and cover) with habitat suitability for target fish and invertebrate life stages or water-related recreation suitability. It is useful when relatively steady flow is the major determinant controlling riverine resources. Use of PHABSIM is generally limited to river systems in which dissolved oxygen, suspended sediment, nutrient loading, other chemical aspects of water quality, and interspecific competition do not place the major limits on populations of interest. These limitations to the use of PHABSIM can be abated or removed with models that simulate response of individual fish or fish populations.

Individual-based Models

The Electric Power Research Institute (EPRI) program on compensatory mechanisms in fish populations (CompMech) has the objective of improving predictions of fish population response to increased mortality, loss of habitat, and release of toxicants (EPRI 1996). This technique has been applied by utilities and resource management agencies in assessments involving direct mortality due to entrainment, impingement, or fishing; instream flow; habitat alteration (e.g., thermal discharge, water-level fluctuations, water diversions, exotic species); and ecotoxicity. Compensation is defined as the capacity of a population to self-mitigate decreased growth, reproduction, or survival of some individuals in the population by increased growth, reproduction, or survival of the remaining individuals. The CompMech approach over the past decade has been to represent in simulation models the processes underlying daily growth, reproduction, and survival of individual fish (hence the classification of individual-based models) and then to aggregate over individuals to the population level.

The models can be used to make short-term predictions of survival, growth, habitat utilization, and consumption for critical life stages. For the longer term, the models can be used to project population abundance through time to assess the risk that abundance will fall below some threshold requiring mitigation. For stream situations, several CompMech models have been developed that couple the hydraulic simulation method of PHABSIM directly with an individual-based model of reproduction and young-of-year dynamics, thereby eliminating reliance on the habitat-based component of PHABSIM (Jager et al. 1993). The CompMech model of smallmouth bass is being used to evaluate the effects of alternative flow regimes on nest success, growth, mortality, and ultimately year class strength in a Virginia stream to identify instream flows that protect fisheries with minimum impact on hydropower production.

A model of coexisting populations of rainbow and brown trout in California is being used to evaluate alternative instream flow and temperature scenarios (Van Winkle et al. 1996). Model predictions will be compared with long-term field observations before and after experimental flow increases; numerous scientific papers are expected from this intensive study.

An individual-based model of smolt production by Chinook salmon, as part of an environmental impact statement for the Tuolumne River in California, considered the minimum stream flows necessary to ensure continuation and maintenance of the anadromous fishery (FERC 1996). That model, the Oak Ridge Chinook salmon model (ORCM), predicts annual production of salmon smolts under specified reservoir minimum releases by evaluating critical factors, including influences on upstream migration of adults, spawning and incubation of eggs, rearing of young, and predation and mortality losses during the downstream migration of smolts. Other physical habitat analyses were used to supplement the population model in evaluating benefits of alternative flow patterns. These habitat evaluations are based on data from an instream flow study; a stream temperature model was used to estimate flows needed to maintain downstream temperatures within acceptable limits for salmon.

SALMOD

The conceptual and mathematical models for the Salmonid Population Model (SALMOD) were developed for Chinook salmon in concert with a 12-year flow evaluation study in the Trinity River of California using experts on the local river system and fish species in workshop settings (Williamson et al. 1993, Bartholow et al. 1993). SALMOD was used to simulate young-of-year production, assuming that the flow schedules to be evaluated were released from Lewiston Reservoir in every year from 1976 to 1992 (regardless of observed reservoir inflow, storage, and release limitations).

The structure of SALMOD is a middle ground between a highly aggregated classical population model that tracks cohorts/size groups for a generally large area without spatial resolution, and an individual-based model that tracks individuals at a great level of detail for a generally small area. The conceptual model states that fish growth, movement, and mortality are directly related to physical hydraulic habitat and water temperature, which in turn relate to the timing and amount of regulated streamflow. Habitat capacity is characterized by the hydraulic and thermal properties of individual mesohabitats, which are the model's spatial computational units.

Model processes include spawning (with redd superimposition), growth (including maturation), movement (freshet-induced, habitat-induced, and seasonal), and mortality (base, movement-related, and temperature-related). The model is limited to freshwater habitat for the first 9 months of life; estuarine and ocean habitats are not included. Habitat area is computed from flow/habitat area functions developed empirically. Habitat capacity for each life stage is a fixed maximum number per unit of habitat available. Thus, a maximum number of individuals for each computational unit is calculated for each time step based on streamflow and habitat type. Rearing habitat capacity is derived from empirical relations between available habitat area and number of individual fish observed.

Partly due to drought conditions, most of the flow alternatives to be evaluated did not actually occur during the flow evaluation study. When there is insufficient opportunity to directly observe and evaluate impacts of flow alternatives on fish populations, SALMOD can be used to simulate young-of-the-year production that may result from proposed flow schedules to be released or regulated by a control structure such as a reservoir or diversion.

Other physical habitat analyses can be used to supplement population models in evaluating benefits of alternative flow patterns. In the Trinity River Flow Study, a stream temperature model was used to estimate flows needed to maintain downstream temperatures within acceptable limits for salmon. Both the ORCM (FERC 1996) and SALMOD models concentrated on development, growth, movement, and mortality of young-of-year Chinook salmon but with different mechanistic inputs, spatial resolution, and temporal precision.

Vegetation-Hydroperiod Modeling

In most cases, the dominant factor that makes the riparian zone distinct from the surrounding uplands, and the most important gradient in structuring variation within the riparian zone, is site moisture conditions, or hydroperiod (**Figure 7.39**). Hydroperiod is defined as the depth, duration, and frequency of inundation and is a powerful determinant of what plants are likely to be found in various positions in the riparian zone. Formalizing this relation as a vegetation-hydroperiod model can provide a powerful tool for analyzing existing distributions of riparian vegetation, casting forward or backward in time to alternative distributions, and designing new distributions. The suitability of site conditions for various species of plants can be described with the same conceptual approach used to model habitat suitability for animals. The basic logic of a vegetation-hydroperiod model is straightforward. How wet a site is has a lot to do with what plants typically grow on the site. It is possible to measure how wet a site is and, more importantly, to predict how wet a site will be based on the relation of the site to a stream. From this, it is possible to estimate what vegetation is likely to occur on the site.

FAST FORWARD

Preview Chapter 8's information on vegetation-hydroperiod model.

Components of a Vegetation-hydroperiod Model

The two basic elements of the vegetation-hydroperiod relation are the physical conditions of site moisture at various locations and the suitability of those sites for various plant species. In the simplest case of describing existing patterns, site moisture and vegetation can be directly measured at a number of locations. However, to use the vegetation-hydroperiod model to predict or design new situations, it is necessary to predict new site moisture conditions. The most useful vegetation-hydroperiod models have the following three components:

- *Characterization of the hydrology or pattern of streamflow.* This can take the form of a specific sequence of flows, a summary of how often different flows occur, such as a flow duration or flood frequency curve, or a representative flow value, such as bankfull discharge or mean annual discharge.
- *A relation between streamflow and moisture conditions at sites in the riparian zone.* This relation can be measured as the water surface elevation at a variety of discharges and summarized as a stage vs. discharge curve. It can also be calculated by a number of hydraulic models that relate water surface elevations to discharge, taking into account variables of channel geometry and roughness or resistance to flow. In some cases, differences in simple elevation above the channel bottom may serve as a reasonable approximation of differences in inundating discharge.
- *A relation between site moisture conditions and the actual or potential vegetation distribution.* This relation expresses the suitability of a site for a plant species or cover type based on the moisture conditions at the site. It can be determined by sampling the distribution of vegetation at a variety of sites with known moisture conditions and then deriving probability distributions of the likelihood of finding a plant on a site given the moisture conditions at the site. General relations are also available from the literature for many species.

The nature and complexity of these components can vary substantially and still provide a useful model. However, the components must all be expressed in consistent units and must have a domain of application that is appropriate to the questions being asked of the model (i.e., the model must be capable of changing the things that need to be changed to answer the question). In many cases, it may be possible to formulate a vegetation-hydroperiod model using representations of stream hydrology and hydraulics that have been developed for other analyses such as channel stability, fish habitat suitability, or sediment dynamics.

Identifying Non-equilibrium Conditions

In altered or degraded stream systems, current moisture conditions in the riparian zone may be dramatically unsuitable for the current, historical, or desired riparian vegetation. Several conditions can be relatively easily identified by comparing the distribution of vegetation to the distribution of vegetation suitabilities.

- The hydrology of the stream has been altered; for example, if streamflow has diminished by diversion or flood attenuation, sites in the riparian zone may be drier and no longer suitable for the historic vegetation or for current long-lived vegetation that was established under a previous hydrologic regime.
- The inundating discharges of plots in the riparian zone have been altered so that streamflow no longer has the same relation to site moisture conditions; for example, levees, channel modifications, and bank treatments may have either increased or decreased the discharge required to inundate plots in the riparian zone.
- The vegetation of the riparian zone has been directly altered, for example, by clearing or planting so that the vegetation on plots no longer corresponds to the natural vegetation for which the plots are suitable.

Figure 7.39: Vegetation/water relationship. *Soil moisture conditions often determine the plant communities in riparian areas.* Source: C. Zabawa.

In many degraded stream systems all of these things have happened. Understanding how the moisture conditions of plots correspond to the vegetation in the current system, as well as how they will correspond in the restored system, is an important element of formulating reasonable restoration objectives and designing a restoration plan.

Vegetation Effects of System Alterations

In a vegetation-hydroperiod model, vegetation suitability is determined by streamflow and the inundating discharges of plots in the riparian zone. The model can be used to predict effects of alteration in streamflow or the relations of streamflow to plot moisture conditions on the suitability of the riparian zone for different types of vegetation. Thus, the effects of flow alterations and changes in channel or bottomland topography proposed as part of a stream restoration plan can be examined in terms of changes in the suitability of various locations in the riparian zone for different plant species.

Flooding Tolerances of Various Plant Species

There is a large body of information on the flooding tolerances of various plant species. Summaries of this literature include Whitlow and Harris (1979) and the multivolume Impact of Water Level Changes on Woody Riparian and Wetland Communities (Teskey and Hinckley 1978, Walters et al. 1978, Lee and Hinckley 1982, Chapman et al. 1982). This type of information can be coupled to site moisture conditions predicted by applying discharge estimates or flood frequency analyses to the inundating discharges of sites in the riparian zone. The resulting relation can be used to describe the suitability of sites for various plant species, e.g., relatively flood-prone sites will likely have relatively flood-tolerant plants. Inundating discharge is strongly related to relative elevation within the floodplain. Other things being equal (i.e., within a limited geographic area and with roughly equivalent hydrologic regimes), elevation relative to a representative water surface line, such as bankfull discharge or the stage at mean annual flow, can thus provide a reasonable surrogate for site moisture conditions. Locally determined vegetation suitability can then be used to determine the likely vegetation in various elevation zones.

Extreme Events and Disturbance Requirements

Temporal variability is a particularly important characteristic of many stream ecosystems. Regular seasonal differences in biological requirements are examples of temporal variability that are often incorporated into biological analyses based on habitat suitability and time series simulations. The need for episodic extreme events is easy to ignore because these are so widely perceived as destructive both of biota and of constructed river features. In reality, however, these extreme events seem to be essential to physical channel maintenance and to the long-term suitability of the riverine ecosystem for disturbance-dependent species. Cottonwood in western riparian systems is one well-understood case of a disturbance-dependent species. Cottonwood regeneration from seed is generally restricted to bare, moist sites. Creating these sites depends heavily on channel movement (meandering, narrowing, avulsion) or new flood deposits at high elevations. In some western riparian systems, channel movement and deposition tend to occur infrequently in association with floods. The same events are also responsible for destroying stands of trees. Thus maintaining good conditions for existing stands, or fixing the location of a stream's banks with structural measures, tends to reduce the regeneration potential and the long-term importance of this disturbance-dependent species in the system as a whole.

Zonation of Vegetation

There are a number of statistical procedures for estimating the frequency and magnitude of extreme events (see flood frequency analysis section of chapter 8) and describing various aspects of hydrologic variation. Changing these flow characteristics will likely change some aspect of the distribution and abundance of organisms. Analyzing more specific biological changes generally requires defining the requirements of target species; defining requirements of their food sources, competitors, and predators; and considering how those requirements are influenced by episodic disturbance events.

8 Restoration Design

8.A Valley Form, Connectivity, and Dimension

- *How do you incorporate all the spatial dimensions of the landscape into stream corridor restoration design?*
- *What criteria can be applied to facilitate good design decisions for stream corridor restoration?*

8.B Soil Properties

- *How do soil properties impact the design of restoration activities?*
- *What are the major functions of soils in the stream corridor?*
- *How are important soil characteristics, such as soil microfauna and soil salinity, accounted for in the design process?*

8.C Vegetative Communities

- *What is the role of vegetative communities in stream corridor restoration?*
- *What functions do vegetative communities fulfill in a stream corridor?*
- *What are some considerations in designing plant community restoration to ensure that all landscape functions are addressed?*
- *What is soil bioengineering and what is its role in stream corridor restoration?*

8.D Riparian / Terrestrial Habitat Recovery

- *What are some specific tools and techniques that can be used to ensure recovery of riparian and terrestrial habitat recovery?*

8.E Stream Channel Restoration

- *When is stream channel reconstruction an appropriate restoration option?*
- *How do you delineate the stream reach to be reconstructed?*
- *How is a stream channel designed and reconstructed?*
- *What are important factors to consider in the design of channel reconstruction (e.g., alignment and average slope, channel dimensions)?*
- *Are there computer models that can assist with the design of channel reconstruction?*

8.F Streambank Restoration Design

- *When should streambank stabilization be included in a restoration?*
- *How do you determine the performance criteria for streambank treatment, including the methods and materials to be used?*
- *What are some streambank stabilization techniques that can be considered for use?*

8.G In-Stream Habitat Recovery

- *What are the principal factors controlling the quality of instream habitat?*
- *How do you determine if an instream habitat structure is needed, and what type of structure is most appropriate?*
- *What procedures can be used to restore instream habitat?*
- *What are some examples of instream habitat structures?*
- *What are some important questions to address before designing, selecting or installing an instream habitat structure?*

8.H Land Use Scenarios

- *What role does land use play in stream corridor degradation and restoration?*
- *What design approaches can be used to address the impacts of various land uses (e.g., dams, agriculture, forestry, grazing, mining, recreation, urbanization)?*
- *What are some disturbances that are often associated with specific land uses?*
- *What restoration measures can be used to mitigate the impacts of various land uses?*
- *What are the potential effects of the restoration measures?*

8 Restoration Design

Design can be defined as the intentional shaping of matter, energy, and process to meet an expressed need. Planning and design connect natural processes and cultural needs through exchanges of materials, flows of energy, and choices of land use and management. One test of a successful stream corridor design is how well the restored system sustains itself over time while accommodating identified needs.

*To achieve success, those carrying out restoration design and implementation in variable-land-use settings must understand the stream corridor, watershed, and landscape as a complex of working ecosystems that influence and are influenced by neighboring ecosystems (**Figure 8.1**). The probability of achieving long-term, self-sustaining functions across this spatial complex increases with*

Figure 8.1: Stream running through a wet meadow. *Restoration design must consider site-specific conditions as an integral part of larger systems.*

"Leave It Alone / Let It Heal Itself"

There is a renewed emphasis on recovering damaged rivers (Barinaga 1996). Along with this concern, however, people should be reminded periodically that they serve as stewards of watersheds, not just tinkerers with stream sites. Streams in pristine condition, for example, should not be artificially "improved" by active rehabilitation methods.

At the other end of the spectrum, and particularly where degradation is caused by off-stream activities, the best solution to a river management problem might be to remove the problem source and "let it heal itself." Unfortunately, in severely degraded streams this process can take a long time. Therefore the "leave it alone" concept can be the most difficult approach for people to accept (Gordon et al. 1992).

an understanding of these relationships, a common language for expressing them, and subsequent response. Designing to achieve stream- or corridor-specific solutions might not resolve problems or recognize opportunities in the landscape.

Stream corridor restoration design is still largely in an experimental stage. It is known however, that restoration design must consider site-specific or local conditions to be successful. That is, the design criteria, standards, and specifications should be for the specific project in a specific physical, climatic, and geographic location. These initiatives, however, can and should work with, rather than against, the larger systems of which they are an integral part.

This approach produces multiple benefits, including:

- A healthy, sustainable pattern of land uses across the landscape.
- Improved natural resource quality and quantity.
- Restored and protected stream corridors and associated ecosystems.
- A diversity of native plants and animals.
- A gene pool that promotes hardiness, disease resistance, and adaptability.
- A sense of stewardship for private landowners and the public.
- Improved management measures that avoid narrowly focused and fragmented land treatment.

Building on information presented in Parts I and II, this chapter contains design guidance and techniques to address changes caused by major disturbances and to restore stream corridor structure and function to a desired level. It begins with larger-scale influences that design may have on stream corridor ecosystems, offers design guidance primarily at the stream corridor and stream scales, and concludes with land use scenarios.

The chapter is divided into seven sections.

Section 8.A: Valley Form, Connectivity, and Dimension

This section focuses on restoring structural characteristics that prevail at the stream corridor and landscape scales.

Section 8.B: Soil Properties

The restoration of soil properties that are critical to stream corridor structure and functions are addressed in this section.

Section 8.C: Plant Communities

Restoring vegetative communities is a highly visible and integral component of a functioning stream corridor.

Section 8.D: Habitat Measures

This section presents design guidance for some habitat measures. They are often integral parts of stream corridor structure and functions.

Section 8.E: Stream Channel Restoration

Restoring stream channel structure and functions is often a fundamental step in restoring stream corridors.

Section 8.F: Streambank Restoration

This section focuses on design guidelines and related techniques for streambank stabilization. These measures can help reduce surface runoff and sediment transport to the stream.

Section 8.G: Instream Habitat Recovery

Restoring instream habitat structure and functions is often a key component of stream corridor restoration.

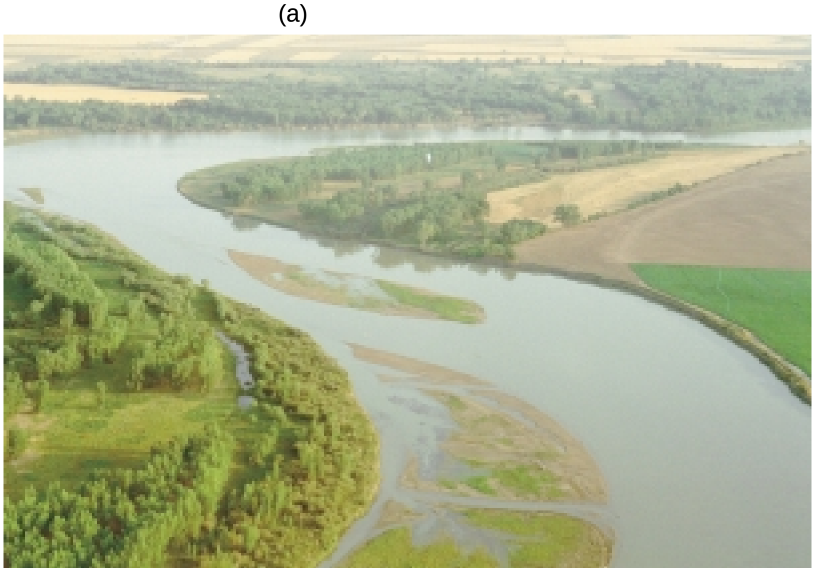
Section 8.H: Land Use Scenarios

This final section offers broad design concepts in the context of major land use scenarios.

8.A Valley Form, Connectivity, and Dimension

Valley form, connectivity, and dimension are variable structural characteristics that determine the interrelationship of functions at multiple scales. Valley intersections (nodes) with tributary stream corridors, slope of valley sides, and floodplain gradient are characteristics of valley form that influence many functions (**Figure 8.2**).

(a)



(b)

Figure 8.2: Stream corridors. *(a) Stream valley side slopes and (b) floodplain gradients influence stream corridor function.*

The broad concept of connectivity, as opposed to fragmentation, involves linkages of habitats, species, communities, and ecological processes across multiple scales (Noss 1991). Dimension encompasses width, linearity, and edge effect, which are critical for movement of species, materials, and energy within the stream corridor and to or from ecosystems in the surrounding landscape. Design should therefore address these large-scale characteristics and their effect on functions.

Valley Form

In some cases, entire stream valleys have changed to the point of obscuring geomorphic boundaries, making stream corridor restoration difficult. Volcanoes, earthquakes, and landslides are examples of natural disturbances that cause changes in valley form. Encroachment and filling of floodplains are among the human-induced disturbances that modify valley shape.

Stream Corridor Connectivity and Dimension

Connectivity and dimensions of the stream corridor present a set of design-related decisions to be made. How wide should the corridor be? How long should the corridor be? What if there are gaps in the corridor? These structural characteristics have a significant impact on corridor functions. The width, length, and connectivity of existing or potential stream corridor vegetation, for example, are critical to habitat functions within the corridor and adjacent ecosystems.

Generally, the widest and most contiguous stream corridor which achieves habitat, conduit, filter, and other functions (see Chapter 2) should be an ecologically derived goal of restoration. Thresholds for each function are likely found at different corridor widths. The appropriate width varies according to soil type, with steep slopes requiring a wider corridor for filter functions. A conservative indicator of effective corridor width is whether a stream corridor can significantly prevent chemical contaminants contained in runoff from reaching the stream (Forman 1995).

As discussed in Chapter 1, the corridor should extend across the stream, its banks, the floodplain, and the valley slopes. It should also include a portion of upland for the entire stream length to maintain functional integrity (Forman and Godron 1986).

A contiguous, wide stream corridor might not be achievable, however, particularly where competing land uses prevail. In these cases, a ladder pattern of natural habitat crossing the floodplain and connecting the upland segments might facilitate sediment trapping during floods and provide hydraulic storage and organic matter for the stream system (Dramstad et al. 1996).

Figure 8.3 presents an example of these connections. The open areas within the ladder pattern are representative of areas that are unavailable for restoration because of competing land uses.

Innovative management practices that serve the functions of the corridor beyond land ownership boundaries can often be prescribed where land owners are supportive of restoration. Altering land cover, reducing chemical inputs, carefully timed mowing, and other management practices can reduce disturbance in the corridor.

Practical considerations may restrict restoration to a zone of predefined width adjacent to the stream. Although often unavoidable, such restrictions tend to result in underrepresentation of older, off-channel environments that support vegetation different from that in stream-front communities. Restricting restoration to a narrow part of the stream corridor usually does not restore the full horizontal diversity of broad floodplains, nor does it fully accommodate functions that occur during flood events, such as use of the floodplain by aquatic species (Wharton et al. 1982).

In floodplains where extensive subsurface hydrologic connections exist, limiting restoration to streamside buffer zones is not recommended since significant amounts of energy, nutrient transformation, and invertebrate activities can occur at great distances from the stream channel outside the buffer areas (Sedell et al. 1990). Similarly, failure to anticipate channel migration or periodic beaver activity might result in a corridor that does not accommodate

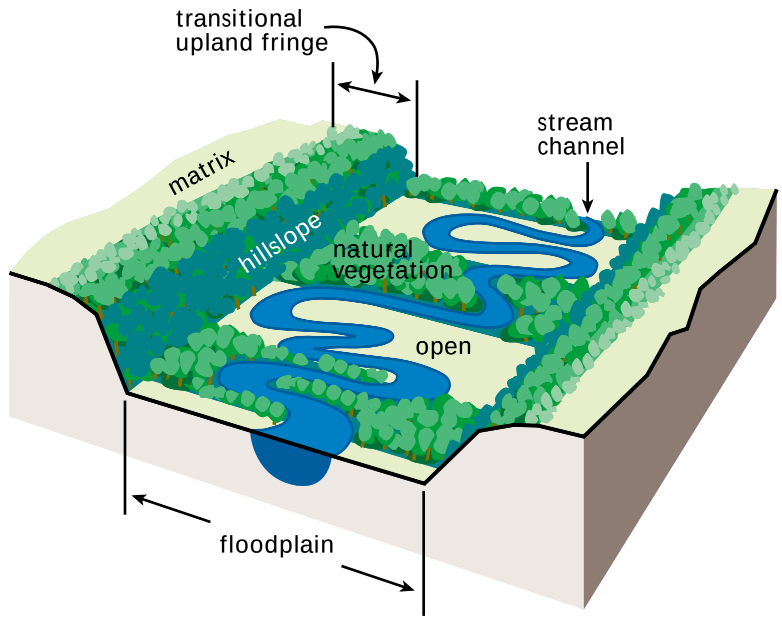


Figure 8.3: Connections across a stream corridor. *A ladder pattern of natural habitat can restore structure and functions where competing land uses prevail.*

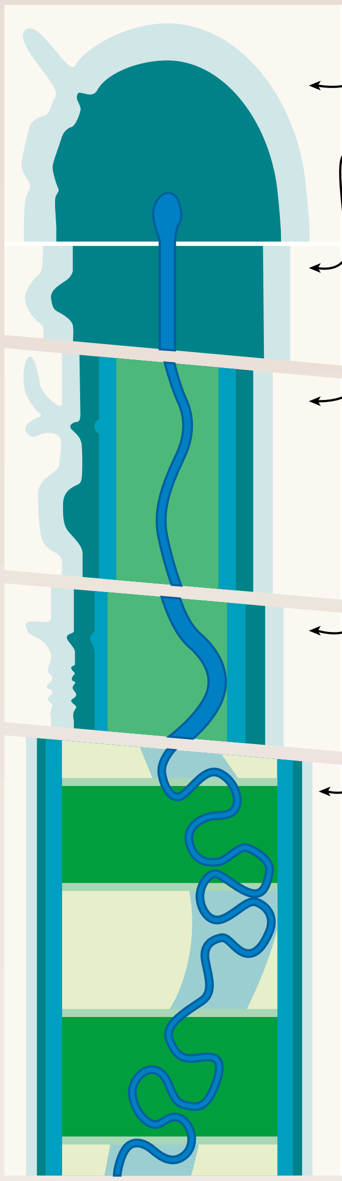
Adapted from Ecology of Greenways: Design and Function of Linear Conservation Areas. Edited by Smith and Hellmund. © University of Minnesota Press 1993.

Corridor Width Variables

*The minimum width of stream corridors based on ecological criteria (**Figure 8.4**). Five basic situations in a river system are identified, progressing from seepage to river. The key variables determining minimum corridor width are listed under each.*

***Figure 8.4: Factors for determining minimum corridor widths.** Stream corridor functions are directly influenced by corridor width.*

Source: Forman 1995. Reprinted with permission of Cambridge University Press.



Seepage

1. Sponge effect for hydrologic flows, mimimizing downstream flooding
2. Control of dissolved-substance inputs from matrix

1st Order Stream

1. Same as for seepage

2nd to 4th Order Stream with Closed Canopy

1. Conduit for upland interior species; both sides of stream so species readily crossing floodplain have alternate routes
2. Control of dissolved-substance inputs from matrix
3. Conduit for streambank and floodplain species, where beaver activities maintain water across the floodplain and alter hillslope vegetation
4. Minimize hillslope erosion
5. Sponge effect for hydrologic flows, minimizing downstream flooding
6. Friction effect, minimizing downstream sedimentation
7. Protect high habitat diversity and species richness of floodplain

2nd to 4th Order Stream with Open Canopy

1. Same as for 2nd to ca. 4th order stream, closed canopy
2. Provide interior habitat for species conduit, as migrating open stream intersects hillslopes causing them to be open habitat

5th to 10th Order River

1. Conduit for upland interior species, on both sides of river so species that rarely can cross the floodplain have a route on each side
2. Provide interior habitat for species conduit, as migrating open river intersects hillslopes causing them to be open habitat
3. Minimize hillslope erosion
4. Shade and logs provide fish habitat where river is adjacent to hillslope
5. Source of soil organic matter, an important base of the river food chain
6. Shade and logs provide fish habitat wherever river is as it migrates across the floodplain
7. Genetic benefit to upland species that can use habitat continuity to infrequently cross floodplain
8. Sponge effect for hydrologic flows, minimizing downstream flooding
9. Friction effect minimizing downstream sedimentation
10. Protect high habitat diversity and species richness of floodplain
11. Conduit for semiaquatic and other organisms dependent on river channel resources

- matrix
- edge portion of corridor in upland
- interior portion of corridor in upland
- hillslope
- floodplain
- meander band
- interior of patch of natural floodplain vegetation
- edge of patch of natural floodplain vegetation
- other ecologically-compatible land use

fundamental dynamic processes (Malanson 1993).

As previously discussed, restoration of an ecologically effective stream corridor requires consideration of uplands adjacent to the channel and floodplain. Hillslopes might be a source area for water maintaining floodplain wetlands, a sediment source for channels on bedrock, and the principal source of organic debris in high-gradient streams.

Despite these considerations, stream corridors are often wrongly viewed as consisting of only the channel and an adjacent vegetative buffer. The width of the buffer is determined by specific objectives such as control of agricultural runoff or habitat requirements of particular animal species. This narrow definition obviously does not fully accommodate the extent of the functions of a stream corridor; but where the corridor is limited by immovable resource uses, it often becomes a part of a restoration strategy.

Cognitive Approach: The Reference Stream Corridor

Ideal stream corridor widths, as previously defined, are not always achievable in the restoration design. A local reference stream corridor might provide dimensions for designing the restoration.

Examination of landscape patterns is beneficial in identifying a reference stream corridor. The reference should provide information about gap width, landform, species requirements, vegetative structure, and boundary characteristics of the stream corridor (**Figure 8.5**).

Restoration objectives determine the desired levels of functions specified by the restoration design. If a nearby stream corridor in a similar landscape setting and with similar land use variables provides these functions adequately, it can be used to indicate the connectivity and width attributes that should be part of the design.

Figure 8.5: A maple in a New Mexico floodplain. *A rare occurrence of a remnant population may reflect desired conditions in a reference stream corridor.*

Analytical Approach: Functional Requirements of a Target Species

The restoration plan objectives can be used to determine dimensions for the stream corridor restoration. If, for example, a particular species requires that the corridor offer interior habitat, the corridor width is sized to provide the necessary habitat. The requirements of the most sensitive species typically are used for optimum corridor dimensions. When these dimensions extend beyond the land base available for restoration, management of adjacent land uses becomes a tool for making the corridor effectively wider than the project parameters.

Optimum corridor dimensions can be achieved through collaboration with individuals and organizations who have management authority over adjacent lands. Dimensions include width of edge effect associated with boundaries of the corridor and pattern variations within the corridor, maximum acceptable width of gaps within the corridor, and maximum number of gaps per unit length of corridor.

Designing for Drainage and Topography

The stream corridor is dependent on interactions with the stream to sustain its character and functions (see Chapter 2). Therefore, to the extent feasible, the restoration process should include blockage of artificial drainage systems, removal or setback of artificial levees, and restoration of natural patterns of floodplain topography, unless these actions conflict with other social or environmental objectives (e.g., flooding or habitat).

Restoration of microrelief is particularly important where natural flooding has been reduced or curtailed because a topographically complex floodplain supports a mosaic of plant communities and ecosystem functions as a result of differential ponding of rainfall and interception of ground water. Microrelief restoration can be accomplished by selective excavation of historic features within the floodplain such as natural wetlands, levees, oxbows, and abandoned channels. Aerial photography and remotely sensed data, as well as observations in reference corridors, provide an indication of the distribution and dimensions of typical floodplain microrelief features.

8.B Soil Properties

Stream corridor functions depend not only on the connectivity and dimensions of the stream corridor, but also on its soils and associated vegetation. The variable nature of soils across and along stream corridors results in diverse plant communities (**Figure 8.6**). When designing stream corridor restoration measures, it is important to carefully analyze the soils and their related potentials and limitations to support diverse native plant and animal communities, as well as for restoration involving channel reconstruction.

Figure 8.6: Distinct vegetation zones along a mountain stream. *Variable soils result in diverse plant communities.*

Where native floodplain soils remain in place, county soil surveys should be used to determine basic site conditions and fertility and to verify that the proposed plant species to be restored are appropriate. Most sites with fine-textured alluvium will not require supplemental fertilization, or fertilizers might be required only for initial establishment. In these cases excessive fertilization could encourage competing weed species or exotics. Soil should always be tested before making any fertilizer design recommendations.

County soil surveys can provide basic information such as engineering limitations or suitabilities. Site-specific soil samples should, however, be collected and tested when the restoration involves alternatives that include stream reconstruction.

The connections and feedback loops between runoff and the structure and functions of streams are described in Chapter 2. The functions of soil and the connection between soil quality, runoff, and water quality are also established in that chapter. These connections need to be identified and considered in any stream corridor restoration plan and design. For all land uses, emphasis needs to be placed on implementing conservation land treatment that promotes soil quality and the ability of the soils to carry out four major functions:

- Regulating and partitioning the flow of water (a conduit and filter function).
- Storing and cycling nutrients and other chemicals (a sink and filter function).
- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials (a filter, sink, and barrier function).
- Supporting biological activity in the landscape (a source and habitat function).

References such as *Field Office Technical Guide* (USDA-NRCS) contain guidance on the planning and selection of conservation practices and are available at most county offices.

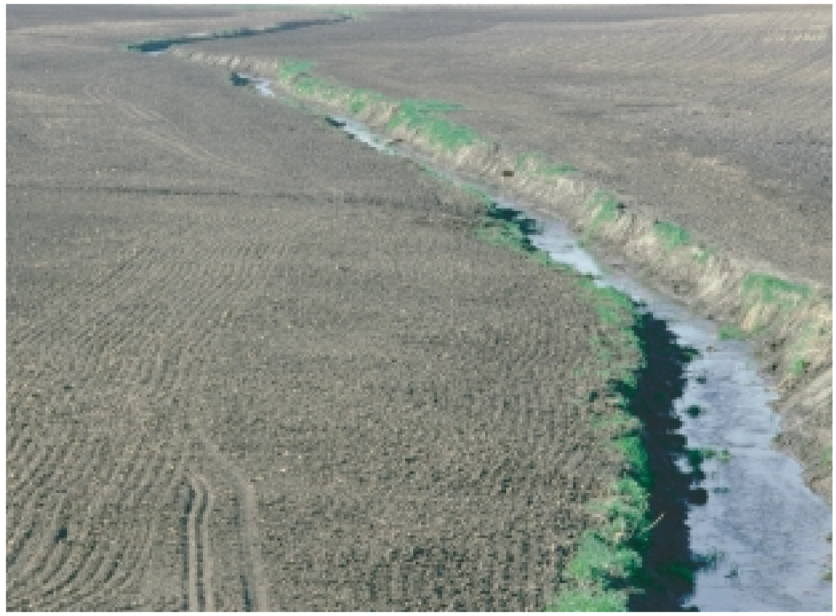


Figure 8.7: Compaction of streamside soil. *Compact soils may require deep plowing, ripping, or vegetative practices to break up the impermeable layer.*

Compaction

Soils that have been in row crops or have undergone heavy equipment traffic (such as that associated with construction) can develop a relatively impermeable compacted layer (plow pan or hard pan) that restricts water movement and root penetration (**Figure 8.7**). Such soils might require deep plowing, ripping, or vegetative practices to break up the pan, although even these are sometimes ineffective. Deep plowing is usually expensive and, at least in the East, should be used only if the planting of a species that is able to penetrate the pan layer is not a viable option.

Soil Microfauna

On new or disturbed substrates, or on row-cropped sites, essential soil microorganisms (particularly mycorrhizal fungi) might not exist. These are most effectively replaced by using rooted plant material that is inoculated or naturally infected with appropriate fungi. Stockpiling and reincorporating local topsoils into the substrate prior to planting is also effective (Allen 1995). Particular care should be taken to avoid disturbing large trees or stumps since the soils around and under them are likely source areas for reestablishment of a wide variety of microorganisms. Inoculation can be useful in restoring some soil mycorrhizal fungi for particular species when naturally infected plant stock is unavailable.

Soil Salinity

Soil salinity is another important consideration in restoration because salt accumulation in the soil can restrict plant growth and the establishment of riparian species. High soil salinity is not common in healthy riparian ecosystems where annual spring floods remove excess salts. Soil salinity can also be altered by leaching salts through the soil profile with irrigation (Anderson et al. 1984). Because of agricultural drainage and altered flows due to dam construction, salt accumulation often contributes to riparian plant community declines.

Soil sampling throughout a restoration site may be necessary since salinity can vary across a floodplain, even on sites of less than 20 acres. If salinity is a problem, one must select plant materials adapted to a saline soil environment.

8.C Plant Communities

Vegetation is a fundamental controlling factor in stream corridor function. Habitat, conduit, filter/barrier, source, and sink functions are all critically tied to the vegetative biomass amount, quality, and condition (**Figure 8.8**). Restoration designs should protect existing native vegetation and restore vegetative structure to result in a contiguous and connected stream corridor.

Restoration goals can be general (e.g., returning an area to a reference condition) or specific (e.g., restoring habitats for particular species of interest such as the least Bell's vireo, Vireo *bellii* [Baird and Rieger 1988], or yellow-billed cuckoo, *Coccyzus americana* [Anderson and Laymon 1988]).

Numerous shrubs and trees have been evaluated as restoration candidates, including willows (Svejcar et al. 1992, Hoag 1992, Conroy and Svejcar 1991, Anderson et al. 1978); alder, serviceberry, oceanspray, and vine maple (Flessner et al. 1992); cottonwood and poplar (Hoag 1992); Sitka and thinleaf alder (Java and Everett 1992); palo verde and honey mesquite (Anderson et al. 1978); and many others. Selection of vegetative species may be based on the desire to provide habitat for a particular species of interest. The current trend in restoration, however, is to apply a multispecies or ecosystem approach.

Figure 8.8: Stream corridor vegetation. *Vegetation is a fundamental controlling factor in the functioning of stream corridors.*

Riparian Buffer Strips

Managers of riparian systems have long recognized the importance of buffer strips, for the following reasons (USACE 1991):

- Provide shade that reduces water temperature.
- Cause deposition of (i.e., filter) sediments and other contaminants.
- Reduce nutrient loads of streams.
- Stabilize streambanks with vegetation.
- Reduce erosion caused by uncontrolled runoff.
- Provide riparian wildlife habitat.
- Protect fish habitat.
- Maintain aquatic food webs.
- Provide a visually appealing greenbelt.
- Provide recreational opportunities.

Although the value of buffer strips is well recognized, criteria for their sizing are variable. In urban stream corridors a wide forest buffer is an essential component of any protection strategy. Its primary value is to provide physical protection for the stream channel from future disturbance or encroachment. A network of buffers acts as the right-of-way for a stream and functions as an integral part of the stream ecosystem.

Often economic and legal considerations have taken precedence over ecological factors. For Vermont, USACE (1991) suggests that narrow strips (100 ft. wide) may be adequate to provide many of the functions listed above. For breeding bird populations on Iowa streams, Stauffer and Best (1980) found that minimum strip widths varied from 40 ft. for cardinals to 700 ft. for scarlet tanagers, American redstarts, and rufous-sided towhees.

In urban settings buffer sizing criteria may be based on existing site controls as well as economic, legal, and ecological factors. Practical performance criteria for sizing and managing urban buffers are presented in the box Designing Urban Stream Buffers. Clearly, no single recommendation would be suitable for all cases.

Because floodplain/riparian habitats are often small in area when compared to surrounding uplands, meeting the minimum area needs of a species, guild, or community is especially important. Minimum area is the amount of habitat required to support the expected or appropriate use and can vary greatly across species and seasons. For example, Skagen (USGS, Biological Resources Division, Ft. Collins, Colorado; unpubl. data) found that, contrary to what might be considered conventional wisdom, extensive stream corridors in southeastern Arizona were not more important to migrating birds than isolated patches or oases of habitat. In fact, oases that were <2.5 miles long and <30 ft. in width had more species and higher numbers of nonbreeding migrants than did corridors. Skagen found that the use of oases, as well as corridors, is consistent with the observed patterns of long distance migrants, where migration occurs along broad fronts rather than north-south corridors. Because small and/or isolated patches of habitat can be so important to migrants, riparian restoration efforts should not overlook the important opportunities they afford.

Existing Vegetation

Existing native vegetation should be retained to the extent feasible, as should woody debris and stumps (**Figure 8.9**). In addition to providing habitat and erosion and sediment control, these features provide seed sources and harbor a

Designing Urban Stream Buffers

The ability of an urban stream buffer to realize its many benefits depends to a large degree on how well it is planned, designed, and maintained. Ten practical performance criteria are offered to govern how a buffer is to be sized, managed, and crossed. The key criteria include:

Criteria 1: Minimum total buffer width.

Most local buffer criteria require that development be set back a fixed and uniform distance from the stream channel. Nationally, urban stream buffers range from 20 to 200 ft. in width from each side of the stream according to a survey of 36 local buffer programs, with a median of 100 ft. (Schueler 1995). In general, a minimum base width of at least 100 feet is recommended to provide adequate stream protection.

Criteria 2: Three-zone buffer system.

*Effective urban stream buffers have three lateral zones—stream side, middle core, and outer zone. Each zone performs a different function, and has a different width, vegetative target and management scheme. The **stream side zone** protects the physical and ecological integrity of the stream ecosystem. The vegetative target is mature riparian forest that can provide shade, leaf litter, woody debris, and erosion protection to the stream. The **middle zone** extends from the outward boundary of the stream side zone, and varies in width, depending on stream order, the extent of the 100-yr floodplain, adjacent steep slopes, and protected wetland areas. Its key functions are to provide further distance between upland development and the stream. The vegetative target for this zone is also mature forest, but some clearing may be allowed for storm water management, access, and recreational uses.*

*The **outer zone** is the buffer's "buffer," an additional 25-ft. setback from the outward edge of the middle zone to the nearest permanent structure. In most instances, it is a residential backyard. The vegetative target for the outer zone is usually turf or lawn, although the property owner is encouraged to plant trees and shrubs, and thus increase the total width of the buffer. Very few uses are restricted in this zone. Indeed, gardening, compost piles, yard wastes, and other common residential activities often will occur in the outer zone.*

Criteria 3: Predevelopment vegetative target.

The ultimate vegetative target for urban stream buffers should be specified as the predevelopment riparian plant community—usually mature forest. Notable exceptions include prairie streams of the Midwest, or arroyos of the arid West, that may have a grass or shrub cover in the riparian zone. In general, the vegetative target should be based on the natural vegetative community present in the floodplain, as determined from reference riparian zones. Turfgrass is allowed for the outer zone of the buffer.

Criteria 4: Buffer expansion and contraction.

Many communities require that the minimum width of the buffer be expanded under certain conditions. Specifically, the average width of the middle zone can be expanded to include:

- *the full extent of the 100-yr floodplain;*
- *all undevelopable steep slopes (greater than 25%);*
- *steep slopes (5 to 25% slope, at four additional ft. of slope per one percent increment of slope above 5%); or*
- *any adjacent delineated wetlands or critical habitats.*

Criteria 5: Buffer delineation.

Three key decisions must be made when delineating the boundaries of a buffer. At what mapping scale will streams be defined? Where does the stream begin and the buffer end? And from what *point should the inner edge of the buffer be measured? Clear and workable delineation criteria should be developed.*

Criteria 6: Buffer crossings.

Major objectives for stream buffers are to maintain an unbroken corridor of riparian forest and to allow for upstream and downstream fish passage in the stream network. From a practical standpoint, however, it is not always possible to try to meet these goals everywhere along the stream buffer network. Some provision must be made for linear forms of development that must cross the stream or the buffer, such as roads, bridges, fairways, underground utilities, enclosed storm drains or outfall channels.

Criteria 7: Storm water runoff.

Buffers can be an important component of the storm water treatment system at a development site. They cannot, however, treat all the storm water runoff generated within a watershed (generally, a buffer system can only treat runoff from less than 10% of the contributing watershed to the stream). Therefore, some kind of structural BMP must be installed to treat the quantity and quality of storm water runoff from the remaining 90% of the watershed.

Criteria 8: Buffers during plan review and construction.

The limits and uses of the stream buffer systems should be well defined during each stage of the development process—from initial plan review, through construction.

Criteria 9: Buffer education and enforcement.

The future integrity of a buffer system requires a strong education and enforcement program. Thus, it is important to make the buffer "visible" to the community, and to encourage greater buffer awareness and stewardship among adjacent residents. Several simple steps can be taken to accomplish this.

- *Mark the buffer boundaries with permanent signs that describe allowable uses*
- *Educate buffer owners about the benefits and uses of the buffer with pamphlets, stream walks, and meetings with homeowners associations*
- *Ensure that new owners are fully informed about buffer limits/uses when property is sold or transferred*
- *Engage residents in a buffer stewardship program that includes reforestation and backyard "bufferscaping" programs*
- *Conduct annual buffer walks to check on encroachment*

Criteria 10: Buffer flexibility.

In most regions of the country, a hundred-foot buffer will take about 5% of the total land area in any given watershed out of use or production. While this constitutes a relatively modest land reserve at the watershed scale, it can be a significant hardship for a landowner whose property is adjacent to a stream. Many communities are legitimately concerned that stream buffer requirements could represent an uncompensated "taking" of private property. These concerns can be eliminated if a community incorporates several simple measures to ensure fairness and flexibility when administering its buffer program. As a general rule, the intent of the buffer program is to modify the location of development in relation to the stream but not its overall intensity. Some flexible measures in the buffer ordinance include:

- *Maintaining buffers in private ownership*
- *Buffer averaging*
- *Density compensation*
- *Variances*
- *Conservation easements*

Figure 8.9: Remnant vegetation and woody debris along a stream. *Attempts should be made to preserve existing vegetation within the stream corridor.*

variety of microorganisms, as described above. Old fencerows, vegetated stumps and rock piles in fields, and isolated shade trees in pastures should be retained through restoration design, as long as the dominant plant species are native or are unlikely to be competitors in a matrix of native vegetation (e.g., fruit trees).

Nonnative vegetation can prevent establishment of desirable native species or become an unwanted permanent component of stream corridor vegetation. For example, kudzu will kill vegetation. Generally, forest species planted on agricultural land will eventually shade out pasture grasses and weeds, although some initial control (disking, mowing, burning) might be required to ensure tree establishment.

Plant Community Restoration

An objective of stream corridor restoration work might be to restore natural patterns of plant community distribution within the stream corridor. Numerous publications describe general distribution patterns for various geomorphic settings and flow conditions (e.g., Brinson et al. 1981, Wharton et al. 1982), and county soil surveys generally describe native vegetation for particular soils. More detailed and site-specific plant community descriptions may be available from state Natural Heritage programs, chapters of The Nature Conservancy, or other natural resources agencies and organizations.

Examination of the reference stream corridor, however, is often the best way to develop information on plant community composition and distribution. Once reference plant communities are defined, design can begin to detail the measures required to restore those communities (**Figure 8.10**). Rarely is it feasible or desirable to attempt to plant the full complement of appropriate species on a particular site. Rather, the more typical approach is to plant the dominant species or those species unlikely to colonize the site readily. For example, in the complex bottom-

Figure 8.10: A thriving and diverse plant community within a stream corridor. *Examination of reference plant communities is often the best way to develop information on the composition and distribution of plant communities at the restoration site.*

land hardwood forests of the Southeast, the usual focus is on planting oaks. Oaks are heavy-seeded, are often shade-intolerant, and may not be able to readily invade large areas for generations unless they are introduced in the initial planting plan, particularly if flooding has been reduced or curtailed. It is assumed that lighter-seeded and shade-tolerant species will invade the site at rates sufficient to ensure that the resulting forest is adequately diverse. This process can be accelerated by planting corridors of fast-growing species (e.g., cottonwoods) across the restoration area to promote seed dispersal.

In areas typically dominated by cottonwoods and willows, the emphasis might be to emulate natural patterns of colonization by planting groves of particular species rather than mixed stands, and by staggering the planting program over a period of years to ensure structural variation. Where conifers tend to eventually succeed riparian hardwoods, some restoration designs may include scattered conifer plantings among blocks of pioneer species, to accelerate the transition to a conifer-dominated system.

Large-scale restoration work sometimes includes planting of understory species, particularly if they are required to meet specific objectives such as providing essential components of endangered species habitat. However, it is often difficult to establish understory species, which are typically not tolerant to full sun, if the restoration area is open. Where particular understory species are unlikely to establish themselves for many years, they can be introduced in adjacent forested sites, or planted after the initial tree plantings have matured sufficiently to create appropriate understory conditions. This may also be an appropriate approach for introducing certain overstory species that might not survive planting in full sun (**Figure 8.11**).

Figure 8.11: Restoration of understory plant species. *Understory species can be introduced at the restoration site after the initial tree plantings have matured sufficiently.*

The concept of focusing restoration actions on a limited group of overstory species to the exclusion of understory and other overstory species has been criticized. The rationale for favoring species such as oaks has been to ensure that restored riparian and floodplain areas do not become dominated by opportunistic species, and that wildlife functions and timber values associated with certain species will be present as soon as possible. It has been documented that heavy-seeded species such as oaks may be slow to invade a site unless planted (see Tennessee Valley Authority Floodplain Reforestation Projects—50 Years Later), but differential colonization rates probably exclude a variety of other species as well. Certainly, it would be desirable to introduce as wide a variety of appropriate species as possible; however, costs and the difficulties of doing supplemental plantings over a period of years might preclude this approach in most instances.

Low Water Availability

In areas where water levels are low, artificial plantings will not survive if their roots cannot reach the zone of saturation. Low water availability was associated with low survival rates in more than 80 percent of unsuccessful revegetation work examined in Arizona (Briggs 1992). Planting long poles (20 ft.) of Fremont cottonwood (Populus fremontii) and Gooding willow in augered holes has been successful where the ground water is more than 10 ft. below the surface (Swenson and Mullins 1985). In combination with an irrigation system, many planted trees are able to reach ground water 10 ft. below the surface when irrigated for two seasons after planting (Carothers et al. 1990). Sites closest to ground water, such as secondary channels, depressions, and low sites where water collects, are the best candidates for planting, although low-elevation sites are more prone to flooding and flood damage to the plantings. Additionally, the roots of many riparian species may become dormant or begin to die if inundated for extended periods of time (Burrows and Carr 1969).

Plant species should be distributed within a restoration site with close attention to microsite conditions. In addition, if stream meandering behavior or scouring flows have been curtailed, special effort is required to maintain communities that normally depend on such behavior for natural establishment. These may include oxbow and swale communities (bald cypress, shrub wetlands, emergent wetlands), as well as communities characteristic of newly deposited soils (cottonwoods, willows, alders, silver maple, etc.). It is important to recognize that planting vegetation on sites where regeneration mechanisms no longer operate is a temporary measure, and long-term management and periodic replanting is required to maintain those functions of the ecosystem.

In the past, stream corridor planting programs often included nonnative species selected for their rapid growth rates, soil binding characteristics, ability to produce abundant fruits for wildlife, or other perceived advantages over native species. These actions sometimes have unintended consequences and often prove to be extremely detrimental (Olson and Knopf 1986). As a result, many local, county, state, and federal agencies discourage or prohibit planting of nonnative species within wetlands or streamside buffers. Stream corridor restoration designs should emphasize native plant species from local sources. It may be feasible in some cases to focus restoration actions on encouraging the success of local seedfall to ensure that locally adapted populations of stream corridor vegetation are maintained on the site (Friedmann et al. 1995).

Plant establishment techniques vary greatly depending on site conditions and species characteristics. In arid regions, the emphasis has been on using poles or cuttings of species that sprout readily, and planting them to depths that will ensure contact with moist soil during the dry season (**Figure 8.12**). Where water tables have declined precipitously, deep auguring and temporary irrigation are used to establish cuttings and rooted or container-grown plants. In environments where precipitation or ground water is adequate to sustain planted vegetation, prolonged irrigation is less common, and bare-root or container-grown plants are often used, particularly for species that do not sprout reliably from cuttings. On large floodplains of the South and East, direct seeding of acorns and planting of dormant bare-root material have been highly successful. Other options, such as transplanting of salvaged plants, have been tried with varying degrees of success. Local experience should be sought to determine the most reliable and efficient plant establishment approaches for particular areas and species, and to determine what problems to expect.

It is important to protect plantings from livestock, beaver, deer, small mammals, and insects during the establishment period. Mortality of vegetation from deer browsing is common and can be prevented by using tree shelters to protect seedlings.

Figure 8.12: Revegetation with the use of deeply planted live cuttings. *In arid regions, poles or cuttings of species that sprout readily are often planted to depths that assure contact with moist soil.*

Horizontal Diversity

Stream corridor vegetation, as viewed from the air, would appear as a mosaic of diverse plant communities that runs from the upland on one side of the stream corridor, down the valley slope, across the floodplain, and up the opposite slope to the upland. With such broad dimensional range, there is a large potential for variation in vegetation. Some of the variation is a result of hydrology and stream dynamics, which will be discussed later in this chapter. Three important structural characteristics of horizontal diversity of vegetation are connectivity, gaps, and boundaries.

Stream corridor restoration designs should emphasize native plant species from local sources.

Connectivity and Gaps

As discussed earlier, connectivity is an important evaluation parameter of stream corridor functions, facilitating the processes of habitat, conduit, and filter/barrier. Stream corridor restoration design should maximize connections between ecosystem functions. Habitat and conduit functions can be enhanced by linking critical ecosystems to stream corridors through design that emphasizes orientation and proximity. Designers should consider functional connections to existing or potential features such as vacant or abandoned land, rare habitat, wetlands or meadows, diverse or unique vegetative communities, springs, ecologically innovative residential areas, movement corridors for flora and fauna, or associated stream systems. This allows for movement of materials and energy, thus increasing conduit functions and effectively increasing habitat through geographic proximity.

Generally, a long, wide stream corridor with contiguous vegetative cover is favored, though gaps are commonplace. The most fragile ecological functions determine the acceptable number and size of gaps. Wide gaps can be barriers to mi-

Tennessee Valley Authority Floodplain Reforestation Projects—50 Years Later

*The oldest known large-scale restoration of forested wetlands in the United States was undertaken by the Tennessee Valley Authority in conjunction with reservoir construction projects in the South during the 1940s. Roads and railways were relocated outside the influence of maximum pool elevations, but where they were placed on embankments, TVA was concerned that they would be subject to wave erosion during periods of extreme high water. To reduce that possibility, agricultural fields between the reservoir and the embankments were planted with trees (**Figure 8.13**). At Kentucky Reservoir in Kentucky and Tennessee, approximately 1,000 acres were planted, mostly on hydric soils adjacent to tributaries of the Tennessee River. Detailed records were kept regarding the species planted and survival rates. Some of these stands were recently located and studied to evaluate the effectiveness of the original reforestation effort, and to determine the extent to which the planted forests have come to resemble natural stands in the area.*

Because the purpose of the plantings was erosion control, little thought was given to recreating natural patterns of plant community composition and structure. Trees were evenly spaced in rows, and planted species were apparently chosen for maximum flood tolerance. As a result, the studied stands had an initial composition dominated by bald cypress, green ash, red maple, and similarly

Figure 8.13: Kentucky Reservoir watershed, 1943.
Planting abandoned farmland with trees.

Figure 8.14: Kentucky Reservoir watershed in 1991. Thriving bottomland hardwood forest.

water-tolerant species, but they did not originally contain many of the other common bottomland forest species, such as oaks.

Shear et al. (in press) compared the plant communities of the planted stands with forests on similar sites that had been established by natural invasion of abandoned fields. They also looked at older stands that had never been converted to agriculture. The younger planted and natural stands were similar to the older stands with regard to understory composition, and measures of stand density and biomass were consistent with patterns typical for the age of the stands. Overstory composition of the planted stands was very different from that of the others, reflecting the original plantings. However, both the planted sites and the fields that had been naturally invaded had few individuals of heavy-seeded species (oaks and hickories), which made up 37 percent of the basal area of the older stands.

*Oaks are an important component of southern bottomlands and are regarded as particularly important to wildlife. In most modern restoration plantings, oaks are favored on the assumption that they will not quickly invade agricultural fields. The stands at Kentucky Reservoir demonstrate that planted bottomland forests can develop structural and understory conditions that resemble those of natural stands within 50 years (**Figure 8.14**). Stands that were established by natural invasion of agricultural fields had similar characteristics. The major compositional deficiency in both of the younger stands was the lack of heavy-seeded species. The results of this study appear to support the practice of favoring heavy-seeded species in bottomland forest restoration initiatives.*

gration of smaller terrestrial fauna and indigenous plant species. Aquatic fauna may also be limited by the frequency or dimension of gaps. The width and frequency of gaps should therefore be designed in response to planned stream corridor functions. Bridges have been designed to allow migration of animals, along with physical and chemical connections of river and wetland flow. In Florida, for example, underpasses are constructed beneath roadways to serve as conduits for species movement (Smith and Hellmund 1993). The Netherlands has experimented with extensive species overpasses and underpasses to benefit particular species (**Figure 8.15**). Although not typically equal to the magnitude of an undisturbed stream corridor lacking gaps, these measures allow for modest functions as habitat and conduit.

Restored plant communities should be designed to exhibit structural diversity and canopy closure similar to that of the reference stream corridor.

The filtering capacity of stream corridors is affected by connectivity and gaps. For example, nutrient and water discharge flowing overland in sheet flow tends to concentrate and form rills. These rills in turn often form gullies. Gaps in vegetation offer no opportunity to slow overland flow or allow for infiltration. Where reference dimensions are similar and transferable, restored plant communities should be designed to exhibit structural diversity and canopy closure similar to that of the reference stream corridor. The reference stream corridor can provide information regarding plant species and their frequency and distribution. Design should aim to maintain the filtering capacity of the stream corridor by minimizing gaps in the corridor's width and length.

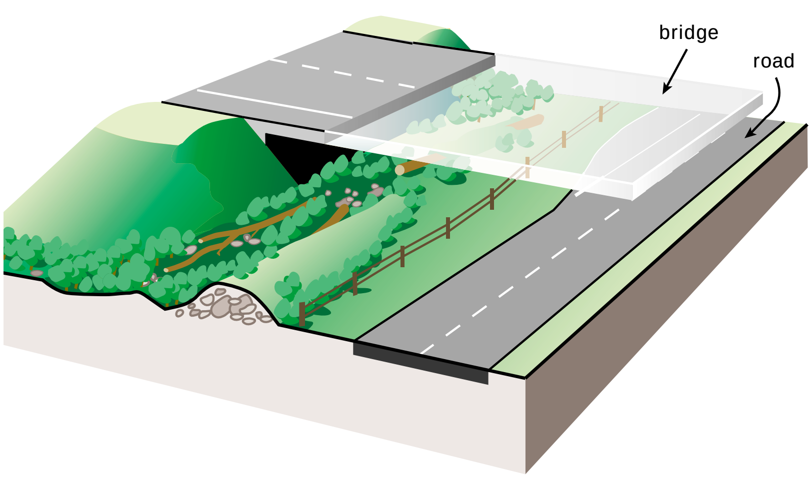


***Figure 8.15*: Underpass design.** *Underpasses should be designed to accommodate both vehicular traffic and movement of small fauna.*

Buffer configuration and composition have also received attention since they influence wildlife habitat quality, including suitability as migration corridors for various species and suitability for nesting habitat. Reestablishment of linkages among elements of the landscape can be critically important for many species (Noss 1983, Harris 1984). However, as noted previously, fundamental considerations include whether a particular vegetation type has ever existed as a contiguous corridor in an area, and whether the predisturbance corridor was narrow or part of an expansive floodplain forest system. Establishment of inappropriate and narrow corridors can have a net detrimental influence at local and regional scales (Knopf et al. 1988). Local wildlife management priorities should be evaluated in developing buffer width criteria that address these issues.

Boundaries

The structure of the edge vegetation between a stream corridor and the adjacent landscape affects the habitat, conduit, and filter functions. A transition between two ecosystems in an undisturbed environment typically occurs across a broad area.

Boundaries between stream corridors and adjacent landscapes may be straight or curvilinear. A straight boundary allows relatively unimpeded movement along the edge, thereby decreasing species interaction between the two ecosystems. Conversely, a curvilinear boundary with lobes of the corridor and adjoining areas reaching into one another encourages movement across boundaries, resulting in increased interaction. The shape of the boundary can be designed to integrate or discourage these interactions, thus affecting the habitat, conduit, and filter functions.

Species interaction may or may not be desirable depending on the project goals. The boundary of the restoration initiative can, for example, be designed to capture seeds or to integrate animals, including those carrying seeds. In some cases, however, this interaction is dictated by the functional requirements of the adjacent ecosystem (equipment tolerances within an agricultural field, for instance).

Vertical Diversity

Heterogeneity within the stream corridor is an important design consideration. The plants that make up the stream corridor, their form (herbs, shrubs, small trees, large trees), and their diversity affect function, especially at the reach and site scales. Stratification of vegetation affects wind, shading, avian diversity, and plant growth (Forman 1995). Typically, vegetation at the edge of the stream corridor is very different from the vegetation that occurs within the interior of the corridor. The topography, aspect, soil, and hydrology of the corridor provide several naturally diverse layers and types of vegetation.

The difference between edge and interior vegetative structure are important design considerations (**Figure 8.16**). An edge that gradually changes from the stream corridor into the adjacent ecosystems will soften environmental gradients and minimize any associated disturbances. These transitional zones encourage species diversity and buffer variable nutrient and energy flows. Although human intervention has made edges more abrupt, the conditions of naturally occurring edge vegetation can be restored through design. The plant community and landform of a restored edge should reflect the structural variations found in the reference stream corridor. To maintain a connected and contiguous vegetative cover at the edge of small gaps, taller vegetation should be designed to continue through the gap. If the gap is wider than can be breached by the tallest or widest vegetation, a more gradual edge may be appropriate.

Vertical structure of the corridor interior tends to be less diverse than that of the

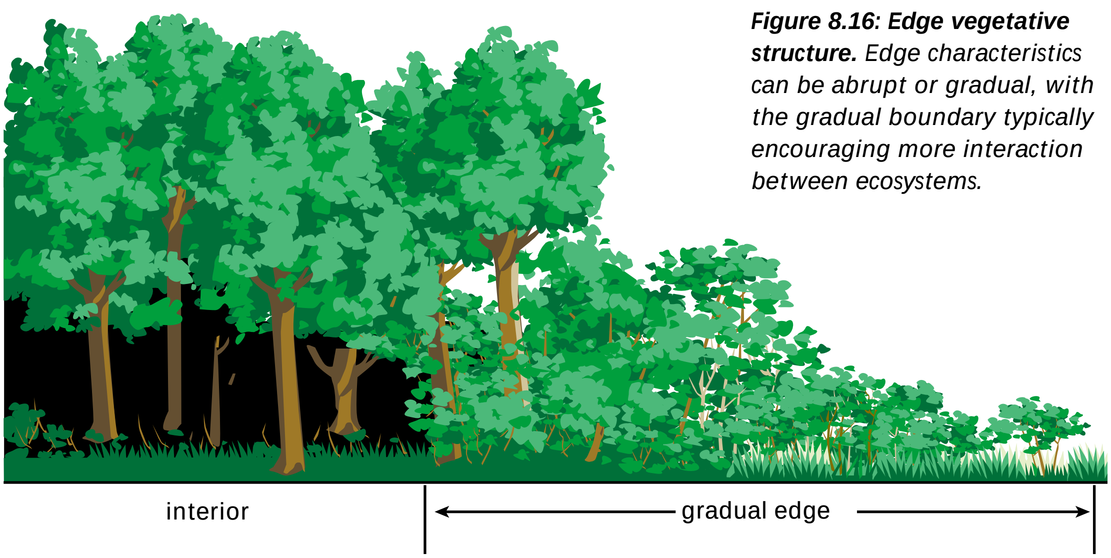


Figure 8.16: Edge vegetative structure. *Edge characteristics can be abrupt or gradual, with the gradual boundary typically encouraging more interaction between ecosystems.*

edge. This is typically observed when entering a woodlot: edge vegetation is shrubby and difficult to traverse, whereas inner shaded conditions produce a more open forest floor that allows for easier movement. Snags and downed wood may also provide important habitat functions. When designing to restore interior conditions of stream corridor vegetation, a vegetation structure should be used that is less diverse than the vegetation structure used at the edge. The reference stream corridor will yield valuable information for this aspect of design.

Influence of Hydrology and Stream Dynamics

Natural floodplain plant communities derive their characteristic horizontal diversity primarily from the organizing influence of stream migration and flooding (Brinson et al. 1981). As discussed earlier, when designing restoration of stream corridor vegetation, nearby reference conditions are generally used as models to identify the appropriate plant species and communities. However, the original cover and older existing trees might have been established before stream regulation or other changes in the watershed that affect flow and sediment characteristics.

A good understanding of current and projected flooding is necessary for design of appropriately restored plant communities within the floodplain. Water management and planning agencies are often the best sources of such data. In wildland areas, stream gauge data may be available, or on-site interpretation of landforms and vegetation may be required to determine whether floodplain hydrology has been altered through channel incision, beaver activity, or other causes. Discussions with local residents and examination of aerial photography may also provide information on water diversions, ground water depletion, and similar changes in the local hydrology.

A vegetation-hydroperiod model can be used to forecast riparian vegetation distribution (Malanson 1993). The model identifies the inundating discharges of various locations in the riparian zone and the resulting suitability of moisture conditions for desired plants. Grading plans, for example, can be adjusted to alter the area inundated by a given discharge and thus increase the area suitable for vegetation associated with a particular frequency and duration of flooding. A focus on the vegetation-hydroperiod relationship will demonstrate the following:

- The importance of moisture conditions in structuring vegetation of the riparian zone;
- The existence of reasonably well accepted physical models for calculating inundation from streamflow and the geometry of the bottomland.
- The likelihood that streamflow and inundating discharges have been altered in degraded stream systems or will be modified as part of a restoration effort.

Generally, planting efforts will be easier when trying to restore vegetation on sites that have suitable moisture conditions for the desired vegetation, such as in replacing historical vegetation on cleared sites that have unaltered streamflow and inundating discharges. Moisture suitability calculations will support designs. Sometimes the restoration objective is to restore more of the desired vegetation than the new flow conditions would naturally support. Direct manipulation by planting and controlling competition can often produce the desired results within the physiological tolerances of the desired species. However, the vegetation on these sites will be out of balance with the site moisture conditions and might require continued maintenance. Management of vegetation can also accelerate succession to a more desirable state.

Projects that require long-term supplemental watering should be avoided due to high maintenance costs and decreased potential for success. Inversely, there may be cases where the absence of vegetation, especially woody vegetation, is desired near the stream channel. Alteration of streamflow or inundating discharges might make moisture conditions on these sites unsuitable for woody vegetation.

The general concept of site suitability for plant species can be extended from moisture conditions determined by inundation to other variables determining plant distribution. For example, Ohmart and Anderson (1986) suggests that restoration of native riparian vegetation in arid southwestern river systems may be limited by unsuitable soil salinities. In many arid situations, depth to ground water might be a more direct measure of the moisture effects of streamflow on riparian sites than actual inundation. Both inundating discharge and depth to ground water are strongly related to elevation. However, depth to ground water may be the more appropriate causal variable for these rarely inundated sites, and a physical model expressing the dependence of alluvial ground water levels on streamflow might therefore be more important than a hydraulic model of surface water elevations.

Some stream corridor plant species have different requirements at different life stages. For example, plants tolerating extended inundation as adults may require a drawdown for establishment, and plants thriving on relatively high and dry sites as adults may be established only on moist surfaces near the water's edge. This can complicate what constitutes suitable moisture conditions and may require separate consideration of establishment requirements, and perhaps consideration of how sites might change over time. The application of simulation models of plant dynamics based on solving sets of explicit rules for how plant composition will change over time may become necessary as increasingly complex details of different requirements at different plant life history stages are incorporated into the evaluation of site suitability. Examples of this type of more sophisticated plant response model include van der Valk (1981) for prairie marsh species and Pearlstine et al. (1985) for bottomland hardwood tree species.

Soil Bioengineering for Floodplains and Uplands

Soil bioengineering is the use of live and dead plant materials, in combination with natural and synthetic support materials, for slope stabilization, erosion reduction, and vegetative establishment.

There are many soil bioengineering systems, and selection of the appropriate system or systems is critical to successful restoration. Reference documents should be consulted to ensure that the principles of soil bioengineering are understood and applied. The NRCS Engineering Field Handbook, Part 650 [Chapter 16, Streambank and Shoreline Protection (USDA-NRCS 1996) and Chapter 18, Soil Bioengineering for Upland Slope Protection and Erosion Reduction (USDA-NRCS 1992)] offers background and guidelines for application of this technology. A more detailed description of soil bioengineering systems is offered in Section 8.F, Streambank Stabilization Design, of this chapter and in Appendix A.

FAST FORWARD

Preview Chapter 8, Section F for more information on soil bioengineering techniques.

8.D Habitat Measures

Other measures may be used to provide structure and functions. They may be implemented as separate actions or as an integral part of the restoration plan to improve habitat, in general, or for specific species. Such measures can provide short-term habitat until overall restoration results reach the level of maturity needed to provide the desired habitat. These measures can also provide habitat that is in short supply. Greentree reservoirs, nest structures, and food patches are three examples. Beaver are also presented as a restoration measure.

Greentree Reservoirs

Short-term flooding of bottomland hardwoods during the dormant period of tree growth enhances conditions for some species (e.g., waterfowl) to feed on mast and other understory food plants, like wild millet and smartweed. Acorns are a primary food source in stream corridors for a variety of fauna, including ducks, nongame birds and mammals, turkey, squirrel, and deer. Greentree reservoirs are shallow, forested floodplain impoundments usually created by building low levees and installing outlet structures (**Figure 8.17**). They are usually flooded in early fall and drained during late March to mid-April. Draining prevents damage to overstory hardwoods (Rudolph and Hunter 1964). Most existing greentree reservoirs are in the Southwest.

The flooding of greentree reservoirs, by design, differs from the natural flood regime. Greentree reservoirs are typically flooded earlier and at depths greater than would normally occur under natural conditions. Over time, modifications of natural flood conditions can result in vegetation changes, lack of regeneration, decreased mast production, tree mortality, and disease. Proper management of green tree reservoirs requires knowledge of the local system—especially the natural flood regime—and the integration of management goals that are consistent with system requirements. Proper management of greentree reservoirs can provide

Figure 8.17: Bottomland hardwoods serving as a greentree reservoir. *Proper management of greentree reservoirs requires knowledge of the local system.*

quality habitat on an annual basis, but the management plan must be well designed from construction through management for waterfowl.

Nest Structures

Loss of riparian or terrestrial habitat in stream corridors has resulted in the decline of many species of birds and mammals that use associated trees and tree cavities for nesting or roosting. The most important limiting factor for cavity-nesting birds is usually the availability of nesting substrate (von Haartman 1957), generally in the form of snags or dead limbs in live trees (Sedgwick and Knopf 1986). Snags for nest structures can be created using explosives, girdling, or topping of trees. Artificial nest structures can compensate for a lack of natural sites in otherwise suitable habitat since many species of birds will readily use nest boxes or other artificial structures. For example, along the Mississippi River in Illinois and Wisconsin, where nest trees have become scarce, artificial nest structures have been erected and constructed for double-crested cormorants using utility poles (Yoakum et al. 1980). In many cases, increases in breeding bird density have resulted from providing such structures (Strange et al. 1971, Brush 1983). Artificial nest structures can also improve nestling survival (Cowan 1959).

Nest structures must be properly designed and placed, meeting the biological needs of the target species. They should also be durable, predator-proof, and economical to build. Design specifications for nest boxes include hole diameter and shape, internal box volume, distance from the floor of the box to the opening, type of material used, whether an internal "ladder" is necessary, height of placement, and habitat type in which to place the box. Other types of nest structures include nest platforms for waterfowl and raptors; nest baskets for doves, owls, and waterfowl; floating nest structures for geese; and tire nests for squirrels. Specifications for nest structures for riparian and wetland nesting species (including numerous Picids, passerines, waterfowl, and raptors) can be found in many sources including Yoakum et al. (1980), Kalmbach et al. (1969), and various state wildlife agency and conservation publications.

Food Patches

Food patch planting is often expensive and not always predictable, but it can be carried out in wetlands or riparian systems mostly for the benefit of waterfowl. Environmental requirements of the food plants native to the area, proper time of year of introduction, management of water levels, and soil types must all be taken into consideration. Some of the more important food plants in wetlands include pondweed (Potamogeton spp.), smartweed (Polygonum spp.), duck potato, spike sedges (Carex spp.), duckweeds (Lemna spp.), coontail, alkali bulrush (Scirpus paludosus), and various grasses. Two commonly planted native species include wild rice (Zizania) and wild millet. Details on suggested techniques for planting these species can be found in Yoakum et al. (1980).

Importance of Beaver to Riparian Ecosystems

Beaver have long been recognized for their potential to influence riparian systems. In rangelands, where loss of riparian functional value has been most dramatic, the potential role of beaver in restoring degraded streams is least understood.

*Beaver dams on headwater streams can positively influence riparian function in many ways, as summarized by Olson and Hubert (1994) (**Figure 8.18**). They improve water quality by trapping sediments behind dams and by reducing stream velocity, thereby reducing bank erosion (Parker 1986). Beaver ponds can alter water chemistry by changing adsorption rates for nitrogen and phosphorus (Maret 1985) and by trapping coliform bacteria (Skinner et al. 1984). The flow regime within a watershed can also be influenced by beaver. Beaver ponds create a sponge-like effect by increasing the area where soil and water meet (**Figure 8.19**). Headwaters retain more water from spring runoff and major storm events, which is released more slowly, resulting in a higher water table and extended summer flows. This increase in water availability, both surface and subsurface, usually increases the width of the riparian zone and, consequently, favors wildlife communities that depend on that vegetation. There can be negative impacts as well, including loss of spawning habitat, increase in water temperatures beyond optimal levels for some fish species, and loss of riparian habitat.*

Figure 8.18: Beaver dam on a headwater stream. *Beavers have many positive impacts on headwater streams.*

Richness, diversity, and abundance of birds, herpetiles, and mammals can be increased by the activities of beaver (Baker et al. 1992, Medin and Clary 1990). Beaver ponds are important waterfowl production areas and can also be used during migration (Call 1970, Ringelman 1991). In some high-elevation areas of the Rocky Mountains, beaver are solely responsible for the majority of local duck production. In addition, species of high interest, such as trumpeter swans, sandhill cranes, moose, mink, and river otters, use beaver ponds for nesting or feeding areas (Collins 1976).

Transplanting Beaver to Restore Stream Functions

Beaver have been successfully transplanted into many watersheds throughout the United States during the past 50 years. This practice was very common during the 1950s after biologists realized the loss of ecological function resulting from overtrapping of beaver by fur traders before the turn of the century. Reintroduction of beaver has restored the U.S. beaver population to 6-12 million, compared to a pre-European level of 60-400 million (Naiman et al. 1986). Much unoccupied habitat or potential habitat still remains, especially in the shrub-steppe ecosystem.

*In forested areas, where good beaver habitat already exists, reintroduction techniques are well established. The first question asked should be "If the habitat is suitable, why are beaver absent?" In the case of newly restored habitat or areas far from existing populations, reintroduction without habitat improvement might be warranted (**Figure 8.20**). Beavers are livetrapped from areas that have excess populations or from areas where they are a nuisance. It is advisable to obtain beavers from habitat that is similar to where they will be introduced to ensure*

Figure 8.19: A beaver pond. *Beaver ponds create a sponge-like effect.*

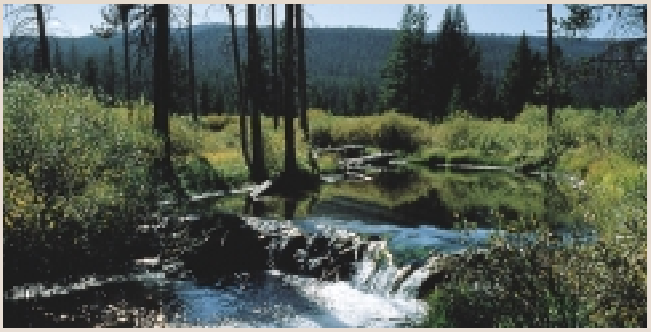


Figure 8.20: Beaver habitat. It is advisable to obtain beaver from habitat that is similar to where they will be introduced.

they are familiar with available food and building materials (Smith and Prichard 1992). This is particularly important in shrub-steppe habitats.

*Reintroduction into degraded riparian areas within the shrub-steppe zone is controversial. Conventional wisdom holds that a yearlong food supply must be present before introducing beaver. In colder climates, this means plants with edible bark, such as willow, cottonwood, or aspen, must be present to provide a winter food supply for beaver (**Figure 8.21**). But often these species are the goal of restoration. In some cases willows or other species can be successfully planted as described in other sections of this document. In other areas, conditions needed to sustain planted cuttings, such as a high water table and minimal competition with other vegetation, might preclude successful establishment. Transplanting beaver before willows are established may create the conditions needed to both establish and maintain riparian shrubs or trees. In these cases it may be helpful to provide beaver with a pickup truck load of aspen or other trees to use as building material at or near the reintroduction site. This may encourage beaver to stay near the site and strengthen dams built of sagebrush or other shrubs (Apple et al. 1985).*

Nuisance Beaver

Unfortunately, beaver are not beneficial in all situations, which is all too obvious to those managing damage control. In many cases where they live in close proximity to humans or features important to humans, beaver need to be removed or their damage controlled. Common problems include cutting or eating desirable vegetation, flooding roads or irrigation ditches by plugging culverts, and increasing erosion by burrowing into the banks of streams or reservoirs. In addition, beaver carry Giardia species pathogens, which can infect drinking water supplies and cause human health problems.

Control of nuisance beaver usually involves removing the problem animals directly or modifying their habitat. Beaver can be livetrapped (Bailey or Hancock traps) and relocated to a more acceptable location or killed by dead-traps (e.g., Conibear #330) or shooting (Miller 1983). In cases where the water level in a dam must be controlled to prevent flooding, a pipe can be placed through the dam with the upstream side perforated to allow water flow.

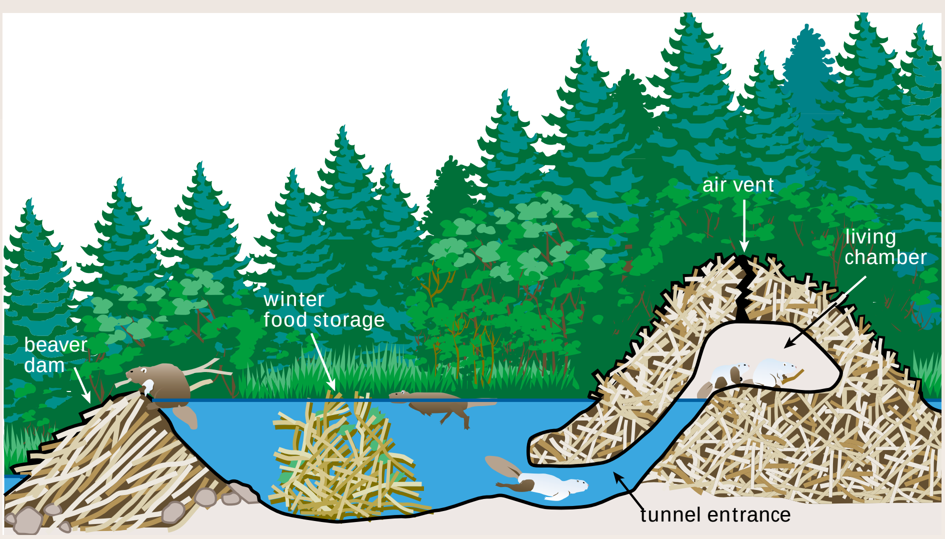


Figure 8.21: A beaver lodge. The living chamber in a beaver lodge is above water and used year-round. Deep entrances enable beavers to obtain food from underwater caches in winter.

8.E Stream Channel Restoration

Some disturbances to stream channels (e.g., from surface mining activities, extreme weather events, or major highway construction) are so severe that restoration within a desired time frame requires total reconstruction of a new channel. Selecting dimensions (width, depth, cross-sectional shape, pattern, slope, and alignment) for such a reconstructed channel is perhaps the most difficult component of stream restoration design. In the case of stream channel reconstruction, stream corridor restoration design can proceed along one of two broad tracks:

1. A single-species restoration that focuses on habitat requirements of certain life stages of species (for example, rainbow trout spawning). The existing system is analyzed in light of what is needed to provide a given quantity of acceptable habitat for the target species and life stage, and design proceeds to remedy any deficiencies noted.
2. An “ecosystem restoration” or “ecosystem management” approach that focuses design resources on the chemical, hydrologic, and geomorphic functions of the stream corridor. This approach assumes that communities will recover to a sustainable level if the stream corridor structure and functions are adequate. The strength of this approach is that it recognizes the complex interdependence between living things and the totality of their environments.

Although methods for single-species restoration design pertaining to treatments for aquatic habitat are included elsewhere in this chapter, the second track is emphasized in this section.

REVERSE

Review Chapter 4's Data Collection Planning section.

Procedures for Channel Reconstruction

If watershed land use changes or other factors have caused changes in sediment yield or hydrology, restoration to an historic channel condition is not recommended. In such cases, a new channel design is needed. The following procedures are suggested:

1. Describe physical aspects of the watershed and characterize its hydrologic response.

   This step should be based on data collected during the planning phase, as described in Chapter 4.

2. Considering reach and associated constraints, select a preliminary right-of-way for the restored stream channel corridor and compute the valley length and valley slope.
3. Determine the approximate bed material size distribution for the new channel.

Many of the channel design procedures described below require the designer to supply the size of bed sediments. If the project is not likely to modify bed sediments, the existing channel bed may be sampled using procedures reviewed in Chapter 7. If predisturbance conditions were different from those of the existing channel, and if those conditions must be restored, the associated sediment size distribution must be determined. This can be done by collecting representative samples of bed sediments from nearby, similar streams; by excavating to locate the predisturbance bed; or by obtaining the information from historic resources.

Like velocity and depth, bed sediment size in natural streams varies continuously in time and space. Particularly troublesome are streams with sediment size distributions that are bimodal mixtures of sand and gravel, for example. The median (D_{50}) of the overall distribution might be virtually absent from the bed. However, if flow conditions allow development of a well-defined armor layer, it might be appropriate to use a higher percentile than the median (e.g., the D_{75}) to represent the bed material size distribution. In some cases, a new channel excavated into a heterogeneous mixture of noncohesive material will develop an armor layer. In such a case, the designer must predict the likely size of the armor layer material. Methods presented by Helwig (1987) and Griffiths (1981) could prove helpful in such a situation.

4. Conduct a hydrologic and hydraulic analysis to select a design discharge or range of discharges.

Conventional channel design has revolved around selecting channel dimensions that convey a certain discharge at or below a certain elevation. Design discharge is usually based on flood frequency or duration or, in the case of canals, on downstream supply needs. Channel restoration, on the other hand, implies designing a channel similar to one that would develop naturally under similar watershed conditions.

Therefore, the first step in selecting a design discharge for restoration is not to determine the controlling elevation for flood protection but to determine what discharge controls channel size. Often this will be at or close to the 1- to 3-year recurrence interval flow. See Chapters 1 and 7 for discussions of channel-forming, effective, and design discharges. Additional guidance regarding streamflow analysis for gauged and ungauged sites is presented in Chapter 7. The designer should, as appropriate to the stream system, compute effective discharge or estimate bankfull discharge.

A sediment rating curve must be developed to integrate with the flow duration curve to determine the effective discharge. The sediment load that is responsible for shaping the channel (bed material load) should be used in the calculation of the effective discharge. This sediment load can be determined from measured data or computed using an appropriate sediment transport equation. If measured suspended sediment data are used, the wash load, typically consisting of particles less than 0.062 mm, should be deleted and only the suspended bed material portion of the suspended load used. If the bed load in the stream is considered to be only a small percentage of the total bed material load, it might be acceptable to simply use the measured suspended bed material load in the effective discharge calculations. However, if the bed load is a significant portion of the load, it should be calculated using an appropriate sediment transport function and then added to the suspended bed material load to provide an estimate of the total bed material load. If bed load measurements are available, which seldom is the case, these observed data can be used.

Flow levels and frequencies that cause flooding also need to be identified to help plan and design out-of-stream restoration measures in the rest of the stream corridor. If flood management is a constraint, additional factors that are beyond the scope of this document enter the design. Environmental features for flood control channels are described elsewhere (Hey 1995, Shields and Aziz 1992, USACE 1989a, Brookes 1988).

Channel reconstruction and stream corridor restoration are most difficult for

Review Chapter 1 and Chapter 7's channel-forming, effective, and design discharges sections.

incised streams, and hydrologic analyses must consider several additional factors. Incised stream channels are typically much larger than required to convey the channel-forming discharge. Restoration of an incised channel may involve raising the bottom of a stream to restore overbank flow and ecological functions of the floodplain. In this type of restoration, compatibility of restored floodplain hydrology with existing land uses must be considered.

REVERSE

Review Chapter 7's hydrologic analysis and stage-discharge relationships sections.

A second option in reconstructing incised channels is to excavate one or both sides to create a new bankfull channel with a floodplain (Hey 1995). Again, adjacent land uses must be able to accommodate the new, excavated floodplain/channel.

A third option is to stabilize the incised channel in place, and to enhance the low-flow channel for environmental benefits. The creation of a floodplain might not be necessary or possible as part of a stream restoration.

In cases where channel sizing, modification, or realignment are necessary, or where structures are required to enhance vertical or lateral stability, it is critical that restoration design also include consideration of the range of flows expected in the future. In urbanizing watersheds, future conditions may be quite different from existing conditions, with higher, sharper, peak flows.

If certain instream flow levels are required to meet restoration objectives, it is imperative that those flows be quantified on the basis of a thorough understanding of present and desired conditions. Good design practice also requires checking stream channel hydraulics and stability at discharges well above and below the design condition. Stability checks (described below) may be quite simple or very sophisticated. Additional guidance on hydrologic analysis and development of stage-discharge relationships are presented in Chapter 7.

5. Predict stable planform type (straight, meandering, or braided).

Channel planform may be classified as straight, braided, or meandering, but thresholds between categories are arbitrary since channel form can vary continuously from straight to single-channel meanders to multiple braids. Naturally straight, stable alluvial channels are rare, but meandering and braided channels are common and can display a wide range of lateral and vertical stability.

Relationships have been proposed that allow prediction of channel planform based on channel slope, discharge, and bed material size (e.g., Chang 1988), but they are sometimes unreliable (Chitale 1973, Richards 1982) and give widely varying estimates of the slope threshold between meandering and braiding. As noted by Dunne (1988), "The planform aspects of rivers are the most difficult to predict," a sentiment echoed by USACE (1994), "... available analytical techniques cannot determine reliably whether a given channel modification will be liable to meander development, which is sensitive to difficult-to-quantify factors like bank vegetation and cohesion."

Stable channel bed slope is influenced by a number of factors, including sediment load and bank resistance to erosion. For the first iteration, restoration designers may assume a channel planform similar to stable reference channels in similar watersheds. By collecting data for stable channels and their valleys in reference reaches, insight can be gained on what the stable configuration would be for the restoration area. The morphology of those stream types can also provide guidance or additional converging lines of evidence that the planform selected by the designer is appropriate.

After initial completion of these five steps, any one of several different paths may be taken to final design. Three approaches are summarized in **Table 8.1**. The tasks are not always executed sequentially because trial and error and reiteration are often needed.

Alignment and Average Slope

In some cases, it might be desirable to divert a straightened stream into a meandering alignment for restoration purposes. Three approaches for meander design are summarized in the adjacent box.

For cases where the design channel will carry only a small amount of bed mate-

Approach A		Approach B (Hey 1994)		Approach C (Fogg 1995)	
Task	**Tools**	**Task**	**Tools**	**Task**	**Tools**
Determine meander geometry and channel alignment.[1]	Empirical formulas for meander wavelength, and adaptation of measurements from predisturbed conditions or nearly undisturbed reaches.	Determine bed material discharge to be carried by design channel at design discharge, compute bed material sediment concentration.	Analyze measured data or use appropriate sediment transport function[2] and hydraulic properties of reach upstream from design reach.	Compute mean flow, width, depth, and slope at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients.
Compute sinuosity, channel length, and slope.	Channel length = sinuosity X valley length. Channel slope= valley slope/ sinuosity.	Compute mean flow, width, depth, and slope at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients, or analytical methods (e.g. White, et.al., 1982, or Copeland, 1994).[3]	Compute or estimate flow resistance coefficient at design discharge.	Appropriate relationship between depth, bed sediment size, and resistance coefficient, modified based on expected sinuosity and bank/berm vegetation.
Compute mean flow width and depth at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients, and resistance equations or analytical methods (e.g. tractive stress, Ikeda and Izumi, 1990, or Chang, 1988).	Compute sinuosity and channel length.	Sinuosity = valley slope/ channel slope. Channel length= sinuosity X valley length.	Compute mean channel slope and depth required to pass design discharge.	Uniform flow equation (e.g. Manning, Chezy) continuity equation, and design channel cross-sectional shape; numerical water surface profile models may be used instead of uniform flow equation.
Compute riffle spacing (if gravel bed), and add detail to design.	Empirical formulas, observation of similar streams, habitat criteria.	Determine meander geometry and channel alignment.	Lay out a piece of string scaled to channel length on a map (or equivalent procedure) such that meander arc lengths vary from 4 to 9 channel widths.	Compute velocity or boundary sheer stress at design discharge.	Allowable velocity or shear stress criteria based on channel boundary materials.
Check channel stability and reiterate as needed.	Check stability.	Compute riffle spacing (if gravel bed), and add detail to design.	Empirical formulas, observation of similar streams, habitat criteria.	Compute sinuosity and channel length.	Sinuosity = valley slope/ channel slope. Channel length= sinuosity X valley length.
		Check channel stability and reiterate as needed.	Check stability.	Compute sinuosity and channel length.	Lay out a piece of string scaled to channel length on a map (or equivalent procedure) such that meander arc lengths vary from 4 to 9 channel widths.
				Check channel stability and reiterate as needed.	Check stability.

1 Assumes meandering planform would be stable. Sinuosity and arc-length are known.

2 Computation of sediment transport without calibration against measured data may give highly unreliable results for a specific channel (USACE, 1994, Kuhnle, et al., 1989).

3 The two methods listed assume a straight channel. Adjustments would be needed to allow for effects of bends.

4 Mean flow width and depth at design discharge will give channel dimensions since design discharge is bankfull. In some situations channel may be increased to allow for freeboard. Regime and hydraulic geometry formulas should be examined to determine if they are mean width or top width.

Table 8.1: Three approaches to achieving final design. *There are variations of the final steps to a restoration design, after the first five steps described in the text are done.*

USACE Channel Restoration Design Procedure

A systematic design methodology has been developed for use in designing restoration projects that involve channel reconstruction (USACE, WES). The methodology includes use of hydraulic geometry relationships, analytical determination of stable channel dimensions, and a sediment impact assessment. The preferred geometry is a compound channel with a primary channel designed to carry the effective or "channel forming" discharge and an overbank area designed to carry the additional flow for a specified flood discharge. Channel width may be determined by analogy methods, hydraulic geometry predictors, or analytically. Currently under development are hydraulic geometry predictors for various stream types. Once a width is determined for the effective discharge, depth and channel slope are determined analytically by balancing sediment inflow from upstream with sediment transport capacity through the restored channel. Meander wavelength is determined by analogy or hydraulic geometry relationships. Assumption of a sine-generated curve then allows calculation of channel planform. The stability of the channel design is then evaluated for the full range of expected discharges by conducting a sediment impact assessment. Refinements to the design include variation of channel widths at crossings and pools, variable lateral depths in pools, coarsening of the channel bed in riffles, and bank protection.

rial load, bed slope and channel dimensions may be selected to carry the design discharge at a velocity that will be great enough to prevent suspended sediment deposition and small enough to prevent erosion of the bed. This approach is suitable only for channels with beds that are stationary or move very infrequently—typically stable cobble- and gravel-bed streams.

Once mean channel slope is known, channel length can be computed by multiplying the straight line downvalley distance by the ratio of valley slope to channel slope (sinuosity). Meanders can then be laid out using a piece of string on a map or an equivalent procedure, such that the meander arc length L (the distance between inflection points, measured along the channel) ranges from 4 to 9 channel widths and averages 7 channel widths. Meanders should not be uniform.

The incised, straightened channel of the River Blackwater (Norfolk, United Kingdom) was restored to a meandering form by excavating a new low-level floodplain about 50 to 65 feet wide containing a sinuous channel about 16 feet wide and 3 feet deep (Hey 1995). Preliminary calculations indicated that the bed of the channel was only slightly mobile at bankfull discharge, and sediment loads were low. A carbon copy design process was used, recreating meander geometry from the mid-19th century (Hey 1994). The River Neath (Wales, United Kingdom), an active gravel-bed stream, was diverted at five locations into meandering alignments to allow highway construction. Existing slopes were maintained through each diversion, effectively illustrating a "slope-first" design (Hey 1994).

Channel Dimensions

Selection of channel dimensions involves determining average values for width and depth. These determinations are based on the imposed water and sediment discharge, bed sediment size, bank vegetation, resistance, and average bed slope. However, both width and depth may be constrained by site factors, which the designer must consider once stability criteria are met. Channel width must be less than the available corridor width, while depth is dependent on the upstream and downstream controlling elevations, resistance, and the elevation of the adjacent ground surface. In some cases, levees or floodwalls might be needed to match site constraints and depth requirements. Average dimensions determined in this step should not be applied uniformly. Instead, in the detailed design step described below, nonuniform slopes and cross sections should be specified to create converging and diverging flow and resulting physical diversity.

The average cross-sectional shape of natural channels is dependent on discharge, sediment inflow, geology, roughness, bed slope, bank vegetation, and bed and bank materials. Although bank vegetation is considered when using some of the empirical tools presented below, many of the analytical approaches do not consider the influence of bank material and vegetation or make unrealistic assumptions (e.g., banks are composed of the same material as the bed). These tools should be used with care. After initial selection of average channel width and depth, designers should consider the compatibility of these dimensions with reference reaches.

Reference Reaches

Perhaps the simplest approach to selecting channel width and depth is to use dimensions from stable reaches elsewhere in the watershed or from similar reaches in the region. The difficulty in this approach is finding a suitable reference reach. A reference reach is a reach of stream outside the project reach that is used to develop design criteria for the project reach.

A reference reach used for stable channel design should be evaluated to make sure that it is stable and has a desirable morphological and ecological condition. In addition, the reference reach must be similar enough to the desired project reach so that the comparison is valid. It must be similar to the desired project reach in hydrology, sediment load, and bed and bank material.

The term reference reach has several meanings. As used above, the reference reach is a reach that will be used as a template for the geometry of the restored channel. The width, depth, slope, and planform characteristics of the reference reach are transferred to the design reach, either exactly or by using analytical or empirical techniques to scale them to fit slightly different characteristics of the project reach (for example, a larger or smaller drainage area).

It is impossible to find an exact replica of the watershed in which the restoration work is located, and subjective judgement may play a role in determining what constitutes similarity. The level of uncertainty involved may be reduced by considering a large number of stable reaches. By classifying the reference streams, width and depth data can be grouped by stream type to reduce the scatter inherent in regional analyses.

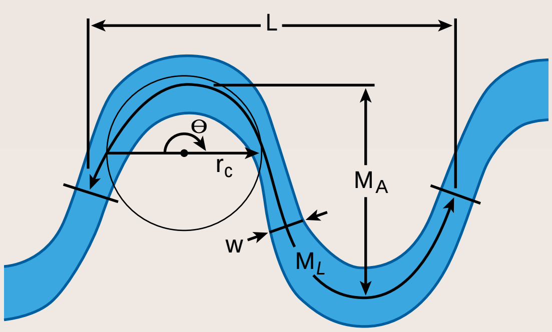
A second common meaning of the term reference reach is a reach with a desired biological condition, which will be used as a target to strive for when comparing various restoration options. For instance, for a stream in an urbanized area, a stream with a similar drainage area in a nearby unimpacted watershed might be used as a reference reach to show what type of aquatic and riparian community might be possible in the project reach. Although it might not be possible to return the urban stream to predevelopment conditions, the characteristics of the reference reach can be used to indicate what direction to move toward. In this use of the term, a reference reach defines desired biological and ecological conditions, rather than stable channel geometry. Modeling tools such as IFIM and RCHARC (see Chapter 7) can be used to determine what restoration options come closest to replicating the habitat conditions of the reference reach (although none of the options may exactly match it).

Meander Design

Five approaches to meander design are described below, not in any intended order of priority. The first four approaches result in average channel slope being determined by meander geometry. These approaches are based on the assumption that the controlling factors in the stream channel (water and sediment inputs, bed material gradation, and bank erosional resistance) will be similar to those in the reference reach (either the restoration reach before disturbance or undisturbed reaches). The fifth approach requires determination of stream channel slope first. Sinuosity follows as the ratio of channel slope to valley slope, and meander geometry ***(Figure 8.22)*** *is developed to obtain the desired sinuosity.*

1. ***Replacement of meanders exactly as found before disturbance (the carbon copy technique).*** *This method is appropriate if hydrology and bed materials are very similar or identical to predisturbance conditions. Old channels are often filled with cohesive soils and may have cohesive boundaries. Accordingly, channel stability may be enhanced by following a previous channel alignment.*

2. ***Use of empirical relationships that allow computation of meander wavelength, L, and amplitude based on channel width or discharge.*** *Chang (1988) presents graphical and algebraic relationships between meander wavelength, width-depth ratio, and friction factor. In addition to meander wavelength, specification of channel alignment requires meander radius of curvature (Hey 1976) and meander amplitude or channel slope. Hey (1976) also suggests that L is not usually uniquely determined by channel width or discharge. Rechard and Schaefer (1984) provide an example of development of regional formulas for meander restoration design. Chapter 7 includes a number of meander geometry relationships developed from regional data sets. Newbury and Gaboury (1993) designed meanders for a straightened stream (North Pine River) by selecting meander amplitude to fit between floodplain terraces. Meander wavelength was set at 12.4 times the channel width (on the high end of the literature range), and radius of curvature ranged from 1.9 to 2.3 times the channel width.*



L meander wavelength
M_L meander arc length
w average width at bankfull discharge
M_A meander amplitude
r_c radius of curvature
Θ arc angle

Figure 8.22: Variables used to describe and design meanders. *Consistent, clear terminology is used in meander design.*
Adapted from Williams 1986.

3. ***Basin-wide analysis to determine fundamental wavelength, mean radius of curvature, and meander belt width in areas "reasonably free of geologic control."*** *This approach has been used for reconstruction of streams destroyed by surface mining in subhumid watersheds of the western United States. Fourier analysis may be used with data digitized from maps to determine fundamental meander wavelength (Hasfurther 1985).*

4. ***Use of undisturbed reaches as design models.*** *If the reach targeted for restoration is closely bounded by undisturbed meanders, dimensions of these undisturbed reaches may be studied for use in the restored reach (**Figure 8.23**). Hunt and Graham (1975) describe successful use of undisturbed reaches as models for design and construction of two meanders as part of river relocation for highway construction in Montana. Brookes (1990) describes restoration of the Elbaek in Denmark using channel width, depth, and slope from a "natural" reach downstream, confirmed by dimensions of a river in a neighboring watershed with similar area, geology, and land use.*

5. ***Slope first.*** *Hey (1994) suggests that meanders should be designed by first selecting a mean channel slope based on hydraulic geometry formulas. However, correlation coefficients for regime slope formulas are always much smaller than those for width or depth formulas, indicating that the former are less accurate. Channel slope may also be determined by computing the value required to convey the design water and sediment discharges (White et al. 1982, Copeland 1994). The main weakness of this approach is that bed material sediment discharge is required by analytical techniques and in some cases (e.g., Hey and Thorne 1986) by hydraulic geometry formulas. Sediment discharges computed without measured data for calibration may be unreliable.*

Site-specific bed material samples and channel geometries are needed to apply these analytical techniques and to achieve confidence in the resulting design.

Figure 8.23: The natural meander of a stream. *Rivers meander to increase length and reduce gradient. Stream restorations often attempt to reconstruct the channel to a previous meandering condition or one "copied" from a reference reach.*

Application of Regime and Hydraulic Geometry Approaches

Typical regime and hydraulic geometry relationships are presented in Chapter 7. These formulas are most reliable for width, less reliable for depth, and least reliable for slope.

Exponents and coefficients for hydraulic geometry formulas are usually determined from data for the same stream, the same watershed, streams of a similar type, or the same physiographic region. Because formula coefficients vary, application of a given set of hydraulic geometry or regime relationships should be limited to channels similar to the calibration sites. Classifying streams can be useful in refining regime relationships (See Chapter 7's section on Stream Classification).

Published hydraulic geometry relationships are usually based on stable, single-thread alluvial channels. Hydraulic geometry relationships determined through stream classification of reference reaches can also be valuable for designing the stream restoration. Channel geometry-discharge relationships are more complex for multithread channels. Individual threads may fit the relationships if their partial bankfull discharges are used in place of the total streamflow. Also, hydraulic geometry relationships for gravel-bed rivers are far more numerous in the literature than those for sand-bed rivers.

A trial set of channel properties (average width, depth, and slope) can be evaluated by using several sets of regime and hydraulic geometry formulas and comparing results. Greatest weight should be given to formulas based on sites similar to the project reach. A logical second step is to use several discharge levels in the best-suited sets of formulas. Because hydraulic geometry relationships are most compatible with single-channel sand and gravel streams with low bed-material sediment discharge, unstable channels (aggrading or degrading profiles) can depart strongly from published relationships.

Literature references to the use of hydraulic geometry formulas for sizing restored channels are abundant. Initial estimates for width and depth for the restored channel of Seminary Creek, which drains an urban watershed in Oakland, California, were determined using regional hydraulic geometry formulas (Riley and MacDonald 1995). Hey (1994, 1995) discusses use of hydraulic geometry relationships determined using regression analyses of data from gravel bed rivers in the United Kingdom for restoration design. Newbury and Gaboury (1993) used regional hydraulic geometry relations based on drainage area to check width and depth of restored channels in Manitoba.

Hydraulic geometry formulas for sizing stream channels in restoration efforts must be used with caution since a number of pitfalls are associated with their use:

- The formulas represent hydraulic geometry only at bankfull or mean annual discharge. Designers must also select a single statistic to describe bed sediment size when using hydraulic geometry relationships. (However, refinements to the Hey and Thorne [1986] formulas for slope in Table 7.5 should be noted.)
- Downstream hydraulic geometry formulas are usually based on the bankfull discharge, the elevation of which can be extremely difficult to identify in vertically unstable channels.
- Exponents and coefficients selected for design must be based on streams with slopes, bed sediments, and bank

materials similar to the one being designed.

- The premise is that the channel shape is dependent on only one or two variables.
- Hydraulic geometry relationships are power functions with a fair degree of scatter that may prove too great for reliable engineering design. This scatter is indicative of natural variability and the influence of other variables on channel geometry.

In summary, hydraulic geometry relationships are useful for preliminary or trial selection of design channel properties. Hydraulic and sediment transport analyses are recommended for final design for the restoration.

Analytical Approaches for Channel Dimensions

Analytical approaches for designing stream channels are based on the idea that a channel system may be described by a finite number of variables. In most practical design problems, a few variables are determined by site conditions (e.g., valley slope and bed material size), leaving up to nine variables to be computed. However, designers have only three governing equations available: continuity, flow resistance (such as Manning, Chezy, and Darcy-Weisbach), and sediment transport (such as Ackers-White, Einstein, and Brownlie). Since this leaves more unknowns than there are equations, the system is indeterminate. Indeterminacy of the stable channel design problem has been addressed in the following ways:

- Using empirical relationships to compute some of the unknowns (e.g., meander parameters).
- Assuming values for one or more of the unknown variables.
- Using structural controls to hold one or more unknowns constant (e.g., controlling width with bank revetments).
- Ignoring some unknown variables by simplifying the channel system. For example, a single sediment size is sometimes used to describe all boundaries, and a single depth is used to describe water depth rather than mean and maximum depth as suggested by Hey (1988).
- Adopting additional governing equations based on assumed properties of streams with movable beds and banks. The design methods based on "extremal hypotheses" fall into this category. These approaches are discussed below under analytical approaches for channels with moving beds.

Table 8.2 lists six examples of analytical design procedures for sand-bed and gravel channels. These procedures are data-intensive and would be used in high-risk or large-scale channel reconstruction work.

REVERSE

Review Chapter 7's section on hydraulic geometry relationships.

Stable Channel Method		Domain	Resistance Equation	Sediment Transport Equation	Third Relation
Copeland	1994	Sand-bed rivers	Brownlie	Brownlie	Left to designer's discretion
Chang	1988	Sand-bed rivers	Various	Various	Minimum stream power
Chang	1988	Gravel-bed rivers	Bray	Chang (similar in form to Parker, Einstein)	Minimum slope
Abou-Saida and Saleh	1987	Sand-bed canals	Liu-Hwang	Einstein-Brown	Left to designer's discretion
White et al.	1981	Sand-bed rivers	White et al.	Ackers-White	Maximum sediment transport
Griffiths	1981	Gravel-bed rivers	Griffiths	Shields entrainment	Empirical stability index

Table 8.2: Selected analytical procedures for stable channel design.

Tractive Stress (No Bed Movement)

Tractive stress or tractive force analysis is based on the idea that by assuming negligible bed material discharge ($Q_s = 0$) and a straight, prismatic channel with a specified cross-sectional shape, the inequality in variables and governing equations mentioned above is eliminated. Details are provided in many textbooks that deal with stable channel design (e.g., Richards 1982, Simons and Senturk 1977, French 1985). Because the method is based on the laws of physics, it is less empirical and region-specific than regime or hydraulic geometry formulas. To specify a value for the force "required to initiate motion," the designer must resort to empirical relationships between sediment size and critical shear stress. In fact, the only difference between the tractive stress approach for design stability analysis and the allowable stress approach is that the effect of cross-sectional shape (in particular, the bank angles) is considered in the former (**Figure 8.24**). Effects of turbulence and secondary currents are poorly represented in this approach.

Tractive stress approaches typically presume constant discharge, zero bed material sediment transport, and straight, prismatic channels and are therefore poorly suited for channels with moving beds. Additional limitations of the tractive stress design approach are discussed by Brookes (1988) and USACE (1994). Tractive stress approaches are appropriate for designing features made of rock or gravel (artificial riffles, revetments, etc.) that are expected to be immobile.

__Figure 8.24: Low energy system with small bank angles.__ Bank angles need to be considered when using the tractive stress approach.

Channels with Moving Beds and Known Slope

More general analytical approaches for designing channels with bed material discharge reduce the number of variables by assuming certain constant values (such as a trapezoidal cross-sectional shape or bed sediment size distribution) and by adding new equations based on an extremal hypothesis (Bettess and White 1987). For example, in a refinement of the tractive stress approach, Parker (1978) assumed that a stable gravel channel is characterized by threshold conditions only at the junction point between bed and banks. Using this assumption and including lateral diffusion of longitudinal momentum due to fluid turbulence in the analysis, he showed that points on the bank experience stresses less than threshold while the bed moves.

Following Parker's work, Ikeda et al. (1988) derived equations for stable width and depth (given slope and bed material gradation) of gravel channels with unvegetated banks composed of noncohesive material and flat beds in motion at bankfull. Channels were assumed to be nearly straight (sinuosity < 1.2) with trapezoidal cross sections free of alternate bars. In a subsequent paper Ikeda and Izumi (1990) extended the derivation to include effects of rigid bank vegetation.

Extremal hypotheses state that a stable channel will adopt dimensions that lead to minimization or maximization of some quantity subject to constraints imposed by the two governing equations (e.g., sediment transport and flow resistance). Chang (1988) combined sediment transport and flow resistance formulas with flow continuity and minimization of stream power at each cross section and through a reach to generate a numerical model of flow and sediment transport. Special relationships for flow and transverse sediment transport in bends were also derived. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield d (bankfull depth) and w (bankfull width), given bankfull Q, S, and D_{50}. Separate sets of curves are provided for sand and gravel bed rivers. Regime-type formulas have been fit to the curves, as shown in **Table 8.3.** These relationships should be used with tractive stress analyses to develop converging data that increase the designer's confidence that the appropriate channel dimensions have been selected.

Subsequent work by Thorne et al. (1988) modified these formulas to account for effects of bank vegetation along gravel-bed rivers. The Thorne et al. (1988) formulas in Table 8.3 are based on the data presented by Hey and Thorne (1986) in Table 7.6.

Channels with Moving Beds and Known Sediment Concentration

White et al. (1982) present an analytical approach based on the Ackers and White sediment transport function, a companion flow resistance relationship, and maximization of sediment transport for a specified sediment concentration. Tables (White et al. 1981) are available to assist users in implementing this procedure. The tables contain entries for sediment sizes from 0.06 to 100 millimeters, discharges up to 35,000 cubic feet per second, and sedi-

Table 8.3: Equations for river width and depth.

Author	Year	Data	Domain	k_1	k_2	k_4	k_5
Chang	1988		Meandering or braided sand-bed rivers with:				
		Equiwidth point-bar streams and stable canals	$0.00238 < SD_{50}^{-0.5} Q^{-0.51}$ and $SD_{50}^{-0.5} Q^{-0.55} < 0.05$	$3.49k_1$*		$3.51k_4$*	0.47
		Straight braided streams	$0.05 < SD_{50}^{-0.5} Q^{-0.55}$ and $SD_{50}^{-0.5} Q^{-0.51} < 0.047$	Unknown and unusual			
		Braided point-bar and wide-bend point-bar streams; beyond upper limit lie steep, braided streams	$0.047 < SD_{50}^{-0.5} Q^{-0.51} <$ indefinite upper limit	$33.2k_1$**	0.93	$1.0k_4$**	0.45
Thorne et al.	1988	Same as for Thorne and Hey 1986	Gravel-bed rivers	1.905 + k_1***	0.47	0.2077 + k_4***	0.42
		Adjustments for bank vegetation[a]	Grassy banks with no trees or shrubs	$w = 1.46\, w_c - 0.8317$		$d = 0.8815\, d_c + 0.2106$	
			1-5% tree and shrub cover	$w = 1.306\, w_c - 8.7307$		$d = 0.5026\, d_c + 1.7553$	
			5-50% tree and shrub cover	$w = 1.161\, w_c - 16.8307$		$d = 0.5413\, d_c + 2.7159$	
			Greater than 50% tree and shrub cover, or incised into flood plain	$w = 0.9656\, w_c - 10.6102$		$d = 0.7648\, d_c + 1.4554$	

Chang equations for determining river width and depth. Coefficients for equations of the form $w = k_1 Q^{K_2}$; $d = K_4 Q^{K5}$; where w is mean bankfull width (ft), Q is the bankfull or dominant discharge ($ft^3/_s$), d is mean bankfull depth (ft), D_{50} is median bed-material size (mm), and S is slope (ft/ft).

[a] w_c and d_c in these equations are calculated using exponents and coefficients from the row labeled "gravel-bed rivers".

$k_1^* = (S\, D_{50}^{-0.5} - 0.00238 Q^{-0.51})^{0.02}$.

$k_4^* = \exp[-0.38\, (420.17 S\, D_{50}^{-0.5} Q^{-0.51} - 1)^{0.4}]$.

$k_1^{**} = (S\, D_{50}^{-0.5})^{0.84}$.

$k_4^{**} = 0.015 - 0.025 \ln Q - 0.049 \ln (S\, D_{50}^{-0.5})$.

$k_1^{***} = 0.2490[\ln(0.0010647 D_{50}^{1.15}/SQ^{0.42})]^2$.

$k_4^{***} = 0.0418 \ln(0.0004419 D_{50}^{1.15}/SQ^{0.42})$.

ment concentrations from 10 to 4,000 parts per million. However, this procedure is not recommended for gravel bed channels (USACE 1994). Sediment concentration at bankfull flow is required as an input variable, which limits the usefulness of this procedure. Procedures for computing sediment discharge, Q_s, are outlined in Chapter 7. Copeland (1994) found that the White et al. (1982) method for channel design was not robust for cohesive bed materials, artificial grade controls, and disequilibrium sediment transport. The method was also found inappropriate for an unstable, high-energy ephemeral sand-bed stream (Copeland 1994). However, Hey (1990) found the Ackers-White sediment transport function performed well when analyzing stability of 18 flood control channels in Britain.

The approach described by Copeland (1994) features use of the Brownlie (1981) flow-resistance and sediment-transport relations, in the form of the software package "SAM" (Thomas et al. 1993). Additional features include the determination of input bed material concentration by computing sediment concentration from hydraulic parameters for an upstream "supply reach" represented by a bed slope, a trapezoidal cross section, bed-material gradation, and a discharge. Bank and bed roughness are composited using the equal velocity method (Chow 1959) to obtain roughness for a cross section. A family of slope-width solutions that satisfy the flow resistance and sediment transport relations are then computed. The designer then selects any combination of channel properties that are represented by a point on the slope-width curve. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth. The current (1996) version of the Copeland procedure assumes a straight channel with a trapezoidal cross section and omits the portion of the cross section above side slopes when computing sediment discharge. Effects of bank vegetation are considered in the assigned roughness coefficient.

The Copeland procedure was tested by application to two existing stream channels, the Big and Colewa Creeks in Louisiana and Rio Puerco in New Mexico (Copeland 1994). Considerable professional judgment was used in selection of input parameters. The Copeland method was found inapplicable to the Big and Colewa Creeks (relatively stable perennial streams with sand-clay beds), but applicable to Rio Puerco (high-energy, ephemeral sand-bed stream with stable profile and unstable banks). This result is not surprising since all stable channel design methods developed to date presume alluvial (not cohesive or bedrock) beds.

Use of Channel Models for Design Verification

In general, a model can be envisioned as a system by whose operation the characteristics of other similar systems may be predicted. This definition is general and applies to both hydraulic (physical) and computational (mathematical) models. The use and operation of computer models has improved in recent years as a result of better knowledge of fluvial hydraulics and the development of sophisticated digital control and data acquisition systems.

Any stream corridor restoration design needs careful scrutiny because its long-term impact on the stream system is not easy to predict. Sound engineering often dictates the use of computer models or physical models to check the validity of a proposed design. Since most practitioners do not have easy access to physical modeling facilities, computer models are much more widely used. Computer models can be run in a qualitative mode with very little data or in a highly precise quantitative mode with a great deal of field data for calibration and verification.

Computer models can be used to easily and cheaply test the stability of a restoration design for a range of conditions, or for a variety of alternative channel configurations. A "model" can vary in cost from several hundred dollars to several hundred thousand dollars, depending on what model is used, the data input, the degree of precision required, and the length and complexity of the reach to be modeled. The decision as to what models are appropriate should be made by a hydraulic engineer with a background in sediment transport.

The costs of modeling could be small compared to the cost of redesign or reconstruction due to failure. If the consequences of a project failure would result in a high risk of catastrophic damage or death, and the site-specific conditions result in an unacceptable level of uncertainty when applying computer models, a physical model is the appropriate tool to use for design.

Physical Models

In some instances, restoration designs can become sufficiently complicated to exceed the capabilities of available computational models. In other situations, time might be of the essence, thus precluding the development of new computational modeling capabilities. In such cases the designer must resort to physical modeling for verification.

Depending on the scaling criteria used to achieve similitude, physical models can be classified as distorted, fixed, or movable-bed models. The theory and practice of physical modeling are covered in detail by French (1985), Jansen et al. (1979), and Yalin (1971) and are beyond the scope of this document. Physical modeling, like computational modeling, is a technology that requires specialized expertise and considerable experience. The U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, has extensively developed the technique of designing and applying physical models of rivers.

Computer Models

Computer models are structured and operated in the same way as a physical model (**Figure 8.25**). One part of the code defines the channel planform, the bathymetry, and the material properties of transported constituents. Other parts of the code create conditions at the boundaries, taking the place of the limiting walls and flow controls in the physical model. At the core of the computer code are the water and sediment transport solvers. "Turning on" these solvers is equivalent to running the physical model. At the end of the simulation run the new channel bathymetry and morphology are described by the model output. This section summarizes computational channel models that can be useful for evaluation of stream corridor restoration designs. Since it is not possible to include every existing model

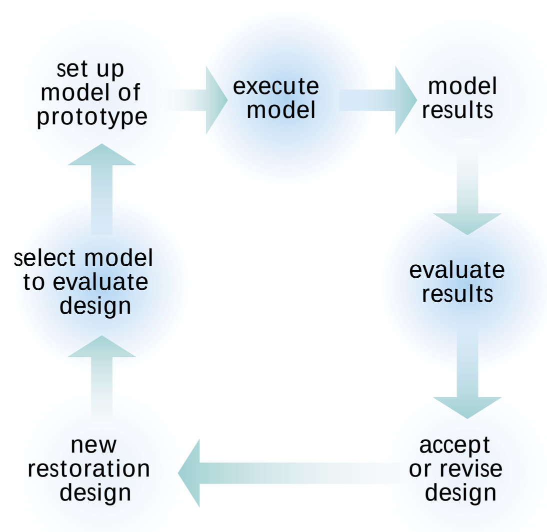


Figure 8.25: Use of models for design evaluation. *Modeling helps evaluate economics and effectiveness of alternative designs.*

Table 8.4: Examples of computational models.

Model	CHARIMA	Fluvial-12	HEC-6	TABS-2	Meander	USGS	D•O•T	GSTARS
Discretization and formulation:								
Unsteady flow | stepped hydrograph	Y | Y	Y | Y	N | Y	Y | Y	N | Y	Y | Y	N | Y	N | Y
One-dimensional | quasi-two-dimensional	Y | N	Y | Y	Y | N	N | N	N | N	N	Y | Y	Y | Y
Two-dimensional | depth-average flow	N	N	N	Y	Y	Y | Y	N	N | Y
Deformable bed | banks	Y | N	Y | Y	Y | N	Y | N	Y | N	Y | N	Y | Y	Y | Y
Graded sediment load	Y	Y	Y	Y	Y	N	Y	Y
Nonuniform grid	Y	Y	Y	Y	Y	Y	Y	Y
Variable time stepping	Y	N	Y	N	N	N	N	Y
Numerical solution scheme:								
Standard step method	N	Y	Y	N	N	N	Y	Y
Finite difference	Y	N	Y	N	Y	Y	Y	Y
Finite element	N	N	N	Y	N	N	N	N
Modeling capabilities:								
Upstream water and sediment hydrographs	Y	Y	Y	Y	Y	Y	Y	Y
Downstream stage specification	Y	Y	Y	Y	Y	N	Y	Y
Floodplain sedimentation	N	N	N	Y	N	N	N	N
Suspended | total sediment transport	Y | N	Y | N	N | Y	Y | N	N | N	N | Y	N | Y	N | Y
Bedload transport	Y	Y	Y	N	Y	N	N	Y
Cohesive sediments	N	N	Y	Y	N	Y	N	Y
Bed armoring	Y	Y	Y	N	N	N	Y	Y
Hydraulic sorting of substrate material	Y	Y	Y	N	N	N	Y	Y
Fluvial erosion of streambanks	N	Y	N	N	N	N	Y	Y
Bank mass failure under gravity	N	N	N	N	N	N	Y	N
Straight | irregular nonprismatic reaches	Y | N	Y | N	Y | N	Y | Y	N | N	N | N	Y | Y	Y | Y
Branched | looped channel network	Y | Y	Y | N	Y | N	Y | Y	N | N	N | N	N | N	N | N
Channel beds	N	Y	N	Y	Y	N	Y	N
Meandering belts	N	N	N	N	N	Y	N	N
Rivers	Y	Y	Y	Y	Y	Y	Y	Y
Bridge crossings	N	N	N	Y	N	N	N	N
Reservoirs	N	Y	Y	N	N	N	N	Y
User support:								
Model documentation	Y	Y	Y	Y	Y	Y	Y	Y
User guide | hot-line support	N | N	Y | N	Y | Y	Y | N	N | N	Y | N	N | N	Y | N

Note: Y = Yes; N = No.

in the space available, the discussion here is limited to a few selected models (**Table 8.4**). In addition, Garcia et al. (1994) review mathematical models of meander bend migration.

These models are characterized as having general applicability to a particular class of problems and are generally available for desktop computers using DOS operating systems. Their conceptual and numerical schemes are robust, having been proven in field applications, and the code can be successfully used by persons without detailed knowledge of the core computational techniques. Examples of these models and their features are summarized in Table 8.4. The acronyms in the column titles identify the following models: CHARIMA (Holly et al. 1990), FLUVIAL-12 (Chang 1990), HEC-6, TABS-2 (McAnally and Thomas 1985), MEANDER (Johannesson and Parker 1985), the Nelson/Smith-89 model (Nelson and Smith 1989), D-O-T (Darby and Thorne 1996, Osman and Thorne 1988), GSTARS (Molinas and Yang 1996) and GSTARS 2.0 (Yang et al. 1998). GSTARS 2.0 is an enhanced and improved PC version of GSTARS. HEC-6, TABS-2, and USGS are federal, public domain models, whereas CHARIMA, FLUVIAL-12, MEANDER, and D-O-T are academic, privately owned models.

With the exception of MEANDER, all the above models calculate at each computational node the fractional sediment load and rate of bed aggradation or degradation, and update the channel topography. Some of them can simulate armoring of the bed surface and hydraulic sorting (mixing) of the underlying substrate material. CHARIMA, FLUVIAL-12, HEC-6, and D-O-T can simulate transport of sands and gravels. TABS-2 can be applied to cohesive sediments (clays and silts) and sand sediments that are well mixed over the water column. USGS is specially designed for gravel bed-load transport. FLUVIAL-12 and HEC-6 can be used for reservoir sedimentation studies. GSTARS 2.0 can simulate bank failure.

Comprehensive reviews on the capabilities and performance of these and other existing channel models are provided in reports by the National Research Council (1983), Fan (1988), Darby and Thorne (1992), and Fan and Yen (1993).

Detailed Design

Channel Shape

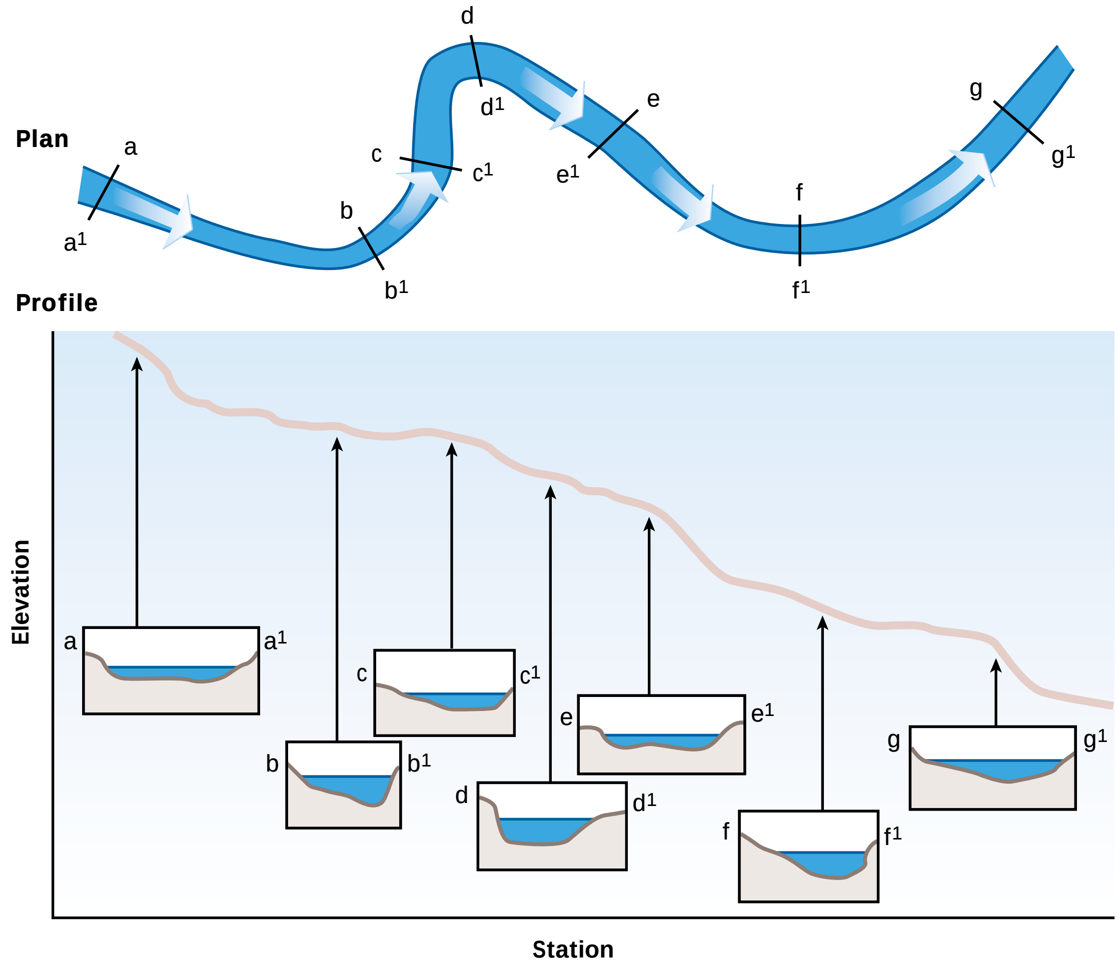
Natural stream width varies continuously in the longitudinal direction, and depth, bed slope, and bed material size vary continuously along the horizontal plane. These variations give rise to natural heterogeneity and patterns of velocity and bed sediment size distribution that are important to aquatic ecosystems.

Widths, depths, and slopes computed during design should be adopted as reach mean values, and restored channels should be constructed with asymmetric cross sections (Hunt and Graham 1975, Keller 1978, Iversen et al. 1993, MacBroom 1981) (**Figure 8.26**). Similarly, meander planform should vary from bend to bend about average values of arc length and radius. A reconstructed floodplain should not be perfectly flat (**Figure 8.27**).

Channel Longitudinal Profile and Riffle Spacing

In stream channels with significant amounts of gravel (D_{50} > 3 mm) (Higginson and Johnston 1989), riffles should be associated with steep zones near meander inflection points. Riffles are not found in channels with beds of finer materials. Studies conducted by Keller and Melhorn (1978) and confirmed by Hey and Thorne (1986) indicate pool-riffle spacing should vary between 3 and 10 channel widths and average about 6 channel widths even in bedrock channels. More recent work by Roy and Abrahams (1980) and Higginson and Johnston (1989) indicates that pool-riffle spacing varies widely within a given channel.

Average riffle spacing is often (but not always) half the meander length since riffles tend to occur at meander inflection points or crossovers. Riffles sometimes appear in groups or clusters. Hey and Thorne (1986) analyzed data from 62 sites on gravel-bed rivers in the United Kingdom and found riffle spacing varied from 4 to 10 channel widths



igure 8.26: Example lan and profile of a aturally meandering tream. *Channel cross ections vary based n width, depth, and lope.*

with the least squares best fit at 6.31 channel widths. Riffle spacing tends to be nearer 4 channel widths on steeper gradients and 8 to 9 channel widths on more gradual slopes (R.D. Hey, personal communication, 1997). Hey and Thorne (1986) also developed regression formulas for riffle width, mean depth, and maximum depth.

Stability Assessment

The risk of a restored channel being damaged or destroyed by erosion or deposition is an important consideration for almost all restoration work. Designers of restored streams are confronted with rather high levels of uncertainty. In some cases, it may be wise for designers to compute risk of failure by calculating the joint probability of design assumptions being false, design equation inaccuracy, and occurrence of extreme hydrologic events during project life. Good design practice also requires checking channel performance at discharges well above and below the design condition. A number of approaches are available for checking both the vertical (bed) and horizontal (bank) stability of a designed stream. These stability checks are an important part of the design process.

Vertical (Bed) Stability

Bed stability is generally a prerequisite for bank stability. Aggrading channels are liable to braid or exhibit accelerated lateral migration in response to middle or point bar growth. Degrading channels widen explosively when bank heights and angles exceed a critical threshold specific to bank soil type. Bed aggradation can be addressed by stabilizing eroding channels upstream, controlling erosion on the watershed, or installing sediment traps, ponds (Haan et al. 1994), or debris basins (USACE 1989b). If aggradation is primarily due to deposition of fines, it can be addressed by narrowing the channel, although a narrower channel might require more bank stabilization.

If bed degradation is occurring or expected to occur, and if modification is planned, the restoration initiative should include flow modification, grade control measures, or other approaches that reduce the energy gradient or the energy of flow. There are many types of grade control structures. The applicability of a particular type of structure to a specific restoration depends on a number of factors, such as hydrologic conditions, sediment size and loading, channel morphology, floodplain and valley characteristics, availability of construction materials, ecological objectives, and time and funding constraints. For more information on various structure designs, refer to Neilson et. al. (1991), which provides a comprehensive literature review on grade control structures with an annotated bibliography. Grouted boulders can be used as a grade control structure. They are a key component in the successful restoration of the South Platte River corridor in Denver, Colorado (McLaughlin Water Engineers, Ltd., 1986).

Grade control structure stilling basins can be valuable habitats in severely degraded warm water streams (Cooper and Knight 1987, Shields and Hoover 1991). Newbury and Gaboury (1993) describe the construction of artificial riffles that serve as bed degradation controls. Kern (1992) used "river bottom ramps" to control bed degradation in a River Danube meander restoration initiative. Ferguson (1991) reviews creative designs for grade control structures that improve streamside habitat and aesthetic resources (**Figure 8.28**).

Figure 8.27: A stream meander and raised floodplain. *Natural floodplains rise slightly between a crossover and an apex of a meander.*

Horizontal (Bank) Stability

Bank stabilization may be necessary in restored channels due to floodplain land uses or because constructed banks are more prone to erosion than "seasoned" ones, but it is less than ideal if ecosystem restoration is the objective.

Figure 8.28: Grade control structure. *Control measures can double as habitat restoration devices and aesthetic features.*

Floodplain plant communities owe their diversity to physical processes that include erosion and deposition associated with lateral migration (Henderson 1986). Bank erosion control methods must be selected with the dominant erosion mechanisms in mind (Shields and Aziz 1992).

Bank stabilization can generally be grouped into one of the following three categories: (1) indirect methods, (2) surface armor, and (3) vegetative methods. Armor is a protective material in direct contact with the streambank. Armor can be categorized as stone, other self-adjusting armor (sacks, blocks, rubble, etc.), rigid armor (concrete, soil cement, grouted riprap, etc.) and flexible mattress (gabions, concrete blocks, etc.). Indirect methods extend into the stream channel and redirect the flow so that hydraulic forces at the channel boundary are reduced to a nonerosive level. Indirect methods can be classified as dikes (permeable and impermeable) and other flow deflectors such as bendway weirs, stream "barbs," and Iowa vanes. Vegetative methods can function as either armor or indirect protection and in some applications can function as both simultaneously. A fourth category is composed of techniques to correct problems caused by geotechnical instabilities.

Guidance on selection and design of bank protection measures is provided by Hemphill and Bramley (1989) and Henderson (1986). Coppin and Richards (1990), USDA-NRCS (1996), and Shields et al. (1995) provide additional detail on the use of vegetative techniques (see following section). Newly constructed channels are more susceptible to bank erosion than older existing channels, with similar inflows and geometries, due to the influence of vegetation, armoring, and the seasoning effect of clay deposition on banks (Chow 1959). In most cases, outer banks of restored or newly constructed meanders will require protection. Structural techniques are needed (e.g., Thorne et al. 1995) if immediate stability is required, but these may incorporate living components. If time permits, the new channel may be constructed "in the dry" and banks planted with woody vegetation. After allowing the vegetation several growing seasons to develop, the stream may be diverted in from the existing channel (R.D. Hey, personal communication, 1997).

Bank Stability Check

Outer banks of meanders erode, but erosion rates vary greatly from stream to stream and bend to bend. Observation of the project stream and similar reaches, combined with professional judgment, may be used to determine the need for bank protection, or erosion may be estimated by simple rules of thumb based largely on studies that relate bend migration rates to bend geometry (e.g., Apmann 1972 and review by Odgaard 1987) (**Figure 8.29**). More accurate prediction of the rate of erosion of a given streambank is at or beyond the current state of the art. No standard methods exist, but several recently developed tools are available. None of these have been used in extremely diverse settings, and users should view them with caution.

Tools for predicting bank erosion may be divided into two groups: (1) those which predict erosion primarily due to the action of water on the streambank surface and (2) those which focus on subsurface geotechnical characteristics.

Among the former is an index of streambank erodibility based on field observations of emergency spillways (Moore et al. 1994, Temple and Moore 1997). Erosion is predicted for sites

Figure 8.29: Channel exhibiting accelerated lateral migration. *Erosion of an outer bank on the Missouri River is a natural process; however, the rate of erosion should be monitored.*

where a power number based on velocity, depth, and bend geometry exceeds an erodibility index computed from tabulated values of streambank material properties. Also among this group are analytical models such as the one developed by Odgaard (1989), which contain rather sophisticated representations of flow fields, but require input of an empirical constant to quantify soil and vegetation properties. These models should be applied with careful consideration of their limitations. For example, Odgaard's model should not be applied to bends with "large curvature."

The second group of predictive tools focuses on banks that undergo mass failure due to geotechnical processes. Side slopes of deep channels may be high and steep enough to be geotechnically unstable and to fail under the influence of gravity. Fluvial processes in such a situation serve primarily to remove blocks of failed material from the bank toe, leading to a resteepened bank profile and a new cycle of failure, as shown in **Figure 8.30**. Study of bank failure processes along incised channels has

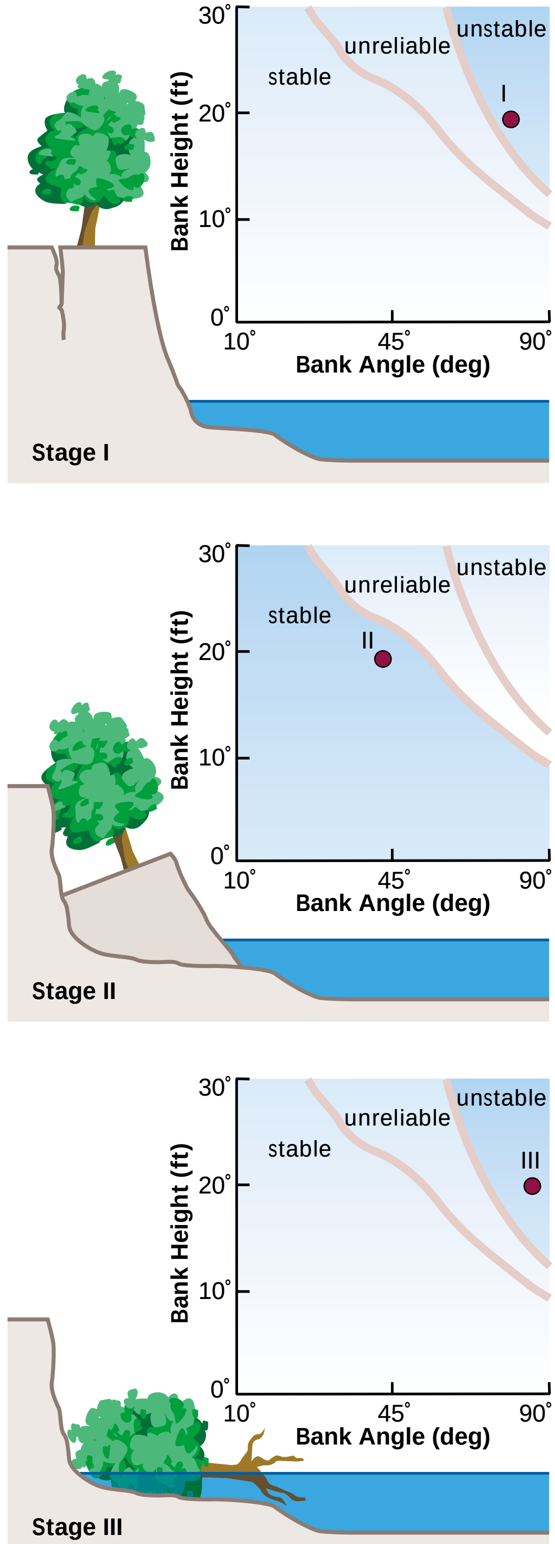


Figure 8.30: Bank failure stages. *Stability of a bank will vary from stable to unstable depending on bank height, bank angle, and soil conditions.*

led to a procedure for relating bank geometry to stability for a given set of soil conditions (Osman and Thorne 1988). If banks of a proposed design channel are to be higher than about 10 feet, stability analysis should be conducted. These analyses are described in detail in Chapter 7. Bank height estimates should allow for scour along the outside of bends. High, steep banks are also susceptible to internal erosion, or piping, as well as streambanks of soils with high dispersion rates.

Allowable Velocity Check

Fortier and Scobey (1926) published tables regarding the maximum nonscouring velocity for given channel boundary materials. Different versions of these tables have appeared in numerous subsequent documents, notably Simons and Senturk (1977) and USACE (1991). The applicability of these tables is limited to relatively straight silt and sand-bed channels with depths of flow less than 3 feet and very low bed material loads. Adjustments to velocities have been suggested for situations departing from those specified. Although slight refinements have been made, these data still form the basis of the allowable velocity approach.

Figure 8.31 contains a series of graphs that summarize the tables and aid in selecting correction factors for flow depth, sediment concentration, flow frequency, channel curvature, bank slope, and channel boundary soil properties. Use of the allowable velocity approach is not recommended for channels transporting a significant load of material larger than 1 mm. The restoration design, however, should also consider the effects of hydraulic roughness and the protection afforded by vegetation.

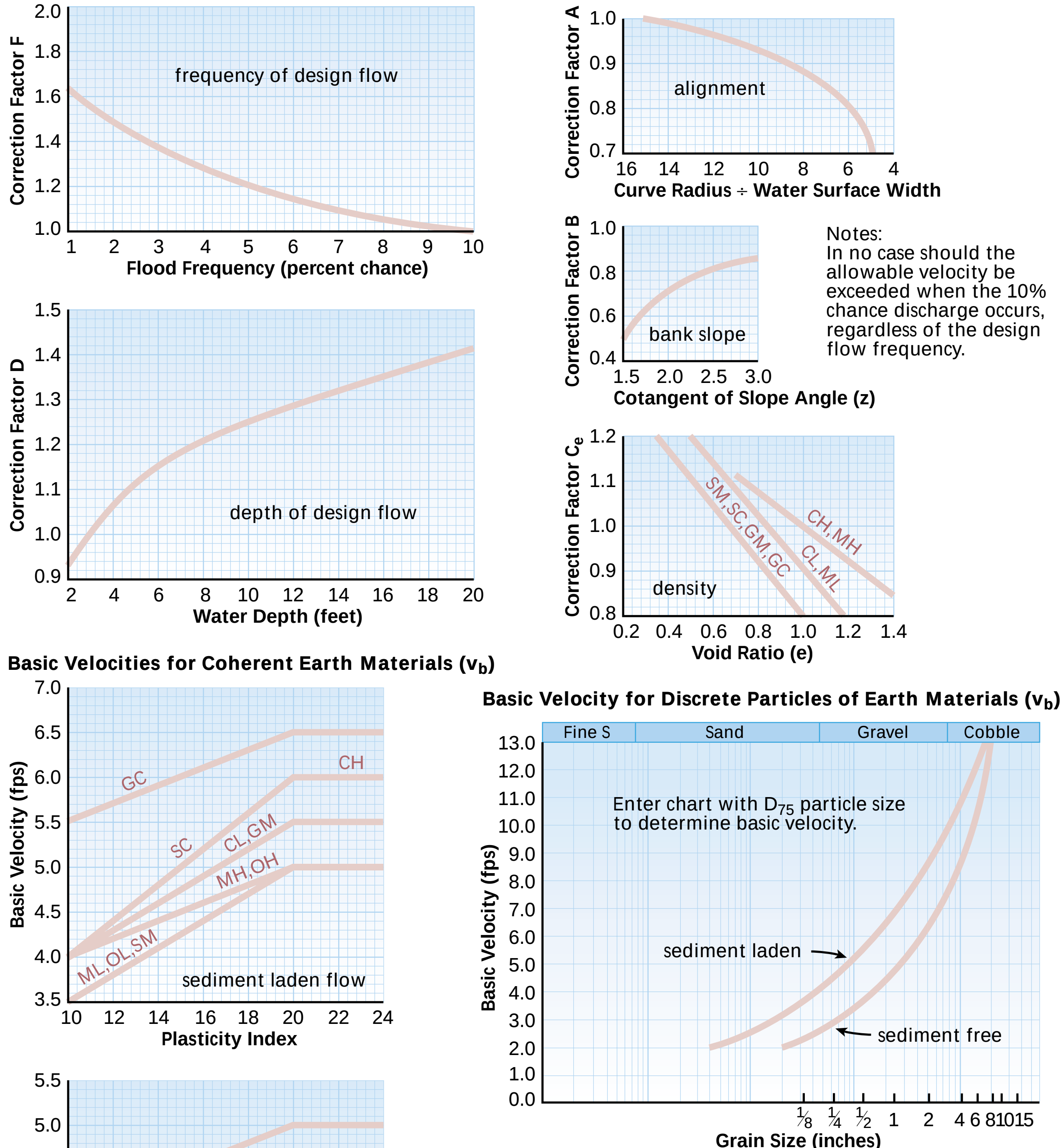
Perhaps because of its simplicity, the allowable velocity method has been used directly or in slightly modified form for many restoration applications. Miller et al. (1983) used allowable velocity criteria to design man-made gravel riffles located immediately downstream of a dam releasing a constant discharge of sediment-free water. Shields (1983) suggested using allowable velocity criteria to size individual boulders placed in channels to serve as instream habitat structures. Tarquin and Baeder (1983) present a design approach based on allowable velocity for low-order ephemeral streams in Wyoming landscapes disturbed by surface mining. Velocity of the design event (10-year recurrence interval) was manipulated by adjusting channel length (and thus slope), width, and roughness. Channel roughness was adjusted by adding meanders, planting shrubs, and adding coarse bed material. The channel width-to-depth ratio design was based on the pre-mining channel configuration.

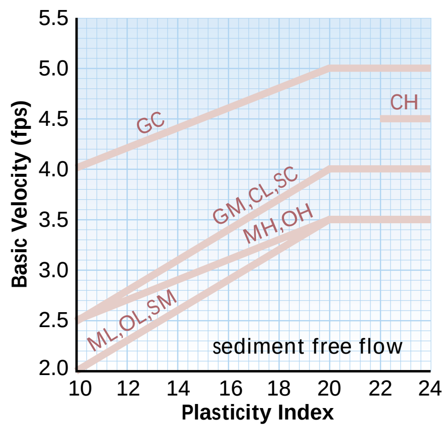
Allowable Stress Check

Since boundary shear stress is more appropriate than velocity as a measure of the forces driving erosion, graphs have also been developed for allowable shear stress. The average boundary shear stress acting on an open channel conveying a uniform flow of water is given by the product of the unit weight of water (γ, lb/ft^3) times the hydraulic radius (R, ft) times the bed slope S:

$$\tau = \gamma RS$$

Figure 8.32 is an example of allowable shear stress criteria presented in graphical form. The most famous graphical presentation of allowable shear stress criteria is the Shields diagram, which depicts conditions necessary for initial movement of noncohesive particles on



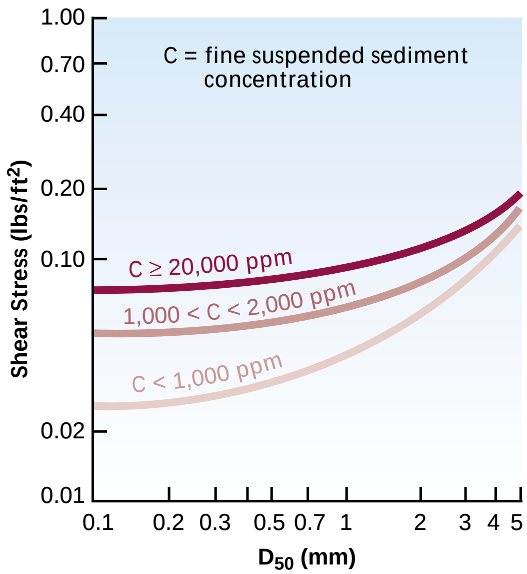


Allowable Velocities for Unprotected Earth Channels	
Channel Boundary Materials	**Allowable Velocity**
Discrete Particles	
Sediment Laden Flow	
D_{75} > 0.4mm	basic velocity chart value x D x A x B
D_{75} < 0.4mm	2.0 fps
Sediment Free Flow	
D_{75} > 0.2mm	basic velocity chart value x D x A x B
D_{75} < 0.2mm	2.0 fps
Coherent Earth Materials	
PI > 10	basic velocity chart value x D x A x F x C_e
PI < 10	2.0 fps

Figure 8.31: Allowable velocities for unprotected earth channels. *Curves reflect practical experience in design of stable earth channels.*

Source: USDA Soil Conservation Service 1977.

__Figure 8.32: Allowable mean shear stress for channels with boundaries of non-cohesive material larger than 5 mm carrying negligible bed material load.__
Shear stress diminishes with increased suspended sediment concentrations.
Source: Lane 1955.



a flat bed straight channel in terms of dimensionless variables (Vanoni 1975). The Shields curve and other allowable shear stress criteria (e.g., Figure 10.5, Henderson 1966; Figure 7.7, Simons and Senturk 1977) are based on laboratory and field data. In simplest form, the Shields criterion for channel stability is (Henderson 1966):

$$RS/[(S_s\text{-}1)D_s] < \text{a constant}$$

$$\text{for } D_s > \sim 6 \text{ mm}$$

where S_s is the specific gravity of the sediment and D_s is a characteristic bed sediment size, usually taken as the median size, D_{50}, for widely graded material. Note that the hydraulic radius, R, and the characteristic bed sediment size, D_s, must be in the same units for the Shields constant to be dimensionless. The dimensionless constant is based on measurements and varies from 0.03 to 0.06 depending on the data set used to determine it and the judgment of the user (USACE 1994).

These constant values are for straight channels with flat beds (no dunes or other bedforms). In natural streams, bedforms are usually present, and values of this dimensionless constant required to cause entrainment of bed material may be greater than 0.06. It should be noted that entrainment does not imply channel erosion. Erosion will occur only if the supply of sediment from upstream is less than that transported away from the bed by the flow. However, based on a study of 24 gravel-bed rivers in the Rocky Mountain region of Colorado, Andrews (1984) concluded that stable gravel-bed channels cannot be maintained at values of the Shields constant greater than about 0.080. Smaller Shields constant values are more conservative with regard to channel scour, but less conservative with regard to deposition. If S_s = 2.65, and the constant is assumed to be 0.06, the equation above simplifies to D_{50} = 10.1RS.

Allowable shear stress criteria are not very useful for design of channels with beds dominated by sand or finer materials. Sand beds are generally in motion at design discharge and have dunes, and their shear stress values are much larger than those indicated by the Shields criterion, which is for incipient motion on a plane bed. Allowable shear stress data for cohesive materials show more scatter than those for sands and gravels (Grissinger et al. 1981, Raudkivi and Tan 1984), and experience and observation with local channels are preferred to published charts like those shown in Chow (1959). Models of cohesive soil erosion require field or laboratory evaluation of model parameters or constants. Extrapolation of laboratory flume results to field conditions is difficult, and even field tests are subject to site-specific influences. Erosivity of cohesive soils is affected by the chemical composition of the soil, the soil water, and the stream, among other factors.

However, regional shear stress criteria may be developed from observations of channels with sand and clay beds. For example, USACE (1993) determined that reaches in the Coldwater River Watershed in northwest Mississippi should be stable with an average boundary shear stress at channel-forming (2-year) discharge of 0.4 to 0.9 lb/ft^2.

The value of the Shields constant also varies with bed material size distribution, particularly for paved or armored beds. Andrews (1983) derived a regression relationship that can be expressed as:

$$RS/[(S_s - 1)D_i] < 0.0834\ (D_i/D_{50})^{-0.872}$$

When the left side of the above expression equals the right, bed-sediment particles of size D_i are at the threshold of motion. The D_{50} value in the above expression is the median size of subsurface material. Therefore, if D_{50} = 30 mm, particles with a diameter of 100 mm will be entrained when the left side of the above equation exceeds 0.029. This equation is for self-formed rivers that have naturally sorted gravel and cobble bed material. The equation holds for values of D_i/D_{50} between 0.3 and 4.2. It should be noted that R and D_i on the left side of the above equation must be expressed in the same units.

Practical Guidance: Allowable Velocity and Shear Stress

Practical guidance for application of allowable velocity and shear stress approaches is provided by the Natural Resources Conservation Service (USDA-NRCS), formerly the U.S. Soil Conservation Service (SCS)(1977), and USACE (1994). See Figure 8.31.

Since form roughness due to sand dunes, vegetation, woody debris, and large geologic features in streams dissipates energy, allowable shear stress for bed stability may be higher than indicated by laboratory flume data or data from uniform channels. It is important to compute cross-sectional average velocities or shear stresses over a range of discharges and for seasonal changes in the erosion resistance of bank materials, rather than for a single design condition. Frequency and duration of discharges causing erosion are important factors in stability determination. In cobble- or boulder-bed streams, bed movement sometimes occurs only for discharges with return periods of several years.

Computing velocity or shear stress from discharge requires design cross sections, slope, and flow resistance data. If the design channel is not extremely uniform, typical or average conditions for rather short channel reaches should be considered. In channels with bends, variations in shear stress across the section can lead to scour and deposition even when average shear stress values are within allowable limits. The NRCS (formerly SCS) (1977) gives adjustment factors for channel curvature in graphical form that are based on very limited data (see Figure 8.31). Velocity distributions and stage-discharge relations for compound channels are complex (Williams and Julien 1989, Myers and Lyness 1994).

Allowable velocity or shear stress criteria should be applied to in-channel flow for a compound cross section with overbank flow, not cross-sectional average conditions (USACE 1994). Channel flow resistance predictors that allow for changing conditions with changing discharge and stage should be used rather than constant resistance values.

If the existing channel is stable, design channel slope, cross section, and roughness may be adjusted so that the current and proposed systems have matching curves of velocity versus discharge (USACE 1994). This approach, while based on allowable velocity concepts, releases the procedure from published empirical values collected in other rivers that might be intrinsically different from the one in question.

Allowable Stream Power or Slope

Brookes (1990) suggested the product of bankfull velocity and shear stress, which is equal to the stream power per unit bed area, as a criterion for stability in stream restoration initiatives. This is based on experience with several restoration initiatives in Denmark and the United Kingdom with sandy banks, beds of glacial outwash sands, and a rather limited range of bankfull discharges (~15 to 70 cfs). These data are plotted as squares, triangles, and circles in **Figure 8.33**.

Brookes suggested that a stream power value of 2.4 $ft\text{-}lb/sec/ft^2$ discriminated well between stable and unstable channels. Projects with stream powers less than about 1.0 $ft\text{-}lb/sec/ft^2$ failed through deposition, whereas those with stream powers greater than about 3.4 $ft\text{-}lb/sec/ft^2$ failed through erosion.

Since these criteria are based on observation of a limited number of sites, application to different stream types (e.g., cobble-bed rivers) should be avoided. However, similar criteria may be developed for basins of interest. For example, data points representing stable reaches in the Coldwater River watershed of northwestern Mississippi are shown in Figure 8.34 as stars. This watershed is characterized by incised, straight (channelized) sand-bed channels with cohesive banks. Slopes for stable reaches were measured in the field, and 2-year discharges were computed using a watershed model (HEC-1) (USACE 1993).

Brookes' stream power criterion is one of several region-specific stability tests. Others include criteria based on slope and shear stress. Using empirical data and observation, the Corps of Engineers has developed relationships between slope and drainage area for various watersheds in northwestern Mississippi (USACE 1989c). For example, stable reaches in three watersheds had slopes that clustered around the regression line:

$$S = 0.0041\ A^{-0.365}$$

where A is the contributing drainage area in square miles. Reaches with much steeper slopes tended to be degra-

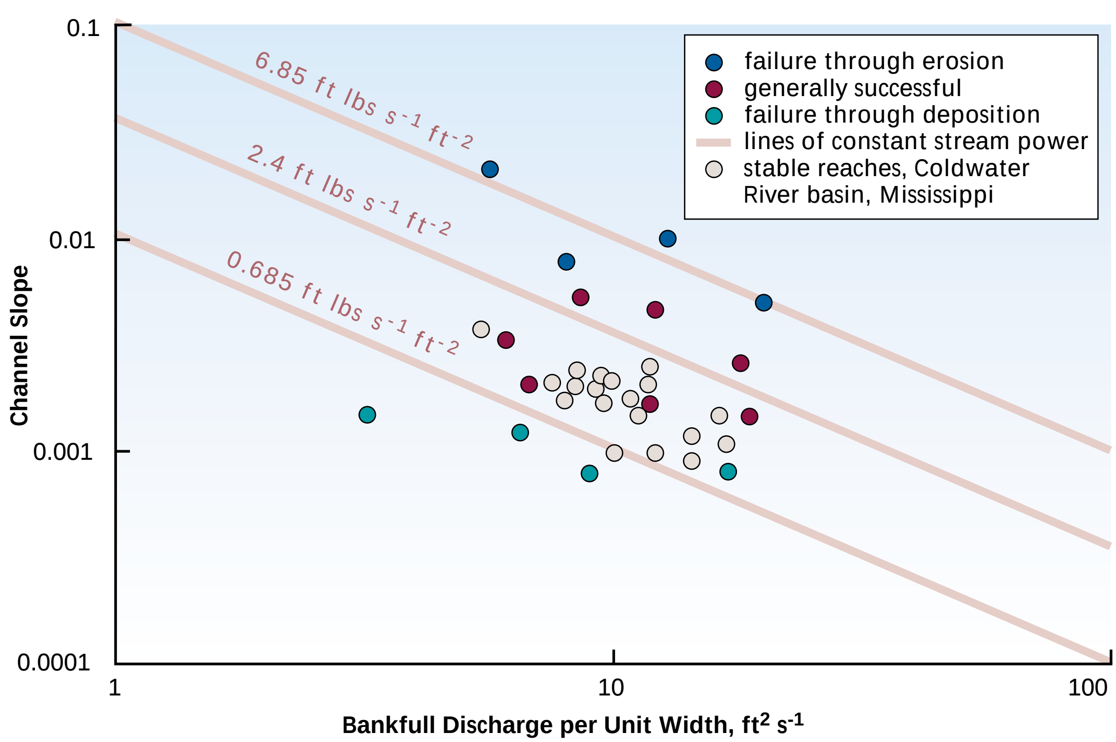


***Figure 8.33:* Brookes' stream power stability criteria.** *Stream power is the product of bankfull velocity and shear stress.*

Allowable Shear Stress

The shape of the bed material size distribution is an important parameter for determining the threshold of motion of individual sediment sizes in a bed containing a mixture of sand and gravel. Beds composed of unimodal (particle-size distribution shows no secondary maxima) mixtures of sand and gravel were found to have a narrow range of threshold shear stresses for all sizes present on the bed surface. For unimodal beds, the threshold of motion of all grain sizes on the bed was found to be estimated adequately by using the Shields curve for the median grain size. Bed sediments composed of bimodal (particle-size distribution shows one secondary maximum) mixtures of sands and gravels were found to have threshold shear stresses that are still a function of grain size, although much less so than predicted by the Shields curve. For bed material with bimodal size distributions, using the Shields curve on individual grain sizes greater than the median size overestimates the threshold of motion and underestimates the threshold of motion for grain sizes less than the median size. Critical shear stresses for gravel beds may be elevated if gravels are tightly interlocked or imbedded.

Jackson and Van Haveren (1984) present an iterative technique for designing a restored channel based on allowable shear stress. Separate calculations were performed for channel bed and banks. Channel design included provision for gradual channel narrowing as the bank vegetation develops, and bank cohesion and resistance to erosion increase. Newbury and Gaboury (1993) use an allowable tractive force graph from Lane (1955) to check stability of channel restoration initiatives in Manitoba streams with cobble and gravel beds. Brookes (1991) gives an example of the application of this method for designing urban channels near London. From a practical standpoint, boundary shear stresses can be more difficult to measure and conceptualize than velocities (Brookes 1995). Allowable shear stress criteria may be converted to allowable velocities by including mean depth as a parameter.

The computed shear stress values are averages for the reach in question. Average values are exceeded at points, for example, on the outside of a bend.

dational, while those with more gradual slopes tended to be aggradational. Downs (1995) developed stability criteria for channel reaches in the Thames Basin of the United Kingdom based entirely on slope: channels straightened during the 20th century were depositional if slopes were less than 0.005 and erosional if slopes were greater.

Sediment Yield and Delivery

Sediment Transport

If a channel is designed using an empirical or a tractive stress approach, computation of sediment-transport capacity allows a rough check to determine whether deposition is likely to be a problem. Sediment transport relationships are heavily dependent on the data used in their development. Inaccuracy may be reduced by selecting transport functions appropriate to the stream type and bed sediment size in question. Additional confidence can be achieved by obtaining calibration data; however, calibration data are not available from a channel yet to be constructed. If the existing channel is reasonably stable, designers can compute a sediment discharge versus streamflow relationship for the existing and proposed design channels using the same sediment transport function and try to match the curves as closely as possible (USACE 1994).

If information is available regarding sediment inflows into the new channel, a multiyear sediment budget can be computed to project likely erosion and deposition and possible maintenance needs. Sediment load can also be computed, using the hydraulic properties and bed material gradations of the upstream supply reach and a suitable sediment transport function. The USACE software SAM (Copeland 1994) includes routines that compute hydraulic properties for uniform flow and sediment discharge for single cross sections of straight channels using any of 13 different sediment transport functions. Cross sections may have complex geometry and boundary materials that vary along the section. Output can be combined with a hydrograph or a flow duration curve to obtain sediment load.

HEC-6 (USACE 1993) is a one-dimensional movable-boundary, open-channel-flow numerical model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods, typically years, although applications to single flood events are possible. A continuous discharge record is partitioned into a series of steady flows of variable discharge and duration. For each discharge, a water surface profile is calculated, providing energy slope, velocity, depth, and other variables at each cross section. Potential sediment transport rates are then computed at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each reach. The amount of scour or deposition at each section is then computed, and the cross section geometry is adjusted for the changing sediment volume. Computations then proceed to the next flow in the sequence, and the cycle is repeated using the updated cross section geometry. Sediment calculations are performed by grain size fractions, allowing the simulation of hydraulic sorting and armoring.

HEC-6 allows the designer to estimate long-term response of the channel to a predicted series of water and sediment supply. The primary limitation is that HEC-6 is one-dimensional, i.e., geometry is adjusted only in the vertical direction. Changes in channel width or planform cannot be simulated. Another Federal sediment routing model is the GSTARS 2.0 (Yang et al. 1998). GSTARS 2.0 can be used for a combination of subcritical and supercritical flow computations without interruption in a semi-two-dimensional manner. The use of stream tube concept in sediment routing enables GSTARS 2.0 to simulate channel geometry changes in a semi-three-dimensional manner.

The amount and type of sediment supplied to a stream channel is an important consideration in restoration because sediment is part of the balance (i.e., between energy and material load) that determines channel stability. A general lack of sediment relative to the amount of stream power, shear stress, or energy in the flow (indexes of transport capacity) usually results in erosion of sediment from the channel boundary of an alluvial channel. Conversely, an oversupply of sediment relative to the transport capacity of the flow usually results in deposition of sediment in that reach of stream.

Bed material sediment transport analyses are necessary whenever a restoration initiative involves reconstructing a length of stream exceeding two meander wavelengths. A reconstruction that modifies the size of a cross section and the sinuosity for such a length of channel should be analyzed to ensure that upstream sediment loads can be transported through the reconstructed reach with minimal deposition or erosion. Different storm events and the average annual transported bed material load also should be examined.

Sediment Discharge Functions

The selection of an appropriate discharge formula is an important consideration when attempting to predict sediment discharge in streams. Numerous sediment discharge formulas have been proposed, and extensive summaries are provided by Alonso and Combs (1980), Brownlie (1981), Yang (1996), Bathurst (1985), Gomez and Church (1989), and Parker (1990).

Sediment discharge rates depend on flow velocity; energy slope; water temperature; size, gradation, specific gravity, and shape of the bed material and suspended-sediment particles; channel geometry and pattern; extent of bed surface covered by coarse material; rate of supply of fine material; and bed configuration. Large-scale variables such as hydrologic, geologic, and climatic conditions also affect the rate of sediment transport. Because of the range and number of variables, it is not possible to select a sediment transport formula that satisfactorily encompasses all the conditions that might be encountered. A specific formula might be more accurate than others when applied to a particular river, but it might not be accurate for other rivers.

Selection of a sediment transport formula should include the following considerations (modified from Yang 1996):

- Type of field data available or measurable within time, budget, and work hour limitations.
- Independent variables that can be determined from available data.
- Limitations of formulas versus field conditions.

If more than one formula can be used, the rate of sediment discharge should be calculated using each formula. The formulas that best agree with available measured sediment discharges should be used to estimate the rate of sediment discharge during flow conditions when actual measurements are not available.

The following formulas may be considered in the absence of any measured sediment discharges for comparison:

- Meyer-Peter and Muller (1948) formula when the bed material is coarser than 5 mm.
- Einstein (1950) formula when bed load is a substantial part of the total sediment discharge.
- Toffaleti (1968) formula for large sand-bed rivers.
- Colby (1964) formula for rivers with depths less than 10 feet and median bed material values less than 0.8 mm.
- Yang (1973) formula for fine to coarse sand-bed rivers.
- Yang (1984) formula for gravel transport when most of the bed material ranges from 2 to 10 mm.
- Ackers and White (1973) or Engelund and Hansen (1967) formula for sand-bed streams having subcritical flow.
- Laursen (1958) formula for shallow rivers with fine sand or coarse silt.

Available sediment data from a gaging station may be used to develop an empirical sediment discharge curve in the absence of a satisfactory sediment discharge formula, or to verify the sediment discharge trend from a selected formula. Measured sediment discharge or concentration should be plotted against streamflow, velocity, slope, depth, shear stress, stream power, or unit stream power. The curve with the least scatter and systematic deviation should be selected as the sediment rating curve for the station.

Sediment Budgets

A sediment budget is an accounting of sediment production in a watershed. It attempts to quantify processes of erosion, deposition, and transport in the basin. The quantities of erosion from all sources in a watershed are estimated using various procedures. Typically, the tons of erosion from the various sources are multiplied by sediment delivery ratios to estimate how much of the eroded soil actually enters a stream. The sediment delivered to the streams is then routed through the watershed.

The sediment routing procedure involves estimating how much of the sediment in the stream ends up being deposited in lakes, reservoirs, wetlands, or floodplains or in the stream itself. An analysis of the soil textures by erosion process is used to convert the tons of sediment delivered to the stream into tons of silt and clay, sand, and gravel. Sediment transport processes are applied to help make decisions during the sediment routing analysis. The end result is the sediment yield at the mouth of the watershed or the beginning of a project reach.

Table 8.5 is a summary sediment budget for a watershed. Note that the information in the table may be from measured values, from estimates based on data from similar watersheds, or from model outputs (AGNPS, SWRRBWQ, SWAT, WEPP, RUSLE, and others. Contact the NRCS National Water and Climate Data Center for more information on these models). Sediment delivery ratios are determined for watershed drainage areas, based on sediment gauge data and reservoir sedimentation surveys.

The watershed is subdivided into subwatersheds at points where significant sediment deposition occurs, such as at bridge or road fills; where stream crossings cause channel and floodplain constrictions; and at reservoirs, lakes, significant flooded areas, etc. Sediment budgets similar to the table are constructed for each subwatershed so the sediment yield to the point of deposition can be quantified.

A sediment budget has many uses, including identification of sediment sources for treatment (**Figure 8.34**). If the goal for a restoration initiative is to reduce sedimentation from a watershed, it is critical to know what type of erosion is producing the most sediment and where that erosion is occurring. In stream corridor restoration, sediment yield (both in terms of quantity and average grain size diameter) to a stream and its floodplain need to be identified and considered in designs. In channel stability investigations, the amount of sand and gravel sediment entering the stream from the watershed needs to be quantified to refine bed material transport calculations.

Example of a Sediment Budget

A simple application of a sediment transport equation in a field situation illustrates the use of a sediment budget. **Figure 8.35** shows a stream reach being evaluated for stability prior to developing a stream corridor restoration plan. Five representative channel cross sections (A, B, C, D, and E) are surveyed. Locations of the cross sections are selected to represent the reach above and below the points where tributary streams, D and E, enter the reach. Additional cross sections would need to be surveyed if the stream at A, B, C, D, or E is not typical of the reach.

An appropriate sediment transport equation is selected, and the transport capacity at each cross section for bed material is computed for the same flow conditions. Figure 8.35 shows the sediment loads in the stream and the transport capacities at each point.

Table 8.5: Example of a sediment budget for a watershed.

Protection Level	Erosion Source	Acres or Miles	Average Erosion Rate (tons/acre/year or tons/bank mile/year)	Annual Erosion (tons/year)	Sediment Delivery Ratio (percent)	Sediment to Streams	Sediment Deposited Uplands & Floodplains (tons/year)	Sediment Delivered to Blue Stem Lake	
								(tons/year)	(percent)
	Sheet, rill, and ephemeral gully								
Adequate	Cropland	6000	3.0	18,000	30	5400	14,380	3620	33.7
Inadequate	Cropland	1500	6.5	9750	30	2930	7790	1960	18.3
Adequate	Pasture/hayland	3400	1.0	3400	20	680	2940	460	4.3
Inadequate	Pasture/hayland	600	6.0	3600	20	720	3120	480	4.5
Adequate	Forestland	1200	0.5	600	20	120	520	80	0.7
Inadequate	Forestland	300	5.5	1650	20	330	1430	220	2.1
Adequate	Parkland	700	1.0	700	30	210	560	140	1.3
Inadequate	Parkland	0	0	0	30	0	0	0	0.0
Adequate	Other	420	2.0	840	20	170	730	110	1.0
Inadequate	Other	0	0	0	20	0	0	0	0.0
	Classic gully	N/A	N/A	600	40	240	440	160	1.5
	Streambank								
	Slight	14	50	100	700	5400	140	560	5.2
	Moderate	10.5	150	1580	100	1580	320	1260	11.7
	Severe	3.5	600	2100	100	2100	420	1680	15.7
			Total erosion	**43,520**			**Total sediment to Blue Stem Lake**	**10,730**	

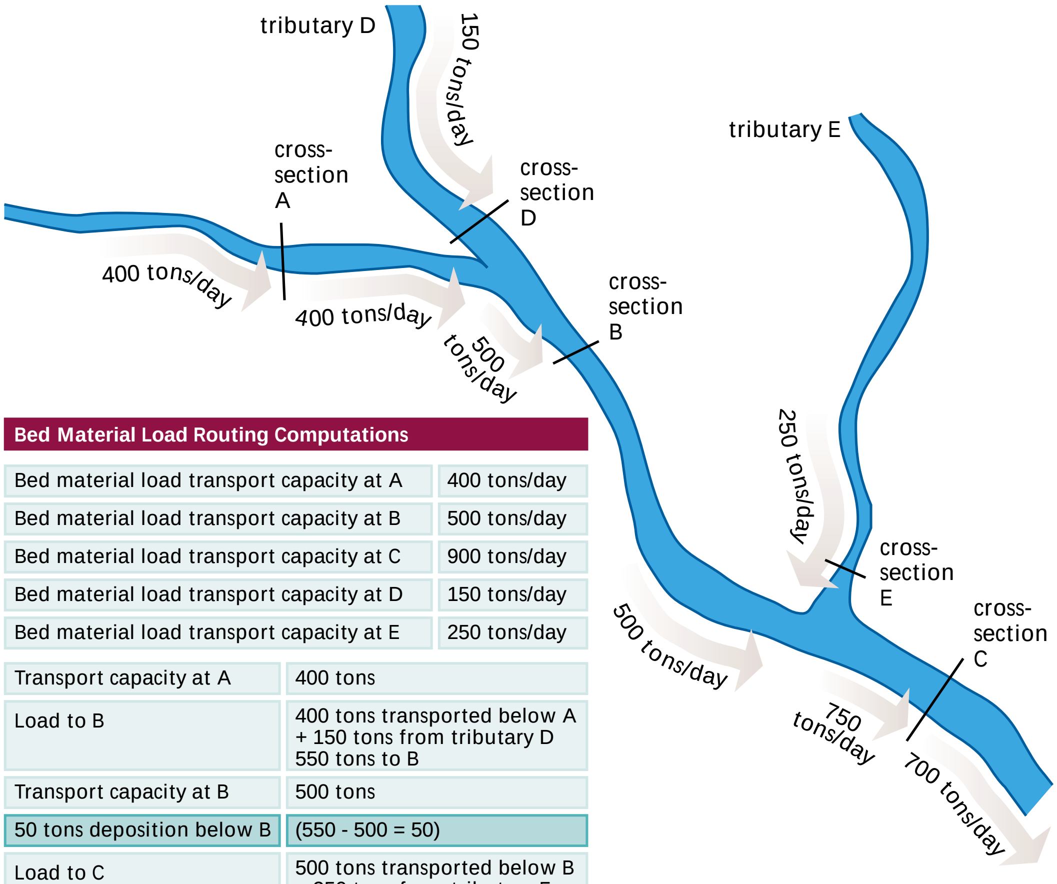
The transport capacities at each point are compared to the sediment load at each point. If the bed material load exceeds the transport capacity, deposition is indicated. If the bed material transport capacity exceeds the coarse sediment load available, erosion of the channel bed or banks is indicated.

Figure 8.35 compares the loads and transport capacities within the reach. The stream might not be stable below B due to deposition. The 50 tons/day deposition is less than 10 percent of the total bed material load in the stream. This small amount of sediment is probably within the area of uncertainty in such analyses. The stream below C probably is unstable due to the excess energy (transport capacity) causing either the banks or bottom to be eroded.

After this type of analysis is complete, the stream should be inspected for

Figure 8.34: Eroded upland area. *Upland sediment sources should be identified in a sediment budget.*

Figure 8.35: ***Sediment budget.*** *Stream reaches should be evaluated for stability prior to developing a restoration plan.*



Bed Material Load Routing Computations

Bed material load transport capacity at A	400 tons/day
Bed material load transport capacity at B	500 tons/day
Bed material load transport capacity at C	900 tons/day
Bed material load transport capacity at D	150 tons/day
Bed material load transport capacity at E	250 tons/day
Transport capacity at A	400 tons
Load to B	400 tons transported below A + 150 tons from tributary D 550 tons to B
Transport capacity at B	500 tons
50 tons deposition below B	(550 - 500 = 50)
Load to C	500 tons transported below B + 250 tons from tributary E 750 tons to C
Transport capacity at C	900 tons
150 tons erosion below C	(750 - 900 = -150 tons)

areas where sediment is building up or where the stream is eroding. If these problem areas do not match the predictions from the calculations, the sediment transport equation may be inappropriate, or the sediment budget, the hydrology, or the channel surveys may be inaccurate.

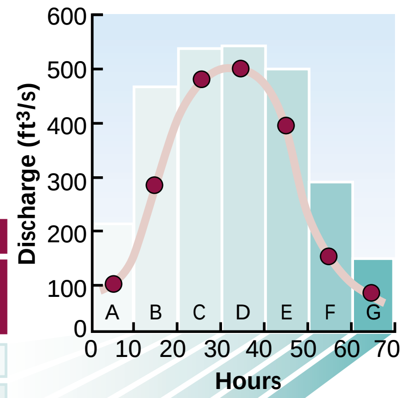
Single Storm versus Average Annual Sediment Discharge

The preceeding example predicts the amount of erosion and deposition that can be expected to occur over one day at one discharge. The bed material transport equation probably used one grain size of sediment. In reality, a variety of flows over varying lengths of time move a variety of sediment particle sizes. Two other approaches should be used to help predict the quantity of bed material sediment transported by a stream during a single storm event or over a typical runoff year.

To calculate the amount of sediment transported by a stream during a single storm event, the hydrograph for the event is divided into equal-length segments of time. The peak flow or the average discharge for each segment is determined. A spreadsheet can be developed that lists the discharges for each segment of a hydrograph in a column (**Table 8.6**). The transport capacity from the sediment rating curve for each discharge is shown in another column (**Figure 8.36**). Since the transport capacity is in tons/day, a third column should include the length of time represented by each segment of the hydro-

Table 8.6: Sediment discharges for segments of a hydrograph. *The amount of sediment discharged through a reach varies with time during a stream flow event.*

Column 1	Column 2	Column 3	Column 4	Column 5
Segment of Hydrograph	Segment Discharge (ft^3/s)	Transport Capacity (tons/day)	Segment Time (days)	Actual Transport (tons)
A	100	150	.42	62
B	280	1700	.42	708
C	483	6000	.42	2500
D	500	6500	.42	2708
E	390	4500	.42	1875
F	155	530	.42	221
G	80	90	.42	38
Total tons transported over the storm				8112



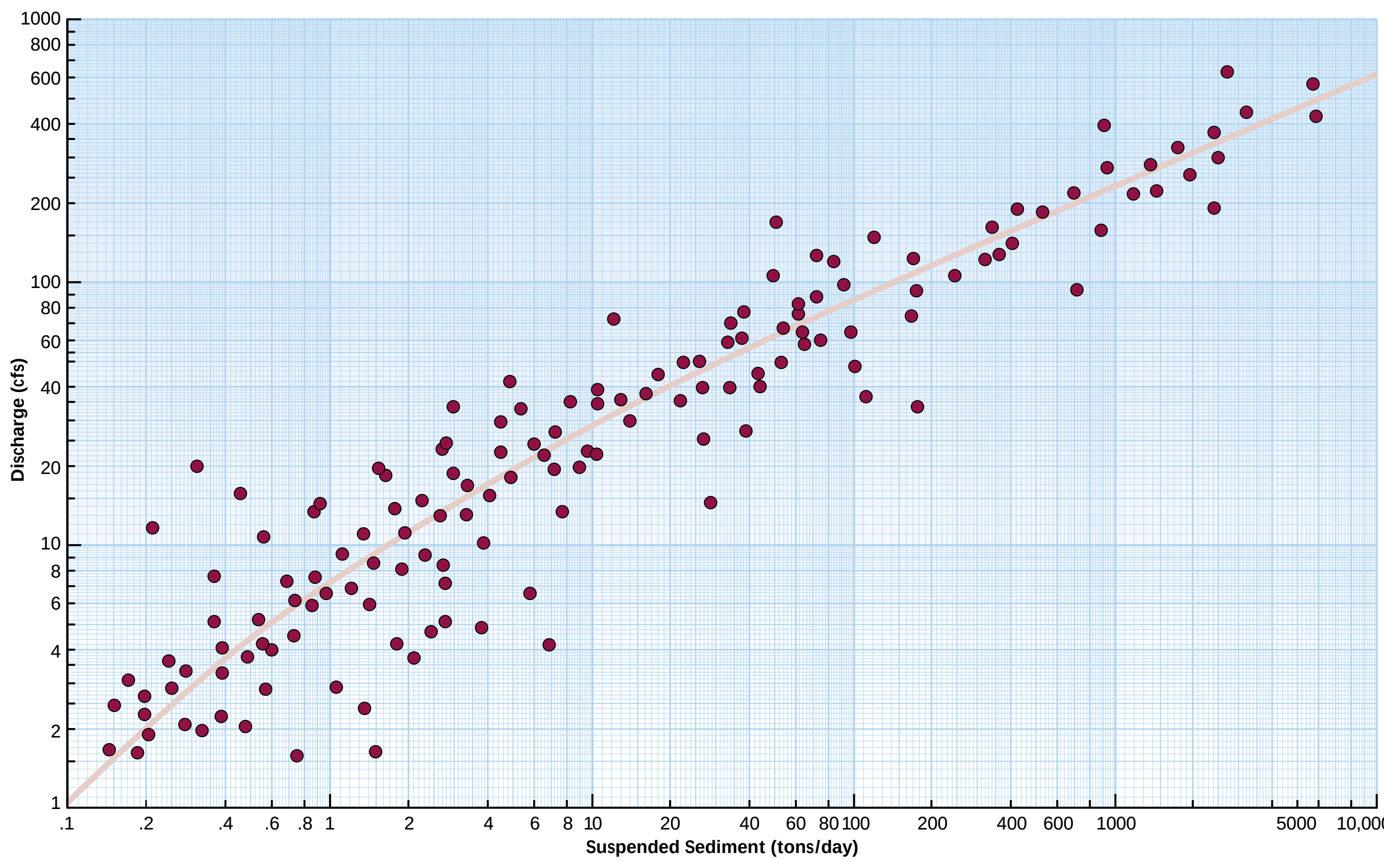


Figure 8.36: Sediment rating curve. *A "sediment rating curve" rates the quantity of sediment carried by a specific stream flow at a defined point or gage.*

graph. This column is multiplied by the transport capacity to create a final column that represents the amount of sediment that could be transported over each segment of the hydrograph. Summing the values in the last column shows the total bed material transport capacity generated by that storm.

Average annual sediment transport in a stream can be determined using a procedure very similar to the storm prediction. The sediment rating curve can be developed from predictive equations or from physical measurements. The annual flow duration curve is substituted for the segmented hydrograph. The same type of spreadsheet described above can be used, and the sum of the values in the last column is the annual sediment-transport capacity (based on predictive equations) or the actual annual sediment transport if the rating curve is based on measured data.

Sediment Discharge After Restoration

After the sediment transport analysis results have been field-checked to ensure that field conditions are accurately predicted, the same analyses are repeated for the new cross sections and slope in a reconstructed stream or stream reach. Plans and designs may be modified if the second analysis indicates significant deposition or erosion could occur in the modified reach. If potential changes in runoff or sediment yield are predicted to occur in the watershed above a potential restoration site, the sediment transport analyses should be done again based on these potential changes.

Stability Controls

The risk of a restored channel's being damaged or destroyed by erosion or deposition can be reduced if economic considerations permit installation of control measures. Control measures are also required if "natural" levels of channel instability (e.g., meander migration) are unacceptable in the restored reach.

In many cases, control measures double as habitat restoration devices or aesthetic features (Nunnally and Shields 1985, Newbury and Gaboury 1993). Control measures may be categorized as bed stabilization devices, bank stabilization devices, and hydrologic measures. Reviews of control measures are found in Vanoni (1975), Simons and Senturk (1977), Petersen (1986), Chang (1988), and USACE (1989b, 1994), and are treated only briefly here. Haan et al. (1994) provide design guidance for sediment control on small watersheds. In all cases, sediment control systems should be planned and designed with the geomorphic evolution of the watershed in mind.

8.F Streambank Restoration

Even where streams retain relatively natural patterns of flow and flooding, stream corridor restoration might require that streambanks be temporarily (years to decades) stabilized while floodplain vegetation recovers. The objective in such instances is to arrest the accelerated erosion often associated with unvegetated banks, and to reduce erosion to rates appropriate for the stream system and setting. In these situations, the initial bank protection may be provided primarily with vegetation, wood, and rock as necessary (refer to Appendix A).

In other cases, land development or modified flows may dictate the use of hard structures to ensure permanent stream stability, and vegetation is used primarily to address specific ecological deficiencies such as a lack of channel shading. In either case (permanent or temporary bank stabilization), streamflow projections are used (as described in Chapter 7) to determine the degree to which vegetation must be supplemented with more resistant materials (natural fabrics, wood, rock, etc.) to achieve adequate stabilization.

The causes of excessive erosion may be reversible through changes in land use, livestock management, floodplain restoration, or water management. In some cases, even normal rates of bank erosion and channel movement might be considered unacceptable due to adjacent development, and vegetation might be used primarily to recover some habitat functions in the vicinity of “hard” bank stabilization measures. In either case, the considerations discussed above with respect to soils, use of native plant species, etc., are applicable within the bank zone. However, a set of specialized techniques can be employed to help ensure plant establishment and improve habitat conditions.

As discussed earlier in this chapter, integration of woody vegetative cuttings, independently or in combination with other natural materials, in streambank erosion control projects is generally referred to as soil bioengineering. Soil-bioengineered bank stabilization systems have not been standardized for general application under particular flow conditions, and the decision as to whether and how to use them requires careful consideration of a variety of factors. On larger streams or where erosion is severe, an effective approach involves a team effort that includes expertise in soils, biology, plant sciences, landscape architecture, geology, engineering, and hydrology.

Soil bioengineering approaches usually employ plant materials in the form of live woody cuttings or poles of readily sprouting species, which are inserted deep into the bank or anchored in various other ways. This serves the dual purposes of resisting washout of plants during the early establishment period, while providing some immediate erosion protection due to the physical resistance of the stems. Plant materials alone are sufficient on some streams or some bank zones, but as erosive forces increase, they can be combined with other materials such as rocks, logs or brush, and natural fabrics (**Figure 8.37**). In some cases, woody debris is incorporated specifically to improve habitat characteristics of the bank and near-bank channel zones.

Preliminary site investigations (see **Figure 8.38**) and engineering analyses must be completed, as described in Chapter 7, to determine the mode of bank failure and the feasibility of using vegetation as a component of bank stabilization work. In addition to the technical analyses of flows and soils, preliminary investigations must include consideration of access, maintenance, urgency, and availability of materials.

Generalizations regarding water levels and flow velocities should be taken only as indications of the experiences reported from various bank stabilization projects. Any particular site must be evaluated to determine how vegetation can or cannot be used. Soil cohesiveness, the presence of gravel lenses, ice accumulation patterns, the amount of sunlight reaching the bank, and the ability to ensure that grazing will be precluded are all considerations in assessing the suitability of vegetation to achieve bank stabilization. In addition, modified flow patterns may make portions of the bank inhospitable to plants because of inappropriate timing of inundation rather than flow velocities and durations (Klimas 1987). The need to extend protection well beyond the immediate focus of erosion and to protect against flanking is an important design consideration.

(a)

(b)

***Figure 8.37: A stabilized streambank.** Plant materials can be combined with other materials such as rocks, logs or brush, and natural fabrics. [(a) during and (b) after.]*

As noted in Section 8.E, streambank stabilization techniques can generally be classified as armor, indirect methods, or vegetative methods. The selection of the appropriate stabilization technique is extremely important and can be expressed in terms of the factors discussed below.

Effectiveness of Technique

The inherent factors in the properties of a given bank stabilization technique, and in the physical characteristics of a proposed work site, influence the suitability of that technique for that site. Effectiveness refers to the suitability and adequacy of the technique. Many techniques can be designed to adequately solve a specific bank stability problem by resisting erosive forces and geotechnical failure. The challenge is to recognize which technique matches the strength of protection against the strength of attack and therefore performs most efficiently when tested by the strongest process of erosion and most critical mechanism of failure. Environmental and economic factors are integrated into the selection procedure, generally making soil bioengineering methods very attractive. The chosen so-

CASE STUDY

Careless Creek, Montana

In the Big Snowy Mountains of central Montana, Careless Creek begins to flow through rangelands and fields until it reaches the Musselshell River. At the beginning of the century, the stream was lined with a riparian cover, primarily of willow. This stream corridor was home to a diversity of wildlife such as pheasant, beaver, and deer.

In the 1930s, a large reservoir was constructed to the west with two outlets, one connected to Careless Creek. These channels were meant to carry irrigation water to the area fields and on to the Musselshell River. Heavy flows during the summer months began to erode the banks (Figure 8.39a). In the following years, ranchers began clearing more and more brush for pasture, sometimes burning it out along a stream.

"My Dad carried farmer's matches in his pocket. There was a worn spot on his pants where he would strike a match on his thigh," said Jessie Zeier, who was raised on a ranch near Careless Creek, recalling how his father often cleared brush.

Any remaining willows or other species were eliminated in the following years as ranchers began spraying riparian areas to control sagebrush. This accelerated the streambank erosion as barren, sometimes vertical, banks began sloughing off chunks of salted g<None>s developed to help the planning effort. Many organizations took part, including the Upper and Lower Musselshell Conservation Districts; Natural Resources Conservation Service; Montana Department of Natural Resources and Conservation; Montana Department of Fish; Wildlife and Parks; Deadman's Basin Water Users Association; U.S. Bureau of Reclamation; Central Montana RC&D; City of Roundup; Roundup Sportsmen; county commissioners; and local landowners.

As part of the planning effort, a geographic information system resource inventory was begun in 1993. The inventory revealed about 50 percent of the banks along the 18 miles of Careless Creek were eroding. The inventory helped to locate the areas causing the most problems. Priority was given to headquarters, corrals, and croplands, where stabilization of approximately 5,000 feet of streambank has taken place, funded by EPA monies.

Passive efforts have also begun to stabilize the banks. Irrigation flows in Careless Creek have been decreased for the past 5 years, enabling some areas, such as the one pictured, to begin to self-heal (Figure 8.39b). Vegetation has been given a chance to root as erosion has begun to stabilize. Other practices, such as fencing, are being implemented, and future treatments are planned to provide a long-term solution.

Figure 8.39: Careless Creek. *(a) Eroded streambank (May 1995) and (b) streambank in recovery (December 1997).*

(a)

(b)

Figure 8.38: Eroded bank. *Preliminary site investigation and analyses are critical to successful streambank stabilization design.*

lution, however, must first fulfill the requirement of being effective as bank stabilization; otherwise, environmental and economic attributes will be irrelevant. Soil bioengineering can be a useful tool in controlling streambank erosion, but it should not be considered a panacea. It must be performed in a judicious manner by personnel experienced in channel processes, biology, and streambank stabilization techniques.

Stabilization Techniques

Plants may be established on upper bank and floodplain areas by using traditional techniques for seeding or by planting bare-root and container-grown plants. However, these approaches provide little initial resistance to flows, and plantings may be destroyed if subjected to high water before they are fully established. Cuttings, pole plantings, and live stakes taken from species that sprout readily (e.g., willows) are more resistant to erosion and can be used lower on the bank (**Figure 8.40**). In addition, cuttings and pole plantings can provide immediate moderation of flow velocities if planted at high densities. Often, they can be placed deep enough to maintain contact with adequate soil moisture levels, thereby eliminating the need for irrigation. The reliable sprouting properties, rapid growth, and general availability of cuttings of willows and other pioneer species makes them particularly appropriate for use in bank revegetation projects, and they are used in most of the integrated bank protection approaches described here (see **Figure 8.41**).

Anchored Cutting Systems

Several techniques are available that employ large numbers of cuttings arranged in layers or bundles, which can be secured to streambanks and partially buried. Depending on how these systems are arranged, they can provide direct protection from erosive flows, prevent erosion from upslope water sources, promote trapping of sediments, and quickly develop dense roots and sprouts. Brush mattresses and woven mats are typically used on the face of a bank and consist of cuttings laid side by side and interwoven or pinned down with jute cord or wire held in place by stakes. Brush layers are cuttings laid on terraces dug into the bank, then buried so that the branch ends extend from the bank. Fascines or wattles are bundles of cuttings tied together, placed in shallow trenches arranged horizontally on the bank face, partially buried, and staked in place. A similar system, called a reed roll, uses partially buried and staked burlap rolls filled with soil and root material or rooted shoots to establish herbaceous species in appropriate habitats. Anchored bundles of live cuttings also have been installed perpendicular to the channel on newly constructed gravel floodplain areas to dissipate floodwater energy and encourage deposition of sediment (Karle and Densmore 1994).

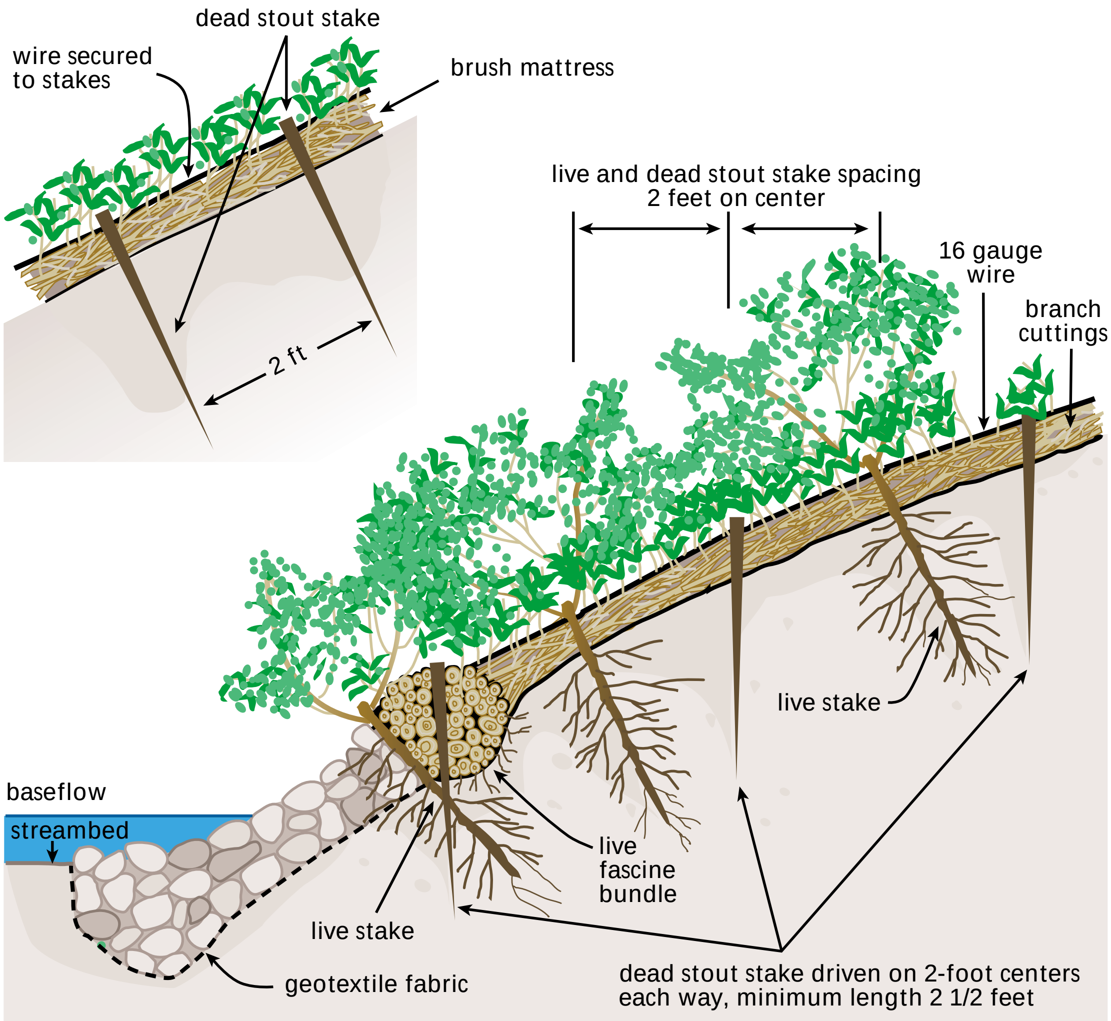


***Figure 8.40*: Cutting systems.** *Details of brushmattress technique.*
Source: USDA-NRCS 1996a.
Note: Rooted/leafed condition of the living plant material is not representative at the time of installation.

Geotextile Systems

Geotextiles have been used for erosion control on road embankments and other upland settings, usually in combination with seeding, or with plants placed through slits in the fabric. In self-sustaining streambank applications, only natural, biodegradable materials should be used, such as jute or coconut fiber (Johnson and Stypula 1993). The typical streambank use for these materials is in the construction of vegetated geogrids, which are similar to brush layers except that the fill soils between the layers of cuttings are encased in fabric, allowing the bank to be constructed of successive "lifts" of soil, alternating with brush layers. This approach allows reconstruction of a bank and provides considerable erosion resistance (see Green River case study). Natural fibers are also used in "fiber-schines," which are sold specifically for streambank applications. These are cylindrical fiber bundles that can be staked to a bank with cuttings or rooted plants inserted through or into the material.

Vegetated plastic geogrids and other nondegradable materials can also be used where geotechnical problems require drainage or additional strength.

Figure 8.41*: *Results of live staking along a streambank. *Pioneer species are often most appropriate for use in bank revegetation projects.*

Integrated Systems

A major concern with the use of structural approaches to streambank stabilization is the lack of vegetation in the zone directly adjacent to the water. Despite a long-standing concern that vegetation destabilizes stone revetments, there has been little supporting evidence and even some evidence to the contrary (Shields 1991). Assuming that loss of conveyance is accounted for, the addition of vegetation to structures should be considered. This can involve placement of cuttings during construction, or insertion of cuttings and poles between stones on existing structures. Timber cribwalls may also be constructed with cuttings or rooted plants extending through the timbers from the backfill soils.

Trees and Logs

Tree revetments are made from whole tree trunks laid parallel to the bank, and cabled to piles or deadman anchors. Eastern red cedar (Juniperus virginiana) and other coniferous trees are used on small streams, where their springy branches provide interference to flow and trap sediment. The principal objective to these systems is the use of large amounts of cable and the potential for trees to be dislodged and cause downstream damage.

Some projects have successfully used large trees in conjunction with stone to provide bank protection as well as improved aquatic habitat (see case study). Large logs with intact root wads are placed in trenches cut into the bank, such that the root wads extend beyond the bank face at the toe (**Figure 8.42**). The logs are overlapped and/or braced with stone to ensure stability, and the protruding rootwads effectively reduce flow velocities at the toe and over a range of flow elevations (**Figure 8.43**). A major advantage of this approach is that it reestablishes one of the natural roles of large woody debris in streams by creating a dynamic near-bank environment that traps organic material and provides colonization substrates for invertebrates and refuge habitats for fish. The logs eventually rot, resulting in a more natural bank. The revetment stabilizes the bank until woody vegetation has matured, at which time the channel can return to a more natural pattern.

In most cases, bank stabilization projects use combinations of the techniques described above in an integrated approach. Toe protection often requires the use of stone, but amounts can be greatly reduced if large logs can also be used. Likewise, stone blankets on the bank face can be replaced with geogrids or supplemented with interstitial plantings. Most upper bank areas can usually be stabilized using vegetation alone, although anchoring systems might be required. The Green River bank restoration case study illustrates one successful application of an integrated approach on a moderate-sized river in Washington State.

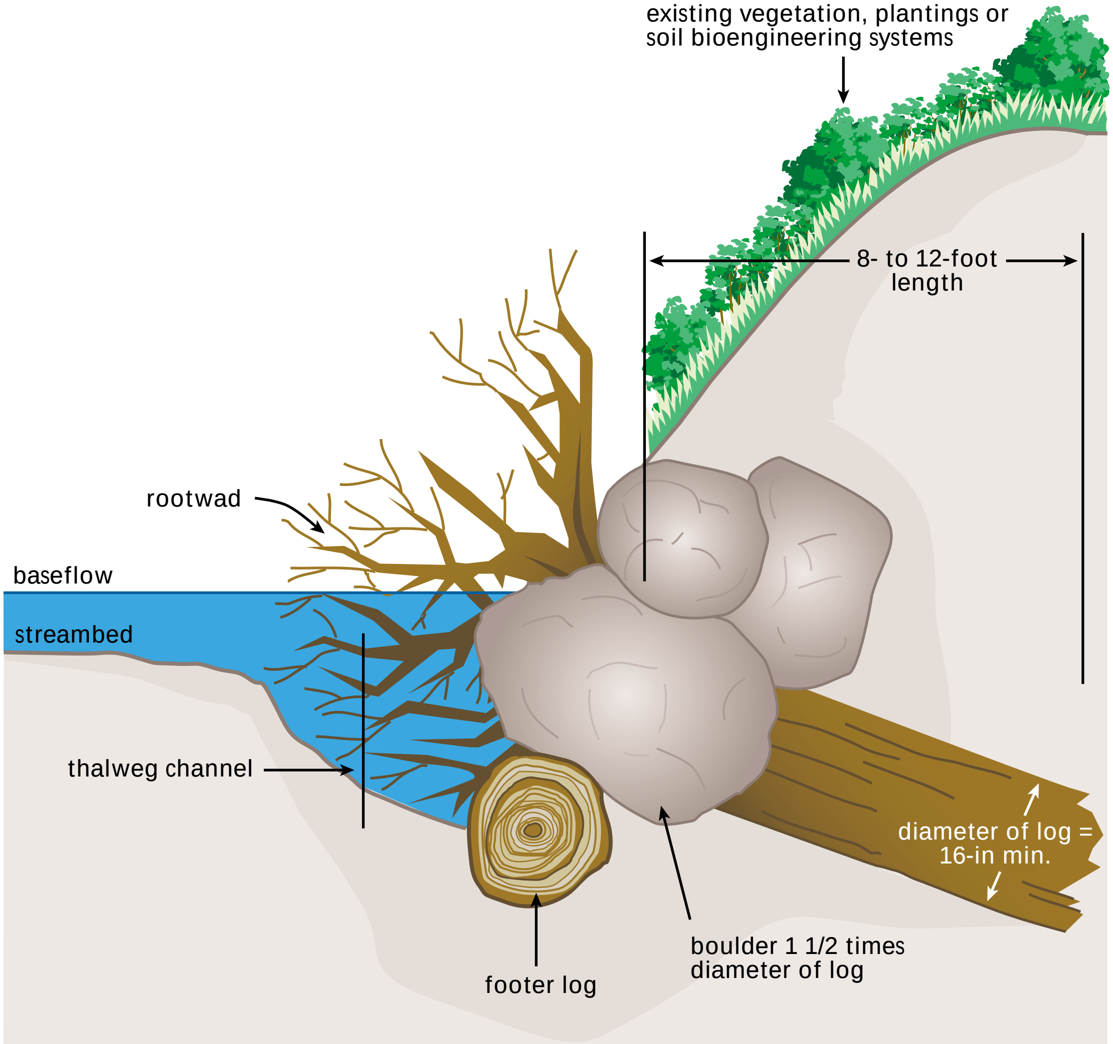


Figure 8.42: Revetment system. *Details of rootwad and boulder technique.* Source: USDA-NRCS 1996a.

Figure 8.43: Installation of logs with intact root wads. *An advantage to using tree revetments is the creation of habitat for invertebrates and fish along the streambank.*

CASE STUDY

Green River Bank Restoration Initiative

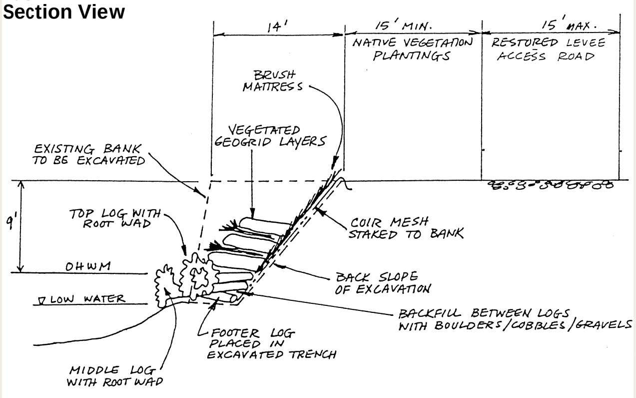
King County, Washington

*The King County, Washington, Surface Water Management Division initiated a bank restoration initiative in 1994 that illustrates a variety of project objectives and soil bioengineering approaches (**Figure 8.44**). The project involved stabilization of the bank of the Green River along a 500-foot section of a meander bend that was rapidly migrating into the adjacent farm field. The project objectives included improvement of fish and wildlife habitat, particularly for salmonids.*

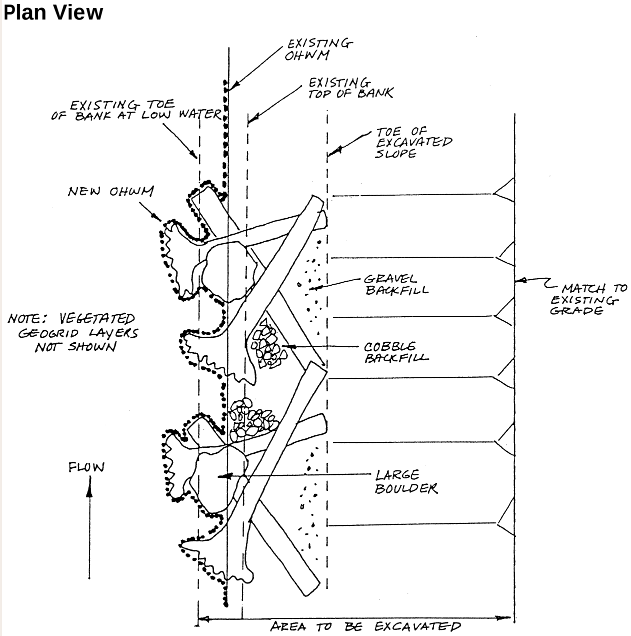
Site investigations included surveys of stream cross sections, velocity measurements at two discharge levels, soil characterizations, and assessment of fish use of existing habitat features in the area. The streambank was vertical, 5 to 10 feet high, and composed of silty-clay-loam alluvium with gravel lenses. Flow velocities were 2 to 5 fps for flows of 200 and 550 cfs. Fish were primarily observed in areas of low velocities and/or near woody debris, and along the channel margins.

*In August, large woody debris was installed along the toe of the bank. The logs were cedar and fir, 25 feet long and 28 to 36 inches in diameter, with root wads 6 to 8 feet in diameter. The logs were placed in trenches cut 15 feet back into the bank so that the root wads extended into the channel, and large (3- to 4-foot diameter) boulders were placed among the logs at the toe. Log and boulder placement was designed to interlock and brace the logs and prevent movement. The project used approximately 10 logs and 20 boulders per 100 lineal feet of bank. In September, vegetated geogrids were installed above the toe zone to stabilize the high bank (**Figure 8.45**). The project was completed with installation of a variety of plants, including container-grown conifers and understory species, in a minimum 25-foot buffer along the top of the bank.*

*Within 2 months of completion, the site was subjected to three high flows, including an 8,430-cfs event in December 1994. Measured velocities along the bank were less than 2 fps at the surface and less than 1 fps 2 feet below the surface, indicating the effectiveness of the root wads in moderating flow velocities (**Figure 8.46**). Some surface erosion and washout of plants along the top bank occurred, and a subsequent event caused minor damage to the geogrid at one location. The maintenance repairs consisted of replanting and placement of additional logs to*



(a)



(b)

Figure 8.44: Construction details.
Source: King County Surface Water Management Division.

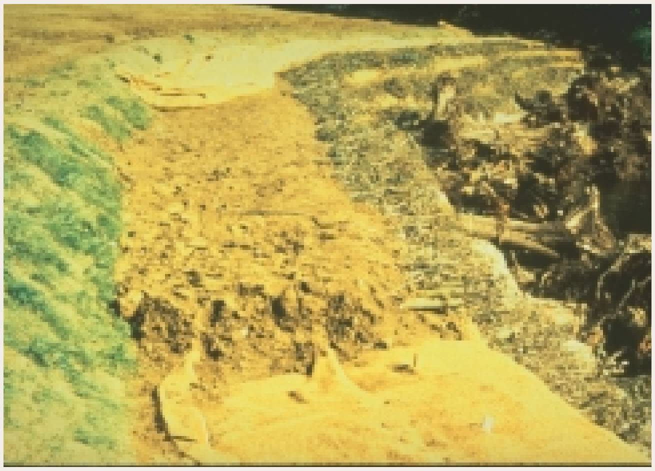


Figure 8.45: Partially installed vegetated geogrid. *Installed above the toe to stabilize high bank.*

Figure 8.46: Completed system. *Note calm water along bankline during high flow.*

*halt undermining of the geogrid. The 1995 growing season produced dramatic growth of the willow cuttings in the geogrid, although many of the planted trees in the overbank zone died (**Figure 8.47**). Initial observations have documented extensive fish use of the slow-water habitats among the root wads at the toe of the bank, and in scour holes created by flows deflected toward the channel bottom.*

The site continues to be carefully monitored, and the effectiveness of the approach has led to the implementation of similar designs elsewhere in the region. The project designers have concluded that future projects of this type should use small plants rather than large rooted material in the overbank zone to reduce costs, improve survival, and minimize damage due to equipment access for maintenance or repair. Based on their observations of fish response along the restored bank and in nearby stream reaches, they also recommend that future projects incorporate a greater variety of woody debris, including brushy material and tree tops, along the toe and lower bank.

Figure 8.47: Completed system after one year. *Note dramatic willow growth from vegetated geogrid.*

8.G Instream Habitat Recovery

As described in Chapter 2, habitat is the place where a population lives and includes living and nonliving components. For example, fish habitat is a place, or set of places, in which a single fish, a population, or an assemblage of fish can find the physical, chemical, and biological features needed for life, including suitable water quality, passage routes, spawning grounds, feeding and resting sites, and shelter from predators and adverse conditions (**Figure 8.48**). Principal factors controlling the quality of the available aquatic habitat include:

- Streamflow conditions.
- Physical structure of the channel.
- Water quality (e.g., temperature, pH, dissolved oxygen, turbidity, nutrients, alkalinity).
- The riparian zone.
- Other living components.

The existing status of aquatic habitats within the stream corridor should be assessed during the planning stage (Part II). Design of channels, structures, or restoration features can be guided and fine tuned by assessing the quality and quantity of habitats provided by the proposed design. Additional guidance on assessing the quantity and quality of aquatic habitat is provided in Chapter 7.

This section discusses the design of instream habitat structures for the purpose of enhancing physical aquatic habitat quality and quantity. It should be noted, however, that the best approach to habitat recovery is to restore a fully functional, well-vegetated stream corridor within a well-managed watershed. Man-made structures are less sustainable and rarely as effective as a stable channel. Over the long term, design should rely on natural fluvial processes interacting with floodplain vegetation and associated woody debris to provide high-quality aquatic habitat. Structures have little effect on populations that are limited by factors other than physical habitat.

Figure 8.48: Instream habitat. *Suitable water quality, passage routes, and spawning grounds are some of the characteristics of fish habitat.*

Instream Habitat Features

The following procedures to restore instream habitat are adapted from Newbury and Gaboury (1993) and Garcia (1995).

- Select stream. Give priority to reaches with the greatest difference between actual (low) and potential (high) fish carrying capacity and with a high capacity for natural recovery processes.
- Evaluate fish populations and their habitats. Give priority to reaches with habitats and species of special interest. Is this a biological, chemical, or physical problem? If a physical problem:
- Diagnose physical habitat problems.
  - Drainage basin. Trace watershed lines on topographical and geological maps to identify sample and rehabilitation basins.
  - Profiles. Sketch main stem and tributary long profiles to identify discontinuities that might cause abrupt changes in stream characteristics (falls, former base levels, etc.).
  - Flow. Prepare flow summary for rehabilitation reach using existing or nearby records if available (flood frequency, minimum flows, historical mass curve). Correct for drainage area differences. Compare magnitude and duration of flows during spawning and incubation to year class strength data to determine minimum and maximum flows required for successful reproduction.
  - Channel geometry survey. Select and survey sample reaches to establish the relationship between channel geometry, drainage area, and bankfull channel-forming discharge (**Figure 8.49**). Quantify hydraulic parameters at design discharge.
  - Rehabilitation reach survey. Survey rehabilitation reaches in sufficient detail to prepare channel cross section profiles and construction drawings and to establish survey reference markers.
  - Preferred habitat. Prepare a summary of habitat factors for biologically preferred reaches using regional references and surveys. Identify multiple limiting factors for the species and life stages of greatest concern. Where possible, undertake reach surveys in reference streams with proven populations to identify local flow conditions, substrate, refugia, etc.
- Design a habitat improvement plan. Quantify the desired results in terms of hydraulic changes, habitat improvement, and population increases. Integrate selection and sizing of rehabilitation works with instream flow requirements.
  - Select potential schemes and structures that will be reinforced by the

Man-made structures are less sustainable and rarely as effective as a stable channel.

Figure 8.49: Surveying a stream. *Channel surveys establish baseline information needed for restoration design.*

existing stream dynamics and geometry. The following section provides additional detail on use of habitat structures.

    - Test designs for minimum and maximum flows and set target flows for critical periods derived from the historical mass curve.

- Implement planned measures.
    - Arrange for on-site location and elevation surveys and provide advice for finishing details in the stream.

- Monitor and evaluate results.
    - Arrange for periodic surveys of the rehabilitated reach and reference reaches, to improve the design, as the channel ages.

FAST FORWARD

Preview Chapter 9 for an introduction to construction and monitoring follow-up activities.

Instream Habitat Structures

Aquatic habitat structures (also called instream structures and stream improvement structures) are widely used in stream corridor restoration. Common types include weirs, dikes, random rocks, bank covers, substrate reinstatement, fish passage structures, and off-channel ponds and coves. Institutional factors have favored their use over more holistic approaches to restoration. For example, it is often easier to obtain authority and funding to work within a channel than to influence riparian or watershed land use. Habitat structures have been used more along cold water streams supporting salmonid fisheries than along warm water streams, and the voluminous literature is heavily weighted toward cold water streams.

In a 1995 study entitled Stream Habitat Improvement Evaluation Project, 1,234 structures were evaluated according to their general effectiveness, the habitat quality associated with the given structure type, and actual use of the structures by fish (Bio West 1995). The study determined approximately 18 percent of the structures need maintenance. Where inadequate flows and excessive sediment delivery occur, structures have a brief lifespan and limited value in terms of habitat improvement. Furthermore, the study concluded that instream habitat structures generally provided increased fish habitat.

Before structural habitat features are added to a stream corridor restoration design, project managers should carefully determine whether they address the real need and are appropriate. Major caveats include the following:

- Structures should never be viewed as a substitute for good riparian and upland management.
- Defining the ecological purpose of a structure and site selection are as important as construction technique.
- Scour and deposition are natural stream processes necessary to create fish habitat. Overstabilization therefore limits habitat potential, whereas properly designed and sited structures can speed ecological recovery.
- Use of native materials (stone and wood) is strongly encouraged.
- Periodic maintenance of structures will be necessary and must be incorporated into project planning.

Instream Habitat Structure Design

Design of aquatic habitat structures should proceed following the steps presented below (Shields 1983). However, the process should be viewed as iterative, and considerable recycling among steps should be expected.

- Plan layout.
- Select types of structures.
- Size the structures.
- Investigate hydraulic effects.

- Consider effects on sediment transport.
- Select materials and design structures.

Each step is described below. Construction and monitoring follow-up activities are described in Chapter 9.

Plan Layout

The location of each structure should be selected. Avoid conflicts with bridges, riparian structures, and existing habitat resources (e.g., stands of woody vegetation). The frequency of structures should be based on the habitat requirements previously determined, within the context of the stream morphology and physical characteristics (see Chapter 7). Care should be taken to place structures where they will be in the water during baseflow. Structures should be spaced to avoid large areas of uniform conditions. Structures that create pools should be spaced five to seven channel widths apart. Weirs placed in series should be spaced and sized carefully to avoid placing a weir within the backwater zone of the downstream structure, since this would create a series of pools with no intervening riffles or shallows.

Select Types of Structures

The main types of habitat structures are weirs, dikes (also called jetties, barbs, deflectors (**Figure 8.50**), spurs, etc.), random rocks (also called boulders), and bank covers (also called lunkers). Substrate reinstatement (artificial riffles), fish passage structures, and off-channel ponds and coves have also been widely employed. Fact sheets on several of these techniques are provided in the *Techniques Appendix*, and numerous design web sites are available (White and Brynildson 1967, Seehorn 1985, Wesche 1985, Orsborn et al. 1992, Orth and White 1993, Flosi and Reynolds 1994).

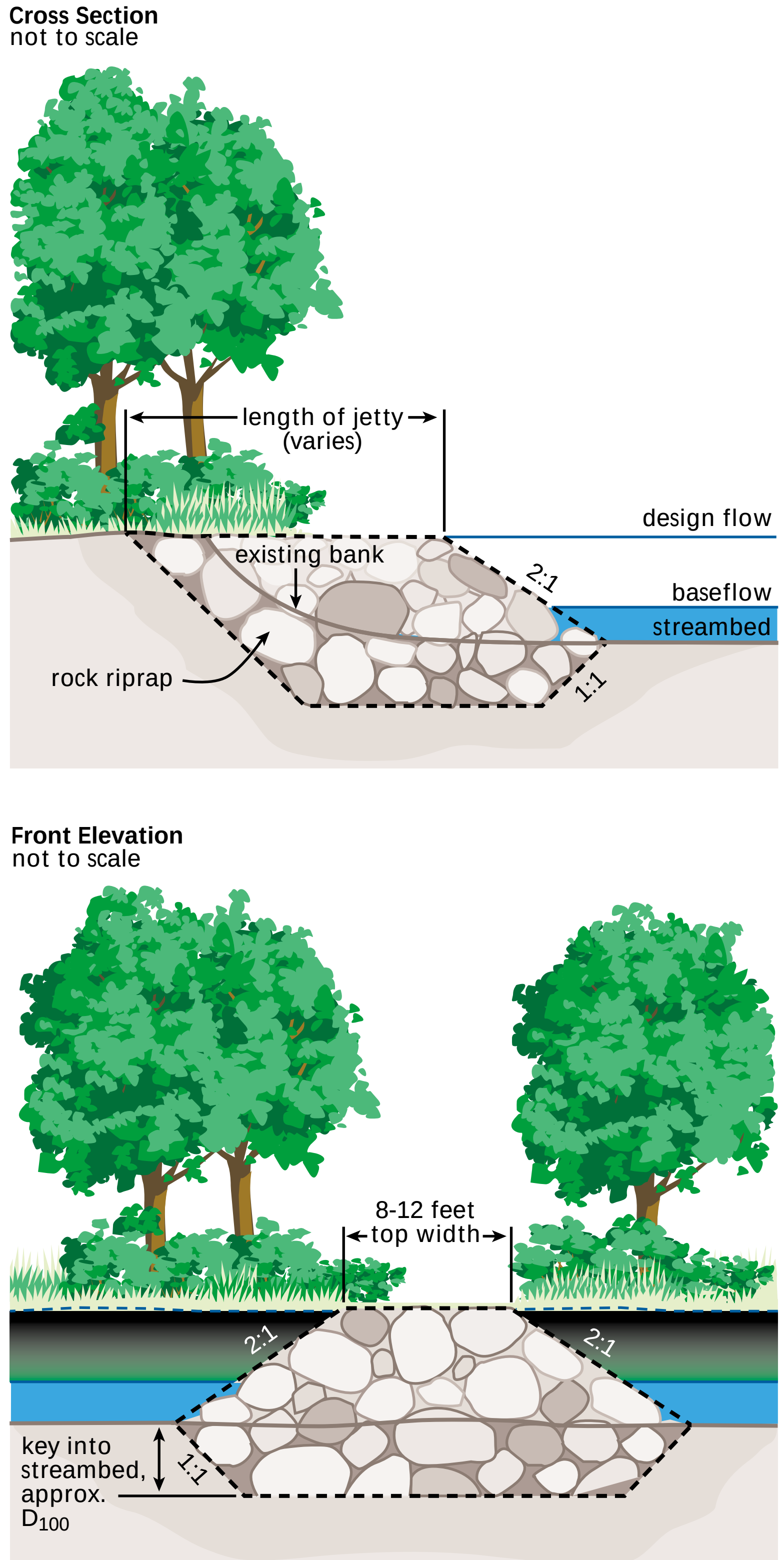


Figure 8.50: Instream habitat structure.
Wing deflector habitat structure.
Source: USDA-NRCS 1996a.

Evidence suggests that traditional design criteria for widespread bank and bed stabilization measures (e.g., concrete grade control structures, homogeneous riprap) can be modified, with no functional loss, to better meet environmental objectives and improve habitat diversity. **Table 8.7** may be used as a general guide to relate structural type to habitat requirement. Weirs are generally more failure-prone than deflectors. Deflectors and random rocks are minimally effective in environments where higher flows do not produce sufficient local velocities to produce scour holes near structures. Random rocks (boulders) are especially susceptible to undermining and burial when placed in sand-bed channels, although all types of stone structures experience similar problems. Additional guidance for evaluating the general suitability of various fish habitat structures for a wide range of morphological stream types is provided by Rosgen (1996). Seehorn (1985) provides guidance for small streams in the eastern United States. The use of any of these guides should also consider the relative stability of the stream, including aggradation and incision trends, for final design.

Size the Structures

Structures should be sized to produce the desired aquatic habitats at the normal range of flows from baseflow to bankfull discharge. A hydrological analysis can provide an estimate of the normal range of flows (e.g., a flow duration curve), as well as an estimate of extreme high and low flows that might be expected at the site (see Chapter 7). In general, structures should be low enough that their effects on the water surface profile will be slight at bankfull discharge. Detailed guidance by structural type is presented in the Techniques Appendix. For informal design, empirical equations like those presented by Heiner (1991) can be used to roughly estimate the depth of scour holes at weirs and dikes.

Investigate Hydraulic Effects

Hydraulic conditions at the design flow should provide the desired habitat; however, performance should also be evaluated at higher and lower flows. Barriers to movement, such as extremely shallow reaches or vertical drops not submerged at higher flows, should be avoided. If the conveyance of the channel is an issue, the effect of the proposed structures on stages at high flow should be investigated. Structures may be included in a standard backwater calculation model as contractions, low weirs, or increased flow resistance (Manning) coefficients, but the amount of increase is a matter of judgment or limited by National Flood Insurance Program ordinances. Scour holes should be included in the channel geometry downstream of weirs and dike since a major portion of the head loss occurs in the scour hole. Hydraulic analysis should include estimation or computation of velocities or shear stresses to be experienced by the structure.

Consider Effects on Sediment Transport

If the hydraulic analysis indicates a shift in the stage-discharge relationship, the sediment rating curve of the restored reach may change also, leading to deposition or erosion. Although modeling analyses are usually not cost-effective for a habitat structure design effort, informal analyses based on assumed relationships between velocity and sediment discharge at the bankfull discharge may be helpful in detecting potential problems. An effort should be made to predict the locations and magnitude of local scour and deposi-

Table 8.7: Fish habitat improvement structures—suitability for stream types.
Source: Rosgen 1996.

Channel Type	Low St. Check Dam	Medium St. Check Dam	Boulder Placement	Bank Boulder Placement	Single Wing Deflector	Double Wing Deflector	Channel Constrictor	Bank Cover
A1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B1-1	Poor	Poor	Good	Excellent	Poor	Poor	Poor	Good
B1	Excellent	Excellent	N/A	N/A	Excellent	Excellent	N/A	Excellent
B2	Excellent	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
B3	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
B4	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
B5	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
C1-1	Poor	Poor	Fair	Excellent	Poor	Poor	Poor	Good
C1	Good	Fair	Fair	Excellent	Good	Good	Fair	Good
C2	Excellent	Good	Good	Excellent	Good	Excellent	Excellent	Good
C3	Fair	Poor	Poor	Good	Fair	Fair	Fair	Good
C4	Fair	Poor	Poor	Good	Poor	Poor	Poor	Fair
C5	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
C6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D1	Fair	Poor	Poor	Fair	Fair	Fair	Fair	Poor
D2	Fair	Poor	Poor	Fair	Fair	Fair	Fair	Poor

Channel Type	Half Log Cover	Floating Log Cover	Submerged Shelter		Migration Barrier	Gravel Traps		Gravel Placement
			Meander	Straight		"V" Shaped	Log	
A1	N/A	N/A	N/A	N/A	Excellent	Good	Poor	Poor
A2	N/A	N/A	N/A	N/A	Excellent	Excellent	Excellent	Poor
B1-1	Good	Good	Good	Excellent	Fair	Good	Good	Fair
B1	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair
B2	Excellent	Excellent	Good	Excellent	Good	Good	Good	Good
B3	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
B4	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
B5	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
C1-1	Good	Good	Good	Excellent	Poor	Fair	Fair	Fair
C1	Good	Good	Good	Excellent	Poor	Fair	Good	Fair
C2	Good	Excellent	Excellent	Excellent	Poor	Good	Excellent	Excellent
C3	Fair	Good	Fair	Good	Poor	N/A	N/A	N/A
C4	Poor	Good	Fair	Good	Poor	Poor	Poor	Poor
C5	Poor	Good	Fair	Good	Poor	Poor	Poor	Poor
C6	N/A	N/A	N/A	N/A	Poor	Poor	Fair	Fair
D1	Poor	Poor	Poor	Poor	Poor	Poor	N/A	Poor
D2	Poor	Poor	Poor	Poor	Poor	N/A	Poor	Poor

Key:
Excellent - No limitation to location of structure placement or special modification in design.
Good - Under most conditions, very effective. Minor modification of design or placement required.
Fair - Serious limitation which can be overcome by placement location, design modification, or stabilization techniques. Generally not recommended due to difficulty of offsetting potential adverse consequences and high probability of reduced effectiveness.
Poor - Not recommended due to morphological character of stream type and very low probability of success.
Not Applicable- Generally not considered since habitat components are not limiting.

Note : A3, A3-a, A4, A4-a, A5, A5-a channel types are not evaluated due to limited fisheries value.

tion. Areas projected to experience significant scour and deposition should be prime sites for visual monitoring after construction.

Select Materials

Materials used for aquatic habitat structures include stone, fencing wire, posts, and felled trees. Priority should be given to materials that occur on site under natural conditions. In some cases, it may be possible to salvage rock or logs generated from construction of channels or other project features. Logs give long service if continuously submerged. Even logs not continuously wet can give several decades of service if chosen from decay-resistant species. Logs and timbers must be firmly fastened together with bolts or rebar and must be well anchored to banks and bed. Stone size should be selected based on design velocities or shear stress.

8.H Land Use Scenarios

As discussed in Chapter 3, most stream corridor degradation is directly attributable to land use practices and/or hydrologic modifications at the watershed level that cause fundamental disruption of ecosystem functions (Beschta et al. 1994) (**Figure 8.51**). Ironically, land use practices, including hydrologic modifications, can offer the opportunity for restoring these same degraded stream corridors. Where feasible, the objective of the restoration design should be to eliminate or moderate disruptive influences sufficiently to allow recovery of dynamic equilibrium over time (NRC 1992).

***Figure 8.51**: Sediment-laden stream.* *Most stream corridor degradation can be attributed to impacts resulting from surrounding land uses.*

If chronic land use impacts on the stream or riparian system cannot be controlled or moderated, or if some elements of the stream network (e.g., headwaters) are not included in the restoration design, it must be recognized that the restoration action may have limited effectiveness in the long-term.

Restoration measures can be designed to address particular, site-specific deficiencies (an eroding bank, habitat features), but if they do not restore self-maintaining processes and the functions of a stream corridor, they must be regarded as a focused "fix" rather than an ecosystem restoration. In cases where land use practices are the direct cause of stream corridor degradation and there is a continuing downward trend in landscape condition, there is little point in expending resources to address symptoms of the problem rather than the problem itself (DeBano and Schmidt 1989).

Design Approaches for Common Effects

Agriculture, forestry, grazing, mining, recreation, and urbanization are some of the principal land uses that can result in disturbance of stream corridor structure and functions. A watershed analysis will help prioritize and coordinate restoration actions (Platts and Rinne 1985, Swanson 1989) and may indicate critical or chronic land use activities causing disturbance both inside and outside the stream corridor. Addressing these in the restoration plan and design, may greatly improve the effectiveness and success of restoration work.

Restoration measures designed in response to these effects may be similar across land uses. Sediment and nutrient management in urban, agricultural, and forest settings, for instance, may require the use of buffer strips. Although the buffer strips have many common design characteristics, each setting has site-specific factors.

Dams

Dams alter the flow of water, sediment, organic matter, and nutrients, resulting in both direct physical and indirect biological effects in tailwaters and downstream riparian and floodplain areas (see Chapter 3). Stream corridors below dams can be partially restored by modifying operation and management approaches. Impacts from the operation of dams on surface water quality and aquatic and riparian habitat should be assessed and the potential for improvement evaluated. The modification of operation approaches, where possible, in combination with the application of properly designed and applied best management practices, can reduce the impacts caused by dams on downstream riparian and floodplain habitats. Best management practices can be applied individually or in combination to protect and improve surface water quality and aquatic habitat in reservoirs as well as downstream. Several approaches have been designed for improving or maintaining acceptable levels of dissolved oxygen (DO), temperature, and other constituents in reservoirs and tailwaters. One design approach uses pumps, air diffusers, or air lifts to induce circulation and mixing of the oxygen-poor but cold hypolimnion with the oxygen-rich but warm epilimnion, resulting in a more thermally uniform reservoir with increased DO. Another design approach for improving water quality in tailwaters for trout fisheries involves mixing of air or oxygen with water passing through the turbines at hydropower dams to improve concentrations of DO. Reservoir waters can also be aerated by venting turbines to the atmosphere or by injecting compressed air into the turbine chamber (USEPA 1993).

Modification to the intakes, the spillway, or the tailrace of a dam can also be designed to improve temperature or DO levels in tailwaters. Installing various types of weirs downstream of a dam achieves similar results. These design practices rely on agitation and turbulence to mix reservoir releases with atmospheric air to increase levels of DO (USEPA 1993).

Adequate fish passage around dams, diversions, and other obstructions may be a critically important component of restoring healthy fish populations to previously degraded rivers and streams. A fact sheet in Appendix A shows an example for fish passages. However, designing, installing, and operating fish passage facilities at dams are beyond the scope of this handbook. Further, the type of fish passage facility and the flows necessary for operation are generally site specific. Further information on fish passage technology can be found in other references, including Environmental Mitigation at Hydroelectric Projects - Volume II. Benefits and Costs of Fish Passage and Protection (Francfort et al., 1994); and Fish Passage Technologies: Protection at Hydropower Facilities (Office of Technology Assessment, Congress of the United States, Washington DC, OTA-ENV-641).

Adjusting operation procedures at some dams can also result in improved quality of reservoir releases and downstream conditions. Partial restoration of stream corridors below dams can be achieved by designing operation procedures that mimic the natural hydrograph, or desirable aspects of the hydrograph. Modifications include scheduling releases or the duration of shutoff periods, instituting procedures for the maintenance of minimum flows, and making seasonal adjustments in pool levels and in the timing and variation of the rates of drawdowns (USEPA 1993).

Modifying operation and management approaches, in combination with the application of properly designed best management practices, can be an effective approach to partially restoring stream corridors below dams. However, dam removal is the only way to begin to fully restore a stream to its natural condition. It is important to note, however, that unless accomplished very carefully, with sufficient studies and modeling and at significant cost, removing a dam can cause more damage downstream (and upstream) than the dam is currently causing until a state of dynamic equilibrium is reached. Dam removal lowers the base level of upstream tributaries, which can cause rejuvenation, bed and bank instability, and increased sediment loads. Dam removal can also result in the loss of wetlands and habitat in the reservoir and tributary deltas.

Three options should be considered—complete removal, partial removal, and staged breaching. The option is selected based on the condition of the dam and future maintenance required if not completely removed, and on the best way to deal with the sediment now stored behind the dam. The following elements must be considered in managing sediment:

- Removing features of dams necessary to restore fish passage and ensure safety.
- Revegetation of the reservoir areas.
- Long-term monitoring of sediment transport and river channel topography, water quality, and aquatic ecology.
- Long-term protection of municipal and industrial water supplies.
- Mitigation of flood impacts caused by long-term river aggradation.
- Quality of sediment, including identification of the lateral and vertical occurrence of toxic or otherwise poor-quality sediment.

Water quality issues are primarily related to suspended sediment concentration and turbidity. These are important to municipal, industrial, and private water users, as well as to aquatic communities. Water quality will primarily be affected by any silt and clay released from the reservoirs and by reestablishment of the natural sediment loads downstream. During removal of the dam and draining of the lake, the unvegetated reservoir bottoms will be exposed. Lakebeds will be expected to have large woody debris and other organic material. A revegetation program is necessary to control dust, surface runoff, and erosion and to restore habitat and aesthetic values. A comprehensive sediment management plan is needed to address the following:

- Sediment volume and physical properties.
- Sediment quality and associated disposal requirements.
- Hydraulic and biological characteristics of the reservoir and downstream channel.
- Alternative measures for sediment management.
- Impacts on downstream environment and channel hydraulics.
- Recommended measures to manage sediment properly and economically.

Objectives of sediment management should include flood control, water quality, wetlands, fisheries, habitat, and riparian rights.

For hydropower dams, the simplest decommissioning program is to dismantle the turbine-generator and seal the water passages, leaving the dam and water-retaining structures in place. No action is taken concerning the sediments since they will remain in the reservoir and the hydraulic and physical characteristics of the river and reservoir will remain essentially unchanged. This approach is viable only if there are no deficiencies in the water-retaining structures (such as inadequate spillway capacity or inadequate factors of safety for stability) and long-term maintenance is ensured. In some cases, decommissioning can include partial removal of water-retaining structures. Partial removal involves demolition of a portion of the dam to create a breach so that it no longer functions as a water-retaining structure.

For additional information, see Guidelines for the Retirement of Hydroelectric Facilities published by the American Society of Civil Engineers (ASCE) in 1997.

Channelization and Diversions

Channelization and flow diversions represent forms of hydrologic modification commonly associated with most principal land uses, and their effects should be considered in all restoration efforts (see Chapter 3). In some cases, restoration design can include the removal or redesign of channel modifications to restore preexisting ecological and flow characteristics.

Modifications of existing projects, including operation and maintenance or management, can improve some negative effects without changing the existing benefits or creating additional problems. Levees may be set back from the stream channel to better define the stream corridor and reestablish some or all of the natural floodplain functions. Setback levees can be constructed to allow for overbank flooding, which provides surface water contact with streamside areas such as floodplains and wetlands.

Instream modifications such as uniform cross sections or armoring associated with channelization or flow diversions may be removed, and design and placement of meanders can be used to reestablish more natural channel characteristics. In many cases, however, existing land uses might limit or prevent the removal of existing channel or floodplain modifications. In such cases, restoration design must consider the effects of existing channel modifications or flow diversions, in the corridor and the watershed.

Exotic Species

Exotic species are another common problem of stream corridor restoration and management. Some land uses have actually introduced exotics that have become uncontrolled, while others have merely created an opportunity for such

CASE STUDY

The Multispecies Riparian Buffer System in the Bear Creek, IA Watershed

Introduction

The Bear Creek Watershed in central Iowa is a small (26.8 mi2) drainage basin located within the Des Moines Lobe subregion of the Western Corn Belt Plains ecoregion, one of the youngest and flattest ecological subregions in Iowa. In general, the land is level to gently rolling with a poorly developed stream network. Soils of the region are primarily developed in glacial till and alluvial, lacustrine, and windblown deposits. Prior to European settlement of the region (ca 1847) the watershed consisted of the vast tallgrass prairie ecosystem, interspersed with wet prairie marshes in topographic lows and gallery forests along larger order streams and rivers. Native forest was limited to the Skunk River corridor into which Bear Creek flows.

Subsequent conversion of the land, including the riparian zone, from native vegetation to row crops, extensive subsurface drainage tile installation, dredge ditching, and grazing of fenced riparian zones have resulted in substantial stream channel modification. Records suggest that artificial drainage of marshes and low prairies in the upper reaches of the Bear Creek watershed was completed about 1902, with ditch dredging completed shortly thereafter. While the main stream pattern appears to have remained about the same since that time, significant channelization continued into the 1970s. Additional intermittent channels have developed in association with new drainage tile and grass waterway installation. Present land use in the Bear Creek watershed is typical of the region, with over 87% of the land area devoted to row crop agriculture.

Landscape modifications and present land-use practices have produced nonpoint source pollution in the watershed, which landowners have addressed by implementing soil conservation practices (e.g. reduced tillage, terracing, grass waterways) and better chemical input management (e.g. more accurate and better timed applications). It has only been recently that placement or enhancement of riparian vegetation or "streamside filter strips" has been recommended to reduce sediment and chemical loading, modify flow regime by reducing discharge extremes, improve structural habitat, and restore energy relationships through the addition of organic matter and reduction in temperature and dissolved oxygen extremes.

The Riparian Management System (RiMS)

The Agroecology Issue Team of the Leopold Center for Sustainable Agriculture, Iowa State University, Ames, IA, is conducting research on the design and establishment of an integrated riparian management system (RiMS) to demonstrate the benefits of properly functioning riparian buffers in the heavily row-cropped landscape of the midwestern U.S. The purpose of the RiMS is to restore the essential ecological functions that riparian ecosystems once provided. Specific objectives of such buffers are to intercept eroding soil and agricultural chemicals from adjacent crop fields, slow floodwaters, stabilize streambanks, provide wildlife habitat, and improve the biological integrity of aquatic ecosystems. The regionalization of this system has been accomplished by designing it with several components, each of which can be modified to fit local landscape conditions and landowner objectives.

The Agroecology Issue Team is conducting detailed studies of important biological and physical processes at both the field and watershed scale to provide the necessary data to allow resource managers to make credible recommendations of buffer placement and design in a wide variety of landscapes. In addition, socioeconomic data collected from landowners in the watershed are being used to identify landowner criteria for accepting RiMS. The team also is quantifying the non-market value placed on the improvement in surface and ground water quality.

The actual development and establishment of the RiMS along Bear Creek was initiated in 1990 along a 0.6-mile length of Bear Creek on the Ron and Sandy Risdal Farm. The buffer strip system has subsequently been planted along 3.5 miles of Bear Creek upstream from this original site. The RiMS consists of three components: 1) a multi-species riparian buffer (MRB), 2) soil bioengineering technologies for streambank stabilization, and 3) constructed wetlands to intercept and process nonpoint source pollutants in agricultural drainage tile water.

Multi-species Riparian Buffer (MRB)

The general MRB consists of three zones. The rapid growth of this buffer community can change a heavily impacted riparian zone into a functioning riparian ecosystem in a few short years. The combinations of trees, shrubs, and native grasses can be modified to fit site conditions (e.g. soils, slope), major buffer biological and physical function(s), owner objectives, and cost-share program requirements.

Soil Bioengineering

It has been estimated that greater than 50% of the stream sediment load in small watersheds in the Midwest is the result of channel erosion. This problem has been worsened by the increased erosive power of streams resulting from stream channelization and loss of riparian vegetation. Several different soil bioengineering techniques have been employed in the Bear Creek watershed. These include the use of willow posts and stakes driven into the bank, live willow fascines, live willow brush mattresses, and biodegradable geotextile anchored with willow stakes on bare slopes. Alternatives used to stabilize the base of the streambank include rock and anchored dead plant material such as cedar or bundled maple.

Constructed Wetlands

Small, constructed wetlands which are integrated into the riparian buffer have considerable potential to remove nitrate and other chemicals from the extensive network of drain tile in the Midwest. To demonstrate this technology, a small (600^{yd2}) wetland was constructed to process drainage tile water from a 12-acre cropped field. The wetland was constructed by excavating a depressional area near the creek and constructing a low berm. The subsurface drainage tile was rerouted to enter the wetland at a point that maximizes residence time of drainage tile water within the wetland. A simple gated water level control structure at the wetland outlet provides control of the water level maintained within the wetland. Cattail rhizomes (Typha glauca Godr.) collected from a local marsh and road ditch were planted within the wetland and native grasses and forbs planted on the constructed berm. Future plans include the construction of additional tile drainage wetlands within the Bear Creek watershed.

System Effectiveness

Long-term monitoring has demonstrated the significant capability of the RiMS to intercept eroding soil from adjacent cropland, intercept and process agricultural chemicals moving in shallow subsurface water, stabilize stream channel movement, and improve instream environments, while also providing wildlife habitat and quality timber products. The buffer traps 70-80% of the sediment carried in surface runoff and has reduced nitrate and atrazine moving in the soil solution to levels well below the maximum contaminant levels specified by the USEPA. Streambank bioengineering systems have virtually stopped bank erosion along treated reaches and are now trapping channel sediment. The constructed wetland has reduced nitrate in the tile drainage water by as much as 80% depending on the season of the year. Wildlife benefits have also appeared in a very short time, with a nearly fivefold increase in bird species diversity observed within the buffer strip versus an adjacent, unprotected stream reach.

While the RiMS function is being assessed through experimental plot work with intensive process monitoring, economic benefits and costs to landowners and society also are being determined. Landowners surveys, focus groups, and one-on-one interviews have identified the concern that water quality should be improved by reducing chemical and sediment inputs by as much as 50%. Landowners are willing to pay for this improved water quality as well as volunteer their time to help initiate the improvements.

CASE STUDY

The Multispecies Riparian Buffer System in the Bear Creek, IA Watershed (continued)

While the RiMS can effectively intercept and treat nonpoint source pollution from the uplands, it should be stressed that a riparian management system cannot replace upland conservation practices. In a properly functioning agricultural landscape, both upland conservation practices and an integrated riparian system contribute to achieving environmental goals and improved ecosystem functioning.

Support for this work is from the Leopold Center for Sustainable Agriculture, the Iowa Department of Natural Resources through a grant from the USEPA under the Federal Nonpoint Source Management Program (Section 319 of the Clean Water Act), and the USDA (Cooperative State Research Education and Extension Service), National Research Initiative Competitive Grants Program, and the Agriculture in Concert with the Environment Program.

exotics to spread. Again, control of exotic species has some common aspects across land uses, but design approaches are different for each land use.

Control of exotics in some situations can be extremely difficult and may be impractical if large acreages or well-established populations are involved. Use of herbicides may be tightly regulated or precluded in many wetland and streamside environments, and for some exotic species there are no effective control measures that can be easily implemented over large areas (Rieger and Kreager 1990). Where aggressive exotics are present, every effort should be made to avoid unnecessary soil disturbance or disruption of intact native vegetation, and newly established populations of exotics should be eradicated.

Nonnative species such as salt cedar (Tamarix spp.) and Russian olive (Elaeagnus angustifolia) can outcompete native plantings and negatively affect their establishment and growth. The likelihood of successful reestablishment often increases when artificial flows created by impoundments are altered to favor native species and when exotics such as salt cedar are removed before revegetation is attempted (Briggs et al. 1994).

Salt cedar is an aggressive, exotic colonizer in the West due to its long period and high rate of seed production, as well as its ability to withstand long periods of inundation. Salt cedar can be controlled either by clearing with a bulldozer or by direct application of herbicide (Sudbrock 1993); however, improper treatments may actually increase the density of salt cedar (Neill 1990).

Controlling exotics and weeds can be important because of potential competition with established native vegetation, colonized vegetation, and artificially planted vegetation in restoration work. Exotics compete for moisture, nutrients, sunlight, and space and can adversely influence establishment rates of new plantings. To improve the effectiveness of revegetation work, exotic vegetation should be cleared prior to planting; nonnative growth must also be controlled after planting. General techniques for control of exotics and weeds are mechanical (e.g., scalping or tilling), chemical (herbicides), and fire. For a review of treatment methods and equipment, see U.S. Forest Service (1965) and Yoakum et al. (1980).

Agriculture

America's Private Land—A Geography of Hope (USDA-NRCS 1996b) challenges all of us to "regain our sense of place and renew our commitment to private landowners and the public." It suggests that as we learn more about the complexity of our environment, harmony with ecological processes that extend across all landscapes becomes more of an imperative than an ideal. Furthermore, conservation provisions of the 1996 Farm Bill and accompanying endeavors such as the National Conservation Buffer Initiative (USDA-NRCS 1997) offer flexibility to care for the land as never before. The following land use scenario attempts to express this flexibility in the context of comprehensive, locally led conservation work, including stream corridor restoration.

This scenario offers a brief glimpse into a hypothetical agricultural setting where the potential results of stream corridor restoration might begin to take form. Computer-generated simulations are used to graphically illustrate potential changes brought about by restoration work and associated comprehensive, on-farm conservation planning. It focuses, conceptually, on vegetative clearing, instream modifications, soil exposure and compaction, irrigation and drainage, and sediment or contaminants as the most disruptive activities associated with agricultural land use. Although an agricultural landscape typical of the Midwest was selected for illustrative purposes, the concepts shown can apply in different agricultural settings.

Hypothetical Existing Conditions

Reminiscent of the highly disruptive agricultural activities discussed in Chapter 3, **Figure 8.52** illustrates hypothetical conditions that focus primarily on production agriculture. Although functionally isolated contour terraces and a waterway have been installed in the nearby cropland, the scene depicts an ecologically deprived landscape. Many of the potential disturbance

Figure 8.52: Hypothetical conditions. *Activities causing change in this agricultural setting.*

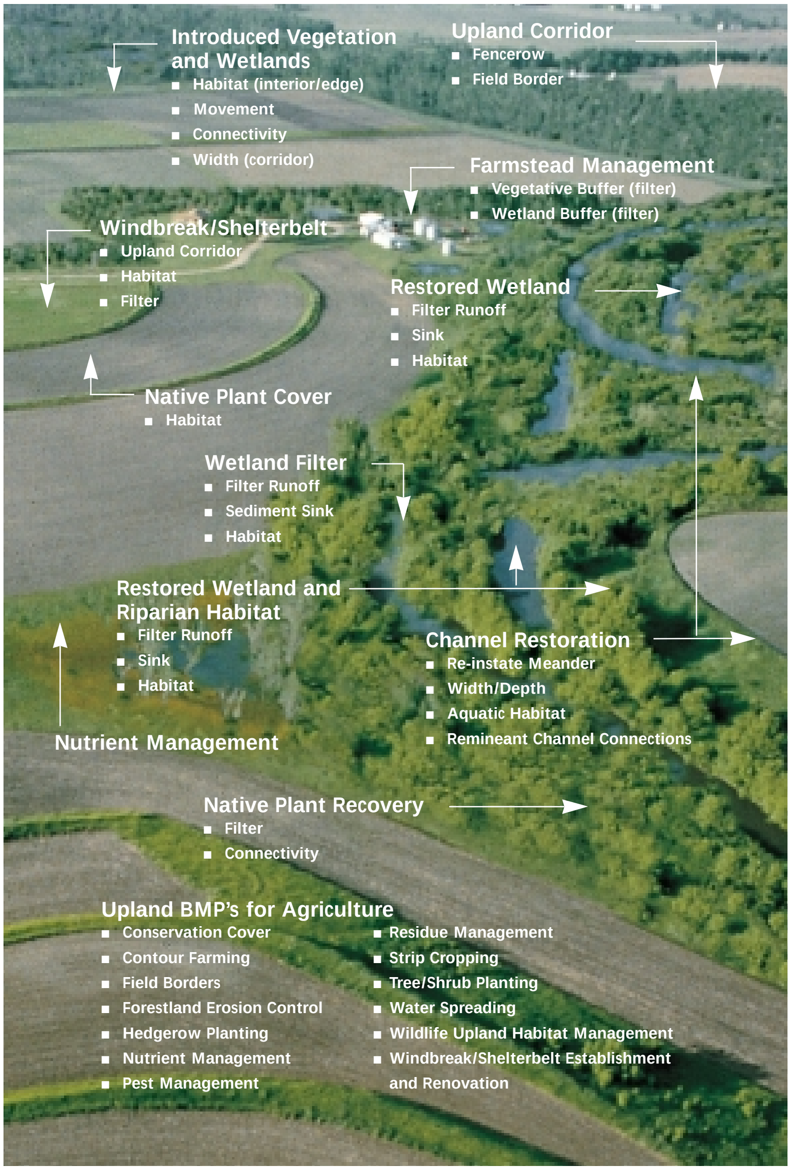


Figure 8.53: Hypothetical restoration response. *Possible results of stream corridor restoration are presented in this computer-altered photograph.*

activities and subsequent changes outlined in Chapter 3 come to mind. Those hypothetically reflected in the figure are highlighted in **Table 8.8**.

Hypothetical Restoration Response

Previous sections of this chapter and earlier chapters identified connectivity and dimension (width) as important structural attributes of stream corridors. Nutrient and water flow, sediment trapping during floods, water storage, movement of flora and fauna, species diversity, interior habitat conditions, and provision of organic materials to aquatic communities were described as just a few of the functional conditions affected by these structural attributes. Continuous indigenous vegetative cover across the widest possible stream corridor was generally identified as the most conducive to serving the broadest range of functions. This discussion went on to suggest that a long, wide stream corridor with contiguous vegetative cover is a favored overall characteristic. A contiguous, wide stream corridor may be unachievable, however, where competing land uses prevail. Furthermore, gaps caused by disturbances (utility crossings, highways and access lanes, floods, wind, fire, etc.) are commonplace.

Restoration design should establish functional connections within and external to stream corridors. Landscape elements such as remnant patches of riparian vegetation, prairie, or forest exhibiting diverse or unique vegetative communities; productive land that can support ecological functions; reserve or abandoned land; associated wetlands or meadows; neighboring springs and stream systems; ecologically innovative residential areas; and movement corridors for flora and fauna (field borders, windbreaks, waterways, grassed terraces, etc.) offer opportunities to establish these connections. An edge (transition zone) that gradually changes from one land use into another will soften environmental gradients and minimize disturbance.

With these and the broad design guidelines presented in previous sections of this chapter in mind, **Figure 8.53** presents a conceptual computer-generated illustration of hypothetical restoration

Table 8.8: Summary of prominent agriculturally related disturbance activities and potential effects.

	Existing Disturbance Activities						
Potential Effects	Vegetative Clearing	Channelization	Streambed Disturbance	Soil Exposure or Compaction	Contaminants	Woody Debris Removal	Piped Discharge/Cont. Outlets
Decreased landscape diversity	■	■	□	□	□	□	□
Point source pollution	□	□	□	□	■	□	■
Nonpoint source pollution	■	■	■	□	■	■	■
Dense compacted soil	■	□	□	■	□	□	□
Increased upland surface runoff	■	□	□	■	□	□	□
Increased sheetflow with surface erosion rill and gully flow	■	□	□	■	□	□	□
Increased levels of fine sediment and contaminants in stream corridor	■	■	■	■	■	■	■
Increased soil salinity	□	□	□	□	■	□	□
Increased peak flood elevation	■	■	□	■	□	■	■
Increased flood energy	■	■	■	■	□	■	■
Decreased infiltration of surface runoff	■	□	□	■	□	□	■
Decreased interflow and subsurface flow to and within the stream corridor	■	■	□	■	■	□	■
Reduced ground water recharge and aquifer volumes	■	□	□	■	□	□	■
Increased depth to ground water	■	■	□	■	□	□	□
Decreased ground water inflow to stream	■	■	□	■	□	□	■
Increased flow velocities	■	■	■	■	□	■	■
Reduced stream meander	□	■	■	□	□	■	■
Increased or decreased stream stability	■	■	■	□	□	■	■
Increased stream migration	■	□	■	□	□	■	■
Channel widening and downcutting	■	■	■	□	□	■	■
Increased stream gradient and reduced energy dissipation	□	■	■	□	□	■	■
Increased flow frequency	■	□	□	■	□	□	■
Reduced flow duration	■	■	■	■	□	■	■
Decreased capacity of floodplain and upland	■	□	□	■	■	□	■
Increased sediment and contaminants	■	□	□	■	■	■	■
Decreased capacity of stream	□	■	■	□	■	■	■
Reduced stream capacity to assimilate nutrients/pesticides	■	■	■	■	■	■	■
Confined stream channel with little opportunity for habitat development	□	■	■	□	□	□	□
Increased streambank erosion and channel scour	■	■	■	■	□	■	■
Increased bank failure	■	■	□	■	□	■	■
Loss of instream organic matter and related decomposition	■	■	■	□	□	■	■
Increased instream sediment, salinity, or turbidity	■	■	■	□	■	■	■
Increased instream nutrient enrichment, sedimentation, and contaminants leading to eutrophication	■	□	■	■	■	■	■

■ Activity has potential for direct impact.   □ Activity has potential for indirect impact.

Table 8.8: Summary of prominent agriculturally related disturbance activities and potential effects (continued).

	Existing Disturbance Activities						
Potential Effects	Vegetative Clearing	Channelization	Streambed Disturbance	Soil Exposure or Compaction	Contaminants	Woody Debris Removal	Piped Discharge/Cont. Outlets
Highly fragmented stream corridor with reduced linear distribution of habitat and edge effect	■	■	□	□	□	■	□
Loss of edge and interior habitat	■	■	■	□	□	■	□
Decreased connectivity and dimension (width) within corridor and to associated ecosystems	■	■	■	□	□	□	□
Decreased movement of flora and fauna species for seasonal migration, dispersal repopulation	■	■	■	□	□	□	□
Reduced stream capacity to assimilate nutrients/pesticides	■	■	■	■	■	■	■
Increase of opportunistic species, predators	■	■	□	□	■	■	■
Increased exposure to solar radiation, weather, and temperature	■	■	■	■	□	■	□
Magnified temperature and moisture extremes in corridor	■	■	□	■	□	□	□
Loss of riparian vegetation	■	■	■	■	□	■	■
Decreased source of instream shade, detritus, food, and cover	■	■	■	□	□	□	■
Loss of edge diversity	■	■	□	□	□	□	□
Increased water temperature	■	■	■	□	□	□	■
Impaired aquatic habitat	■	■	■	□	■	□	■
Reduced invertebrate population	■	■	■	□	■	□	■
Loss of wetland function	□	■	■	□	□	□	□
Reduced instream oxygen	□	■	■	□	■	□	■
Invasion of exotic species	■	■	■	□	□	□	□
Reduced gene pool	■	■	■	□	□	□	■
Reduced species diversity	■	■	■	■	□	□	■

■ Activity has potential for direct impact. □ Activity has potential for indirect impact.

results. **Table 8.9** identifies some of the restoration measures hypothetically implemented and their potential effects on restoring conditions within the stream corridor and surrounding landscape.

Forestry

Stream corridors are a source of large volumes of timber. Timber harvesting and related forest management practices in riparian corridors often necessitate stream corridor restoration. Forest management may be an on-going land use and part of the restoration effort. Regardless, accessing and harvesting timber affects streams in many ways including:

- Alteration of soil conditions.
- Removal of the forest canopy.
- Reduction in the potential supply of large organic (woody) debris (Belt et al. 1992).

Table 8.9: Summary of prominent restoration measures and potential resulting effects.

	Restoration Measures						
Potential Resulting Effects	Wetlands	Riparian Habitat	Upland Corridors	Windbreaks/Shelterbelts	Native Plant Cover	Stream Channel Restoration	Upland BMPs for Agriculture
Increased landscape diversity	■	■	■	■	■	■	■
Increased stream order	□	□	□	□	□	■	□
Reduced point source pollution	■	□	□	□	□	□	□
Reduced nonpoint source pollution	■	■	■	■	■	■	■
Increased soil friability	□	□	□	□	■	□	■
Decreased upland surface runoff	□	□	□	■	■	□	■
Decreased sheetflow, width, surface erosion, rill and gully flow	□	■	□	□	■	□	■
Decreased levels of fine sediment and contaminants in stream corridor	■	■	■	■	■	□	■
Decreased soil salinity	□	■	□	□	■	□	■
Decreased peak flood elevation	■	■	■	■	■	■	■
Decreased flood energy	■	■	■	■	■	■	■
Increased infiltration of surface runoff	■	■	■	■	■	■	■
Increased interflow and subsurface flow to and within stream corridor	■	■	□	□	■	■	■
Increased ground water recharge and aquifer volumes	■	■	■	■	■	■	■
Decreased depth to ground water	■	■	■	■	■	■	■
Increased ground water inflow to stream	■	■	■	□	■	■	■
Decreased flow velocities	■	■	■	■	■	■	■
Increased stream meander	□	□	□	□	□	■	□
Increased stream stability	■	■	■	□	■	■	■
Decreased stream migration	■	■	■	□	■	■	■
Reduced channel widening and downcutting	■	■	■	□	■	■	■
Decreased stream gradient and increased energy dissipation	■	■	□	□	□	■	■
Decreased flow frequency	■	■	■	□	■	□	■
Increased flow duration	■	■	■	□	■	■	■
Increased capacity of floodplain and upland	■	■	■	■	■	□	■
Decreased sediment and contaminants	■	■	■	■	■	□	■
Increased capacity of stream	■	■	□	□	□	■	□
Increased stream capacity to assimilate nutrients/pesticides	■	■	□	□	□	■	□
Enhanced stream channel with more opportunity for habitat development	■	■	□	□	□	■	□
Decreased streambank erosion and channel scour	■	■	□	□	□	■	■
Decreased bank failure	■	■	□	□	□	■	□
Gain of instream organic matter and related decomposition	■	■	□	□	□	■	□
Decreased instream sediment, salinity, or turbidity	■	■	■	■	■	■	■

■ Measure contributes directly to resulting effect. □ Measure contributes little to resulting effect.

Table 8.9: Summary of prominent restoration measures and potential resulting effects (continued).

	Restoration Measures						
Potential Resulting Effects	Wetlands	Riparian Habitat	Upland Corridors	Windbreaks/Shelterbelts	Native Plant Cover	Stream Channel Restoration	Upland BMPs for Agriculture
Decreased instream nutrient enrichment, siltation, and contaminants leading to eutrophication	■	■	■	■	■	■	■
Connected stream corridor with increased linear distribution of habitat and edge effect	■	■	□	□	■	■	■
Gain of edge and interior habitat	■	■	■	■	■	■	■
Increased connectivity and dimension (width) within corridor and to associated ecosystems	■	■	■	■	■	■	■
Increased movement of flora and fauna species for seasonal migration, dispersal repopulation	■	■	■	■	■	■	■
Decrease of opportunistic species, predators	■	■	□	□	■	■	■
Decreased exposure to solar radiation, weather, and temperature	■	■	■	■	■	■	■
Decreased temperature and moisture extremes in corridor	■	■	■	■	■	■	■
Increased riparian vegetation	■	■	□	□	■	■	■
Increased source of in stream shade, detritus, food, and cover	■	■	□	□	■	■	■
Increase of edge diversity	■	■	■	■	■	■	■
Decreased water temperature	■	■	■	■	■	■	■
Enhanced aquatic habitat	■	■	□	□	□	■	□
Increased invertebrate population	■	■	□	□	□	■	□
Increased wetland function	■	■	□	□	□	■	■
Increased instream oxygen	■	■	■	□	□	■	■
Decrease of exotic species	■	■	□	□	■	□	■
Increased gene pool	■	■	■	■	■	■	■
Increased species diversity	■	■	■	■	■	■	■

■ Measure contributes directly to resulting effect. □ Measure contributes little to resulting effect.

Forest Roads

The vast majority of the restoration design necessary following timber harvest is usually devoted to the road system, where the greatest alteration of soil conditions has taken place. Inadequate drainage, poor location, improperly sized and maintained culverts, and lack of erosion control measures on road prisms, cut-and-fill slopes, and ditches are problems common to a poor road design (Stoner and McFall 1991). The most extreme road system rehabilitation requires full road closure. Full road closure involves removal of culverts and restoration of the streams that were crossed. It can also involve the ripping or tilling of road surfaces to allow plant establishment. If natural vegetation has not already invaded areas of exposed soils, planting and seeding might be necessary.

Full closure might not be a viable alternative if roads are needed to provide access for other uses. In these circumstances a design to restrict traffic might be appropriate. Voluntary traffic control usually cannot be relied on, so traffic barriers like gates, fences, or earth berms could be necessary. Even with traffic restriction, roads require regular inspection for existing or potential maintenance needs. The best time for inspection is during or immediately after large storms or snowmelt episodes so the effectiveness of the culverts and road drainage features can be witnessed first-hand. Design should address regular maintenance activities including road grading, ditch cleaning, culvert cleaning, erosion control vegetation establishment, and vegetation management.

BMP Implementation and Section 319 of the Clean Water Act

Section 319 of the Clean Water Act of 1987 required the states to identify and submit BMPs for USEPA approval to help control nonpoint sources of pollution. As of 1993, 41 of 50 states had EPA-approved voluntary or regulatory BMP programs dealing with silvicultural (forest management) activities. The state BMPs are all similar; the majority deal with roads. Montana, for example, has a total of 55 specifically addressed forest practices. Of those 55 practices, 35 deal with road planning and location, road design, road maintenance, road drainage, road construction, and stream crossings.

Buffer Strips in Forestry

Forested buffer strips are generally more effective in reducing sediment and chemical loadings in the stream corridor than vegetated filter strips (VFS). However, they are susceptible to similar problems with concentrated flows. Buffers constructed as part of a conservation system increase effectiveness. A stiff-stemmed grass hedge could be planted upslope of either a VFS or a woody riparian forest buffer. The stiff-stemmed grass hedge keeps sediment out of the buffer and increases shallow sheet flow through the buffer.

Most state BMPs also have special sections devoted to limitations for forest management activities in riparian “buffer strips” (also referred to as Streamside Management Zones or Streamside Protection Zones).

Budd et al. (1987) developed a procedure for determining buffer widths for streams within a single watershed in the Pacific Northwest. They focused their attention primarily on maintenance of fish and wildlife habitat quality (stream temperature, food supply, stream structure, sediment control) and found that effective buffer widths varied with the slope of adjacent uplands, the distribution of wetlands, soil and vegetation characteristics, and land use. They concluded that practical determinations of stream buffer width can be made using such analyses, but it is clear that a generic buffer width which would provide habitat maintenance while satisfying human demands does not exist. The determination of buffer widths involves a broad perspective that integrates ecological functions and land use. The section on design approaches to common effects at the beginning of this chapter also includes some discussion on stream buffer width.

Stream corridors have varied dimensions, but stream buffer strips have legal dimensions that vary by state (**Table 8.10**). The buffer may be only part of the corridor or it may be all of it. Unlike designing stream corridors for recreation features or grazing use, designing for timber harvest and related forest management activities is quite regimented by law and regulation. Specific requirements vary from state to state; the state Forester's office or local Extension Service can provide guidance on regulatory issues. USDA Natural Resource Conservation Service offices and Soil and Water Conservation District offices also are sources of information. Refer to Belt et al. (1992) and Welsch (1991) for guidance on riparian buffer strip design, function, and management. Salo and Cundy (1987) provide information on forestry effects on fisheries.

Grazing

The closer an ecosystem is managed to allow for natural ecological processes to function, the more successful a restoration strategy will be. In stream corridors that have been severely degraded by grazing, rehabilitation should begin with grazing management to allow for vegetative recovery.

Vegetative recovery is often more effective than installing a structure. The vegetation maintains itself in perpetuity, allows streams to function in ways that artificial structures cannot replicate, and provides resiliency that allows riparian systems to withstand a variety of environmental conditions (Elmore and Beschta 1987)

Designs that promote vegetative recovery after grazing are beneficial in a number of ways. Woody species can provide resistance to channel erosion and improve channel stability so that other species can become established. As vegetation becomes established, channel elevation will increase as sediment is deposited within and along the banks of the channel (aggradation), and water tables will rise and may reach the root zone of plants on former terraces or floodplains. This aggradation of the channel and the rising water table

State	Stream Class	Buffer Strip Requirements		
		Width	Shade or Canopy	Leave Trees
Idaho	Class I*	Fixed minimum (75 feet)	75% current shade[a]	Yes, number per 1000 feet, dependent on stream width[b]
	Class II**	Fixed minimum (5 feet)	None	None
Washington	Type 1, 2, and 3*	Variable by stream width (5 to 100 feet)	50%, 75% if temperature > 60ºF	Yes, number per 1000 feet, dependent on stream width and bed material
	Type 4**	None	None	25 per 1000 feet, 6 inches diameter
California	Class I and Class II*	Variable by slope and stream class (50 to 200 feet)	50% overstory and/or understory; dependent on slope and stream class	Yes; number to be determined by canopy density
	Class III**	None[b]	50% understory[e]	None[e]
Oregon	Class I**	Variable, 3 times stream width (25 to 100 feet)	50% existing canopy, 75% existing shade	Yes; number per 1000 feet and basal area per 1000 feet by stream width
	Class II special protection**	None[f]	75% existing shade	None

* Human water supply or fisheries use.

** Streams capable of sediment transport (CA) or other influences (ID and WA) or significant impact (OR) on downstream waters.

[a] In ID, the shade requirement is designed to maintain stream temperatures.

[b] In ID, the leave tree requirement is designed to provide for recruitment of large woody debris.

[c] May range as high as 300 feet for some types of timber harvest.

[d] To be determined by field inspection.

[e] Residual vegetation must be sufficient to prevent degradation of downstream beneficial uses.

[f] In eastern OR, operators are required to "leave stabilization strips of undergrowth... sufficient to prevent washing of sediment into Class I streams below."

Table 8.10: Buffer strip requirements by state.

CASE STUDY

Pacific Northwest Floods of 1996

Floods, Landslides, and Forest Management— 'The Rest of The Story'

*Warm winds, intense rainfall, and rapid snowmelt during the winter of 1995-96 and again in the winter of 1996-97 caused major flooding, landslides, and related damage throughout the Pacific Northwest (**Figure 8.54**). Such flooding had not been seen for more than 30 years in hard-hit areas. Damage to roads, campgrounds, trails, watersheds, and aquatic resources was widespread on National Forest Service lands. These events offered a unique opportunity to investigate the effects of severe weather, examine the influence and effectiveness of various forest management techniques, and implement a repair strategy consistent with ecosystem management principles.*

The road network in the National Forests was heavily damaged during the floods. Decisions about the need to replace roads are based on long-term access and travel requirements. Relocation of roads to areas outside floodplains is a measure being taken. Examination of road crossings at streams concluded with design recommendations to keep the water moving, align culverts horizontally and longitudinally with the stream channel, and minimize changes in stream channel cross section at inlet basins to prevent debris plugs.

Many river systems were also damaged. In some systems, however, stable, well-vegetated slopes and streambanks combined with fully functioning floodplains buffered the effects of the floods. Restoration efforts will focus on aiding natural processes in these systems. Streambank stabilization and riparian plantings will be commonly used. Examination of instream structure durability concluded that structures are more likely to remain in place if they are in fourth-order or smaller streams and are situated in a manner that maintains a connection between the structure and the streambank. They will be most durable in watersheds with low landslide/debris torrent frequency.

(a)

(b)

Figure 8.54: 1996 Landslides. *(a) April landslide: debris took out the track into the Greenwater River and (b) July landslide: debris took out the road and deposited debris into the river.*

allow more water to be stored during wet seasons, thereby prolonging flow even during periods of drought (Elmore and Beschta 1987).

Kauffman et al. (1993) observed that fencing livestock out of the riparian zone is the only grazing strategy that consistently results in the greatest rate of vegetative recovery and the greatest improvement in riparian function. However, fencing is very expensive, requires considerable maintenance, and can limit wildlife access—a negative impact on habitat or conduit functions.

Some specialized grazing strategies hold promise for rehabilitating less severely impacted riparian and wetland areas without excluding livestock for long periods of time. The efficiency of a number of grazing strategies with respect to fishery needs are summarized in **Tables 8.11 and 8.12** (from Platts 1989). They summarize the influence of grazing systems and stream system characteristics on vegetation response, primarily from a western semiarid perspective. Some general design recommendations for selecting a strategy include the following (Elmore and Kauffmann 1994):

- Each strategy must be tailored to a particular stream or stream reach. Management objectives and components of the ecosystem that are of critical value must be identified (i.e., woody species recovery, streambank restoration, increased habitat diversity, etc.). Other information that should be identified includes present vegetation, potential of the site for recovery, the desired future condition, and the current factors causing habitat degradation or limiting its recovery.
- The relationships between ecological processes that must function for riparian recovery should be described. Factors affecting present condition (i.e., management stress vs. natural stress) and conditions required for the stream to resume natural functions need to be assessed. Anthropogenic factors causing stream degradation must be identified and changed.
- Design and implementation should be driven by attainable goals, objectives, and management activities that will achieve the desired structure and functions.
- Implementation should include a monitoring plan that will evaluate management, allowing for corrections or modifications as necessary, and a strong compliance and use supervision program.

The main consideration for selecting a grazing system is to have an adequate vegetative growing season between the period of grazing and timing of high-energy runoff. It is impossible to provide a cookie-cutter grazing strategy for every stream corridor; designs have to be determined on the ground, stream by stream, manager by manager. Simply decreasing the number of livestock is not a solution to degraded riparian conditions; rather, restoring these degraded areas requires fundamental changes in the ways that livestock are grazed (Chaney et al. 1990).

Clearly, the continued use of grazing systems that do not include the functional requirements of riparian vegetation communities will only perpetuate riparian problems (Elmore and Beschta 1987). Kinch (1989) and Clary and Webster (1989) provide greater detail on riparian grazing management and designing alternative grazing strategies. Chaney et al. (1990) present photo histories of a number of interesting grazing restoration case studies, and of the

Table 8.11: Evaluation and rating of grazing strategies.

Strategy[a]	Level to Which Riparian Vegetation is Commonly Used	Control of Animal Distribution (Allotment)	Streambank Stability	Brushy Species Condition	Seasonal Plant Regrowth	Stream Riparian Rehabilitation Potential	Fishery Needs Rating[b]
Continuous season-long (cattle)	Heavy	Poor	Poor	Poor	Poor	Poor	1
Holding (sheep or cattle)	Heavy	Excellent	Poor	Poor	Fair	Poor	1
Short duration-high intensity (cattle)	Heavy	Excellent	Poor	Poor	Poor	Poor	1
Three herd-four pasture (cattle)	Heavy to moderate	Good	Poor	Poor	Poor	Poor	2
Holistic (cattle or sheep)	Heavy to light	Good	Poor to good	Poor	Good	Poor to excellent	2-9
Deferred (cattle)	Moderate to heavy	Fair	Poor	Poor	Fair	Fair	3
Seasonal suitability (cattle)	Heavy	Good	Poor	Poor	Fair	Fair	3
Deferred-rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Stuttered deferred-rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Winter (sheep or cattle)	Moderate to heavy	Fair	Good	Fair	Fair to good	Good	5
Rest-rotation (cattle)	Heavy to moderate	Good	Fair to good	Fair	Fair to good	Fair	5
Double rest-rotation (cattle)	Moderate	Good	Good	Fair	good	Good	6
Seasonal riparian preference (cattle or sheep)	Moderate to light	Good	Good	Good	Fair	Fair	6
Riparian pasture (cattle or sheep)	As prescribed	Good	Good	Good	Good	Good	8
Corridor fencing (cattle or sheep)	None	Excellent	Good to excellent	Good to excellent	Good	Excellent	9
Rest-rotation with seasonal preference (sheep)	Light	Good	Good to excellent	Good to excellent	Good	Excellent	9
Rest or closure (cattle or sheep)	None	Excellent	Excellent	Excellent	Excellent	Excellent	10

[a] Jacoby (1989) and Platts (1989) define these management strategies

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

Table 8.12: Generalized relationships between grazing systems, stream system characteristics, and riparian vegetation response.

Grazing System	Steep Low Sediment Load	Steep High Sediment Load	Moderate Low Sediment Load	Moderate High Sediment Load	Flat Low Sediment Load	Flat High Sediment Load
No grazing	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Winter or dormant season	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Early growing season	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Deferred or late season	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Three-pasture rest rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Deferred rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks + to 0	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs + Herbs + Banks +
Early rotation	Shrubs + Herbs + Banks 0 to –	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks + to 0	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Season-long	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –
Spring and fall	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks 0 to +
Spring and summer	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks 0 to +

Note: – = decrease; + = increase; 0 = no change. Stream gradient: 0 to 2% = flat; 2 to 4% = moderate; > 4% = steep. Banks refers to bank stability.

CASE STUDY

Oven Run, Pennsylvania

The effects of abandoned mines draining into the surrounding lands cause dramatic changes in the area (**Figure 8.55**(a)). Runoff with high levels of minerals and acidity can denude the ground of vegetation, expose the soil, and allow erosion with the sediment further stressing streams and wetland. Any efforts to restore streams in this environment must deal with the problem if any success is to be likely.

The Natural Resources Conservation Service, formerly known as the Soil Conservation Service, has been working on the Oven Run project along with the Stonycreek Conemaugh River Improvement (SCRIP) to improve water quality in a 4-mile reach above the Borough of Hooversville. SCRIP is a group of local and state government as well as hundreds of individuals interested in improving the water quality in an area on Pennsylvania's Degraded Watersheds list.

The initial goal of improving water quality resulted in improving habitat and aesthetic qualities. The water coming into Hooversville had higher-than-desired levels of iron, manganese, aluminum, sulfate, and acidity. Six former strip mines, which had a range of problems, were identified. They included deep mine openings that have large flows of acid mine drainage, acid mine seepage into streams, eroding spoil areas, areas of ponded water that infiltrate into ground water (adding to the acid mine drainage), and areas downhill of seepage and deep mine drainage that are denuded and eroding.

Control efforts included grading and vegetating the abandoned mine to reduce infiltration through acid-bearing layers and reduce erosion and sedimentation, surface water controls to carry water around the sites to safer outlets, and treating discharge flow with anoxic limestone drains and chambered passive wetland treatments (Figure 8.55(b)). Additionally, 1,000 feet of trees were planted along one of the site streams to shade the Stoneycreek River. Average annual costs for the six sites were estimated to be $503,000 compared to average annual benefits of $513,000.

The sites are being monitored on a monthly basis, and 4 years after work was begun the treatments have had a measurable success. The acid influent has been neutralized, and the effluent is now a net alkaline. Iron, aluminum, and manganese levels have been reduced, with iron now at average levels of 0.5 mg/L from average levels of 35 mg/L.

(a)

Figure 8.55: Stream corridor (a) before and (b) after restoration.

(b)

short-term results of some of the available grazing strategies.

Mining

Post-mining reclamation of stream corridors must begin with restoration of a properly functioning channel. Because many of the geologic and geomorphic controls associated with the pre-disturbance channel may have been obliterated by mining operations, design of the post-mining channel often requires approaches other than mimicking the pre-disturbance condition. Channel alignment, slope, and size may be determined on the basis of empirical relations developed from other streams in the same hydrologic and physiographic settings (e.g., Rechard and Schaefer 1984, Rosgen 1996). Others (e.g., Hasfurther 1985) have used a combination of empirical and theoretical approaches for design of reclaimed channels. Total reconstruction of stream channels is treated at length in Section 8.E. Other sections of the chapter address stabilization of streambanks, revegetation of floodplains and terraces, and restoration of aquatic and terrestrial habitats. Additional guidance is available in Interfluve, Inc. (1991).

Surface mining is usually associated with large-scale disturbances in the contributing watershed, therefore, a rigorous hydrological analysis of pre- and post-mining conditions is critical for stream corridor restoration of disturbed systems. The hydrologic analysis should include a frequency analysis of extreme high- and low-flow events to assess channel performance in the post-mining landscape.

Hydrologic modeling may be required to generate runoff hydrographs for the post-mining channel because watershed geology, soils, vegetation, and topography may be completely altered by mining operations. Thus, channel design and stability assessments will be based on modeled runoff rates reflecting expected watershed conditions. The hydrologic analysis for post-mining restoration should also address sediment production from the reclaimed landscape. Sediment budgets (see Chapter 7) will be needed for both the period of vegetation establishment and the final revegetated condition.

The hydrologic analyses will provide restoration practitioners with the flow and sediment characteristics needed for restoration design. The analyses may also indicate a need for at least temporary runoff detention and sediment retention during the period of vegetation establishment. However, the post-mining channel should be designed for long-term equilibrium with the fully reclaimed landscape.

Water quality issues (e.g., acid mine drainage) often control the feasibility of stream restoration in mined areas and should be considered in design.

Recreation

Both concentrated and dispersed recreational use of stream corridors can cause damage and ecological change. Ecological damage primarily results from the need for access for the recreational user. A trail often will develop along the shortest or easiest route to the point of access on the stream. Additional resource damage may be a function of the mode of access to the stream: motorcycles and horses cause far more damage to vegetation and trails than do pedestrians. Control of streambank access in developed recreation sites must be part of a restoration design. On undeveloped or unmanaged sites, such control is more difficult but still very necessary (**Figure 8.56**).

Rehabilitation of severely degraded recreation areas may require at least temporary use restrictions. Even actively eroding trails, camp and picnic sites, and stream access points can be stabilized through temporary site closure and combinations of soil and vegetation restoration (Wenger 1984, Marion and Merriam 1985, Hammitt and Cole 1987). Closure will not provide a long-term solution if access is restored without addressing the cause of the original problem. Rather, new trails and recreation sites should be located and constructed based on an understanding of vegetation capabilities, soil limitations, and other physical site characteristics. Basically, the keys to a successful design are:

- Initially locating or moving use to the most damage-resistant sites.
- Influencing visitor use.
- Hardening use areas to make them more resistant.
- Rehabilitating closed sites.

Urbanization

Few land uses have the capacity to alter water and sediment yield from a drainage as much as the conversion of a watershed from rural to urban conditions; thus, few land uses have greater potential to affect the natural environment of a stream corridor.

As a first step in hydrologic analyses, designers should characterize the nature of existing hydrologic response and the likelihood for future shifts in water and sediment yield. Initially, construction activities create excess sediment that can be deposited in downstream channels and floodplains. As impervious cover increases, peak flows increase. Water becomes cleaner as more area is covered with landscaping or impervious material. The increased flows and cleaner

Figure 8.56: Controlled access. *Control of streambank access is an important part of the restoration design.*
Source: J. McShane.

water enlarge channels, which increases sediment loads downstream.

Determine if the watershed is (a) fully urbanized, (b) undergoing a new phase of urbanization, or (c) is in the beginning stages of urbanization (Riley, 1998).

An increase in the amount of impervious cover in a watershed leads to increased peak flows and resulting channel enlargement (**Figure 8.57**). Research has shown that impervious cover of as little as 10 to 15 percent of a watershed can have significant adverse effects on channel conditions (Schueler 1996). Magnitudes of channel-forming or bankfull flood events (typically 1- to 3-year recurrence intervals) are increased significantly, and flood events that previously occurred once every year or two may occur as often as one or two times a month.

Enlargement of streams with subsequent increases in downstream sediment loads in urbanized watersheds should be expected and accommodated in the design of restoration treatments.

Figure 8.57: Storm water flow on a paved surface. *Impervious surfaces increase peak flows and can result in channel enlargement.* Source: M. Corrigan.

Procedures for estimating peak discharges are described in Chapter 7, and effects of urbanization on magnitude of peak flows must be incorporated into the analysis. Sauer et al. (1983) investigated the effect of urbanization on peak flows by analyzing 199 urban watersheds in 56 cities and 31 states. The objective of the analysis was to determine the increase in peak discharges due to urbanization and to develop regression equations for estimating design floods, such as the 100-year or 1 percent chance annual flood, for ungauged urban watersheds. Sauer et al. (1983) developed regression equations based on watershed, climatic, and urban characteristics that can be used to estimate the 2, 5, 10, 25, 50, 100, and 500-year urban annual peak discharges for ungauged urban watersheds. The equation for the 100-year flood in cubic feet per second (UQ100) is provided as an example:

$$UQ100 = 2.50\ A^{.29}\ SL^{.15}\ (RI2+3)^{1.26}\ (ST+8)^{-.52}\ (13-BDF)^{-.28}\ IA^{.06}\ RQ100^{.63}$$

where the explanatory variables are drainage area in square miles (A), channel slope in feet per mile (SL), the 2-year, 2-hour rainfall in inches (RI2), basin storage in percent (ST), basin development factor (BDF), which is a measure of the extent of development of the drainage system (dimensionless, ranging from 0 to 12), percent impervious area (IA), and the equivalent rural peak discharge in cubic feet per second (RQ100) in the example equation above.

Sauer et al. (1983) provide the allowable range for each variable. The two indices of urbanization in the equation are BDF and IA. They can be used to adjust the rural peak discharge RQ100 (either estimated or observed) to urban conditions.

Sauer et al. (1983) provide equations like the one above and graphs that relate the ratio of the urban to rural peak discharge (UQx/RQx) for recurrence intervals x = 2, 10, and 100 years. The 2-year peak ratio varies from 1.3 to 4.3, depending on the values of BDF and IA; the 10-year ratio varies from 1.2 to 3.1; and the 100-year ratio varies from 1.1 to 2.6. These ratios indicate that urbanization generally has a lesser effect on higher-recurrence-interval floods because watershed soils are more saturated and floodplain storage more fully depleted in large floods, even in the rural condition.

More sophisticated hydrologic analyses than the above are often used, including use of computer models, regional regression equations, and statistical analyses of gauge data. Hydrologic models, such as HEC-1 or TR-20, are often already developed for some urban watersheds.

Once the flood characteristics of the stream are adjusted for urbanization, new equilibrium channel dimensions can be estimated from hydraulic geometry relationships developed using data from stable, alluvial channels in similar (soils, slope, degree of urbanization) watersheds, or other analytical approaches. Additional guidance for design of restored channels is provided earlier in this chapter in the section on channel reconstruction.

Changes in flooding caused by urbanization of a watershed can be mitigated during urban planning through practices designed to control storm runoff. These practices emphasize the use of vegetation and biotechnical methods, as well as structural methods, to maintain or restore water quality and dampen peak runoff rates. Strategies for controlling runoff include the following:

- Increasing infiltration of rainfall and streamflow to reduce runoff and to remove pollutants.
- Increasing surface and subsurface storage to reduce peak flows and induce sediment deposition.
- Filtration and biological treatment of suspended and soluble pollutants (i.e., constructed wetlands).
- Establishment and/or enhancement of forested riparian buffers.
- Management of drainage from the transportation network.
- Introduction of trees, shrubs, etc., for various restoration purposes.

In addition to changes in water yield, urbanization of a watershed frequently generates changes in its sediment yield. In humid climates, vegetative cover prior to urbanization often is adequate to protect soil resources and minimize natural erosion, and the combination of impervious area and vegetation of a fully urban watershed might be adequate to minimize sediment yield. During the period of urbanization, however, sediment yields increase significantly as vegetation is cleared and bare soil is exposed during the construction process. In more arid climates, sediment yield from an urban watershed may actually be lower than the yield from a rural watershed due to the increased impervious area and vegetation associated with landscaping, but the period of urbanization (i.e., construction) is still the time of greatest sediment production.

The effect of urbanization on sediment discharge is illustrated in **Figure 8.58**, which contains data from nine subbasins in a 32-square-mile area in the Rock Creek and Anacostia River Basins north of Washington, DC (Yorke and Herb 1978). During the period of data collection (1963-74), three subbasins remained virtually rural while the others underwent urban development. In 1974, urban land represented from 0 to 60 percent of land use in the nine subbasins. These data were used to develop a relation between suspended sediment yield and the percentage of land under construction. This relation indicated that suspended sediment yield increased about 3.5 times for watersheds with 10 percent of the land area under construction. However, suspended-sediment yields for watersheds where sediment controls (primarily sediment basins) were employed for 50 percent of the construction area were only about one-third of these for areas without controls. The effect of controls is seen in the figure. The three curves present growing season data for three periods of increasing sediment control: 1963-67, when no controls were used on construction sites; 1968-71, when controls were mandatory; and 1972-74, when controls were mandatory and subject to inspection by county officials. It further illustrates that storm runoff is not the only factor affecting storm sedi-

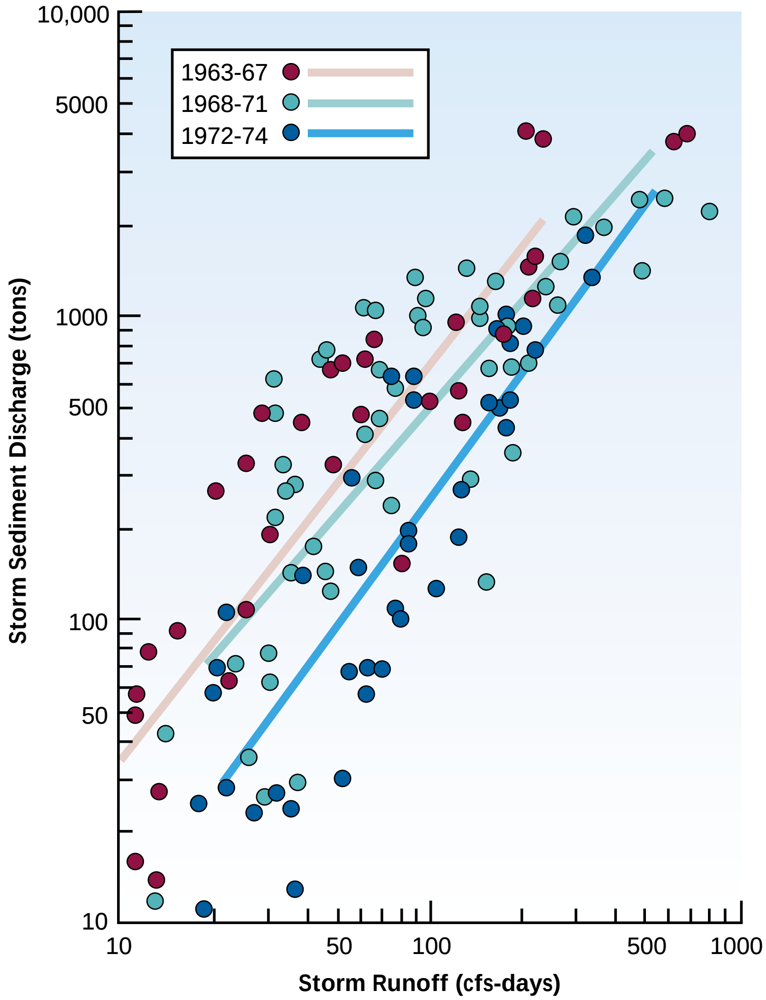


Figure 8.58: Sediment-transport curves for growing season storms. *The effect of urbanization on sediment discharge is illustrated from data collected in a 32-square-mile area.*

ment discharge as evidenced by the significant scatter about each relation.

In addition to sediment basins, management practices for erosion and sediment control focus on the following objectives:

- Stabilizing critical areas along and on highways, roads, and streets.
- Siting and placement of sediment migration barriers.
- Design and location of measures to divert or exclude flow from sensitive areas.
- Protection of waterways and outlets.
- Stream and corridor protection and enhancement.

All of these objectives emphasize the use of vegetation for sediment control. Additional information on BMPs for controlling runoff and sediment in urban watersheds can be found in the *Techniques Appendix*.

In theory, a local watershed management plan might be the best tool to protect a stream corridor from the cumulative impact of urban development; however, in practice, few such plans have realized this goal (Schueler 1996). To succeed, such plans must address the amount of bare ground exposed during construction and the amount of impervious area that will exist during and after development of the watershed. More importantly, success will depend on using the watershed plan to guide development decisions, and not merely archiving it as a one-time study whose recommendations were read once but never implemented (Schueler 1996).

Key Tools of Urban Stream Restoration Design

Restoration design for streams degraded by prior urbanization must consider pre-existing controls and their effects on restoration objectives. Seven restoration tools can be applied to help restore urban streams. (Schereler,1996) These tools are intended to compensate for stream functions and processes that have been diminished or degraded by prior watershed urbanization. The best results are usually obtained when the following tools are applied together.

Tool 1. Partially restore the predevelopment hydrological regime. The primary objective is to reduce the frequency of bankfull flows in the contributing watershed. This is often done by constructing upstream storm water retrofit ponds that capture and detain increased storm water runoff for up to 24 hours before release (i.e., extended detention). A common design storm for extended detention is the one-year, 24 hour storm event. Storm water retrofit ponds are often critical in the restoration of small and midsized streams, but may be impractical in larger streams and rivers.

Tool 2. Reduce urban pollutant pulses. A second need in urban stream restoration is to reduce concentrations of nutrients, bacteria and toxics in the stream, as well as trapping excess sediment loads. Generally, three tools can be applied to reduce pollutant inputs to an urban stream: storm water retrofit ponds or wetlands, watershed pollution prevention programs, and the elimination of illicit or illegal sanitary connections to the storm sewer network

Tool 3. Stabilize channel morphology. Over time, urban stream channels enlarge their dimensions, and are subject to severe bank and bed erosion. Therefore, it is important to stabilize the channel, and if possible, restore equilibrium channel geometry. In addition, it is also useful to provide undercuts or overhead cover to improve fish habitat. Depending on the stream order, watershed impervious cover and the height and angle of eroded banks, a series of different tools can be applied to stabilize the channel, and prevent further erosion. Bank stabilization measures include imbricated rip-rap, brush bundles, soil bioengineering methods such as willow stakes and bio-logs, lunker structures and rootwads. Grade stabilization measures are discussed earlier in this chapter and in Appendix A.

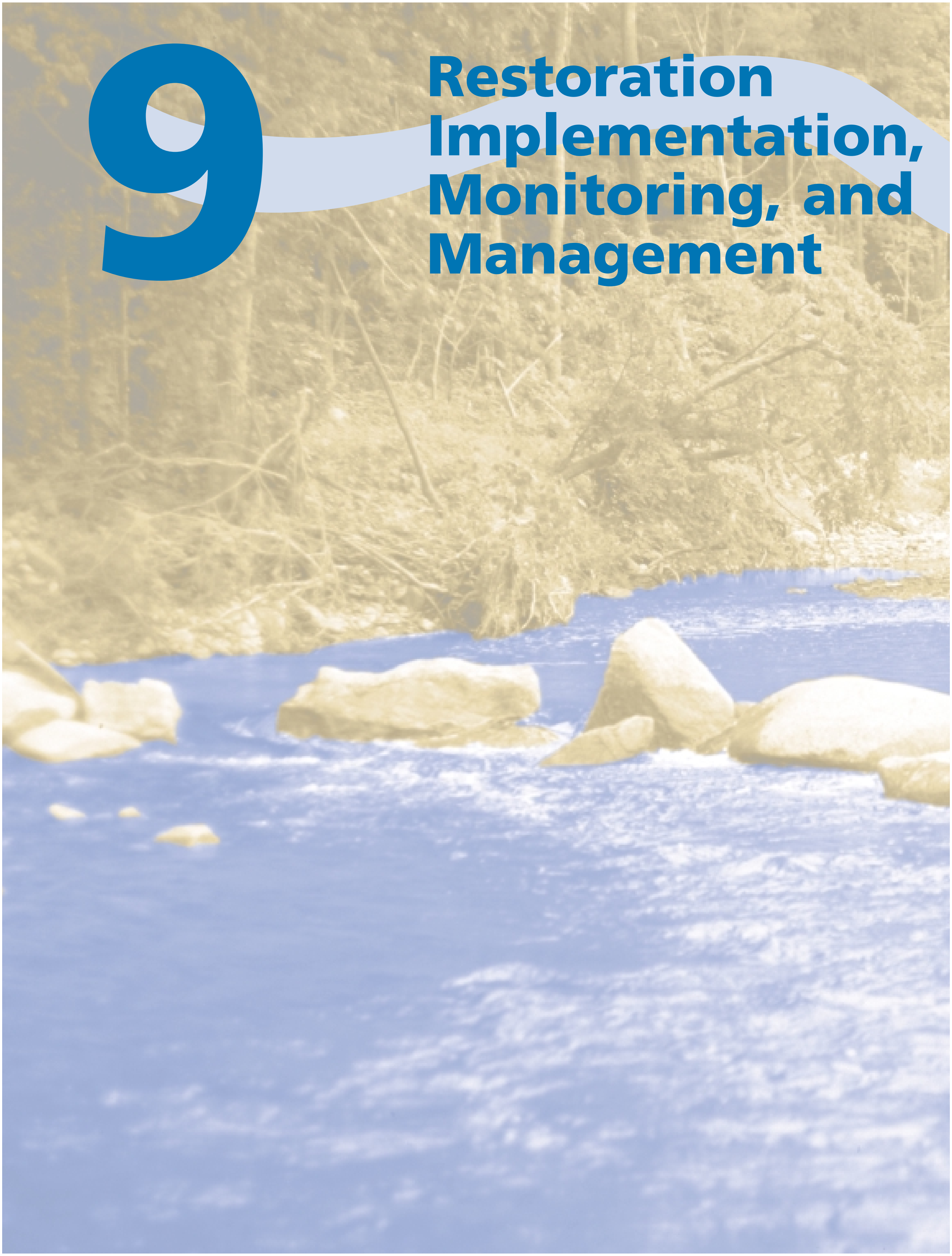
Tool 4. Restore Instream habitat structure. Most urban streams have poor instream habitat structure, often typified by indistinct and shallow low flow channels within a much larger and unstable storm channel. The goal is to restore instream habitat structure that has been blown out by erosive floods. Key restoration elements include the creation of pools and riffles, confinement and deepening of the low flow channels, and the provision of greater structural complexity across the streambed. Typical tools include the installation of log checkdams, stone wing deflectors and boulder clusters along the stream channel.

Tool 5. Reestablish Riparian Cover. Riparian cover is an essential component of the urban stream ecosystem. Riparian cover stabilizes banks, provides large woody debris and detritus, and shades the stream. Therefore, the fifth tool involves reestablishing the riparian cover plant community along the stream network. This can entail active reforestation of native species, removal of exotic species, or changes in mowing operations to allow gradual succession. It is often essential that the riparian corridor be protected by a wide urban stream buffer.

Tool 6. Protect critical stream substrates. A stable, well sorted streambed is often a critical requirement for fish spawning and secondary production by aquatic insects. The bed of urban streams, however, is often highly unstable and clogged by fine sediment deposits. It is often necessary to apply tools to restore the quality of stream substrates at points along the stream channel. Often, the energy of urban storm water can be used to create cleaner substrates—through the use of tools such as double wing deflectors and flow concentrators. If thick deposits of sediment have accumulated on the bed, mechanical sediment removal may be needed.

Tool 7. Allow for recolonization of the stream community. It may be difficult to reestablish the fish community in an urban stream if downstream fish barriers prevent natural recolonization. Thus, the last urban stream restoration tool involves the judgment of a fishery biologist to determine if downstream fish barriers exist, whether they can be removed, or whether selective stocking of native fish are needed to recolonize the stream reach.

9 Restoration Implementation, Monitoring, and Management



9.A Restoration Implementation

- *What are passive forms of restoration and how are they "implemented"?*
- *What happens after the decision is made to proceed with an active rather than a passive restoration approach?*
- *What type of activities are involved when installing restoration measures?*
- *How can impact on the stream channel and corridor be minimized when installing restoration measures (e.g, water quality, air quality, cultural resources, noise)?*
- *What types of equipment are needed for installing restoration measures?*
- *What are some important considerations regarding construction activities in the stream corridor?*
- *How do you inspect and evaluate the quality and impact of construction activities in the stream corridor?*
- *What types of maintenance measures are necessary to ensure the ongoing success of a restoration?*

9.B Monitoring Techniques Appropriate for Evaluating Restoration

- *What methods are available for monitoring biological attributes of streams?*
- *What can assessment of biological attributes tell you about the status of the stream restoration?*
- *What physical parameters should be included in a monitoring management plan?*
- *How are the physical aspects of the stream corridor evaluated?*
- *How is a restoration monitoring plan developed, and what issues should be addressed in the plan?*
- *What are the sampling plan design issues that must be addressed to adequately detect trends in stream corridor conditions?*
- *How do you ensure that the monitoring information is properly collected, analyzed, and assessed (i.e., quality assurance plans)?*

9.C Restoration Management

- *What are important management priorities with ongoing activities and resource uses within the stream corridor?*
- *What are some management decisions that can be made to support stream restoration?*
- *What are some example impacts and management options with various types of resource use within the stream corridor (e.g., forest management, grazing, mining, fish and wildlife, urbanization)?*
- *When is restoration complete?*

9 Restoration Implementation, Monitoring, and Management

*Completion of the restoration design marks the beginning of several important tasks for the stream restoration practitioner. Emphasis must now be placed on prescribing or implementing restoration measures, monitoring and assessing the effectiveness of the restoration, and managing the design to achieve the desired stream corridor conditions (**Figure 9.1**).*

Implementation, management, and monitoring/evaluation may proceed as part of a larger setting, or they may be considered components of a corridor-specific restoration effort. In either case, they require full planning and commitment before the restoration plan is implemented. The technical complexity of a project must be determined by the restoration practitioner based on available resources, technology, and what is necessary to achieve restoration goals. There must be reasonable assurance that there will be continuing access for ongoing inspection, mainte-

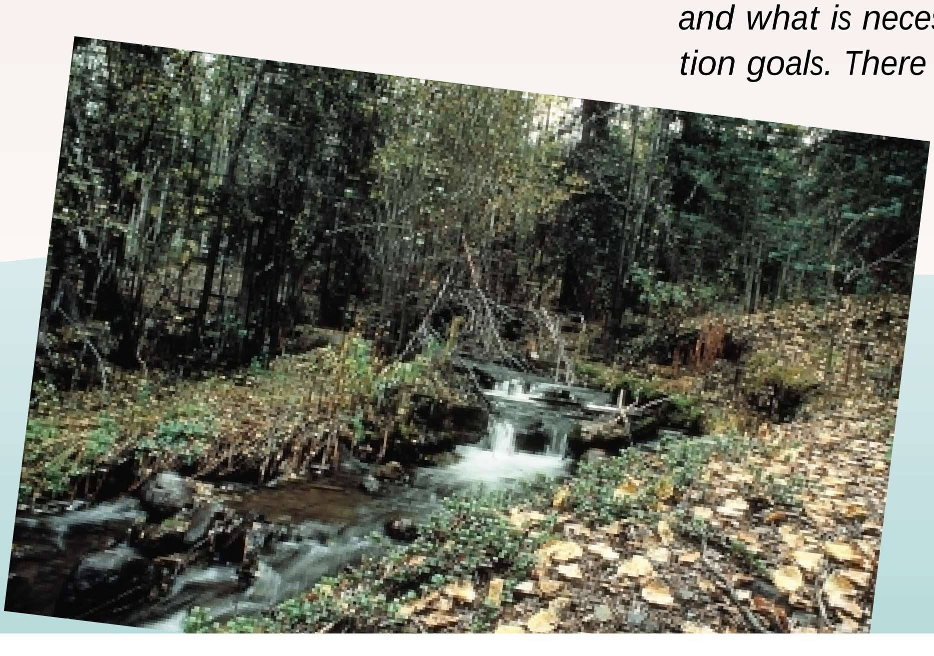


Figure 9.1: A restored stream. *Stream corridor restoration measures must be properly installed, monitored, and managed to be successful.*

nance, emergency repairs, management, and monitoring activities as well. All cooperators should be aware that implementation, monitoring, and management might require unanticipated work, and that plans and objectives might change over time as knowledge improves or as changes occur.

This chapter builds on the discussion of restoration implementation, monitoring, evaluation, and adaptive management presented in Chapter 6. Specifically, it moves beyond the planning components associated with these key restoration activities and discusses some of the technical issues and elements that restoration practitioners must consider when installing, monitoring, and managing stream corridor restoration measures.

The discussion that follows is divided into three major sections.

Section 9.A: Restoration Implementation

This first section describes the implementation of restoration measures beyond just removing disturbance factors and taking other passive approaches that allow the stream corridor to restore itself over time.

Technical considerations relating to site preparation, site clearing, construction, inspection, and maintenance are discussed in this section.

Section 9.B: Monitoring Techniques Appropriate for Evaluating Restoration

The purpose of restoration monitoring is to gather data that will help to determine the success of the restoration effort. This section presents some of the monitoring techniques appropriate for evaluating restoration.

Section 9.C: Restoration Management

Management of the restoration begins with the implementation of the plan. The "adaptive management" approach was presented in Chapter 6 as an important part of the planning process. It provides the flexibility to detect when changes are needed to achieve success and to be able to make the necessary midcourse, short-term corrections.

Ideally, the long-term management of a successful restoration will involve only periodic monitoring to check that the system is sustaining itself through natural processes. However, this is rarely the case for stream corridors in human-inhabited landscapes.

New crops, markets, and government programs can rapidly and significantly alter the physical, chemical, and biological characteristics of stream corridors and their watersheds, destroying restoration efforts. Conversion of rural lands *and wildlands to urban uses and exploitation of natural resources can change the landscape and cause natural processes to become unbalanced, leaving the stream corridor with no way to sustain itself.*

Additionally, natural imbalances can occur due to local and regional climatic changes, predation, disease, fire, genetic changes, and catastrophes like earthquakes, hurricanes, tornadoes, volcanic eruptions, landslides, and floods. Long-term management of the restored stream corridor will therefore require vigilance, anticipation, and reaction to future changes.

9.A Restoration Implementation

Implementation of stream corridor restoration must be preceded by careful planning. Such planning should include the following (at a minimum):

- Determining a schedule.
- Obtaining necessary permits.
- Conducting preimplementation meetings.
- Informing and involving property owners.
- Securing site access and easements.
- Locating existing utilities.
- Confirming sources of materials and ensuring standards of materials.

The careful execution of each planning step will help ensure the success of the restoration implementation. Full restoration implementation, however, involves several actions that require careful execution as well as the cooperation of several participants. See Chapters 4 and 5 for specific guidance on planning a stream corridor initiative.

Site Preparation

Site preparation is the first step in the implementation of restoration measures. Preparing the site requires that the following actions be taken.

Delineating Work Zones

The area in which restoration occurs is defined by many disparate factors. This area is determined most fundamentally by the features of the landscape that must be affected to achieve restoration goals. Boundaries of property ownership, restrictions imposed by permit requirements, and natural or cultural features that might have special significance can also determine the *work zone*. A heavy-equipment operator or crew supervisor cannot be expected to be aware of the multiple requirements that govern where work can occur. Thus, delineation of those zones in the field

Major Elements of Restoration Implementation

- *Review of Plans*
- *Site Preparation*
- *Site Clearing*
- *Installation and Construction*
- *Site Reclamation/Cleanup*
- *Inspection*
- *Maintenance*

should be the first activity conducted on the site. The zones should be marked by visible stakes and more preferably by temporary fencing (usually a bright-colored sturdy plastic netting). This delineation should conform to any special restrictions noted or temporary stakes placed during the preconstruction meeting between the project manager and field inspector.

Preparing Access and Staging Areas

A site is often accessed from a public road in an upland portion of the site. Ideally, for convenience, a staging area for crew, equipment, and materials can be located near an access road close to the restoration site but out of the stream corridor and away from wetlands or areas with highly erodible soils. The staging area should also be out of view from public thoroughfares, if possible, to increase security.

Although property ownership, topography, and preexisting roads make access to every site unique, several principles should guide design, placement, and construction of site access:

- Avoid any sensitive wildlife habitat or plant areas or threatened and endangered species and their designated critical habitat.
- Avoid crossing the stream if at all possible; where crossing is unavoidable, a bridge is almost mandatory.
- Minimize slope disturbance since effective erosion control is difficult on a sloped roadway that will be heavily used.
- Construct roadways with low gradients; ensure that storm water runoff drains to outlets; install an adequate roadbed; and, if possible, set up a truck-washing station at the entrance of the construction site to reduce off-site transport of mud and sediment by vehicles.
- In the event of damage to any private or public access roads used to transport equipment or heavy materials to and from the site, those responsible should be identified and appropriate repairs should be made.

Taking Precautions to Minimize Disturbance

Every effort should be made to minimize and, where possible, avoid site disturbance. Emphasis should be placed on addressing protection of existing vegetation and sensitive habitat, erosion and sediment control, protecting air and water quality, protecting cultural resources, minimizing noise, and providing for solid waste disposal and worksite sanitation.

Protection of Existing Vegetation and Sensitive Habitat

Fencing can be an effective way to ensure protection of areas within the construction site that are to remain undisturbed (e.g., vegetation designated to be preserved, sensitive terrestrial habitat, or sensitive wetland habitat).

As in delineating work zones, fencing should be placed around all protected areas during initial site preparation, even before the access road is fully constructed, if possible, but certainly before wholesale earthmoving begins. Fencing material should be easy to see, and areas should be labeled as protection areas. Caution should always be exercised when grading is planned adjacent to a protected area.

Erosion

Many well-established principles of effective erosion and sediment control can be readily applied to stream corridor restoration (Goldman et al. 1986). Every effort should be made to prevent erosion because prevention is always more effective than having to trap already-eroded sediment particles in runoff. Erosion and sediment controls should be installed during initial site preparation.

The most basic method of control is physical screening of areas to remain undisturbed. Properly chosen, installed, and maintained sediment control measures can provide a significant degree of filtration for sediment-bearing runoff (**Figure 9.2**).

Where undisturbed areas lie downslope of implementation activities, one method of controlling sediment is the use of a silt fence, which is normally made of filter fabric. Silt fences can provide a significant degree of filtration for sediment-bearing runoff, but only if correctly chosen, installed, and maintained. Design guidelines for silt fences include the following:

- Drainage area of 1 acre or less.
- Maximum contributing slope gradient of 2 horizontal to 1 vertical.
- Maximum upslope distance of 100 ft.
- Maximum flow velocity of 1 ft./sec.

Installation is even more critical than material type; most fabric fences fail because either runoff carves a channel beneath them or sediment accumulates against them, causing them to collapse. To help prevent failure, the lower edge of the fabric should be placed in a 4- to 12-inch-deep trench, which is then backfilled with native soil or gravel, and wire fencing should be used to support the fabric.

Figure 9.3 presents example silt fence installation guidelines. Properly installed silt fences commonly fail due to lack of maintenance. One rainfall event can deposit enough sediment that failure will occur during the next rainfall event if the sediment against the fence is not removed.

Figure 9.2: Silt fence at a construction site. *Properly chosen and installed silt fences can provide a significant degree of off-site sediment control.*

Erosion and sediment controls should be installed during initial site preparation.

Straw bales are also common sediment control measures. Bales should be placed in trenches about 4 inches deep, staked into the ground, and placed with their ends (not just corners) abutting each other. **Figure 9.4** presents example straw bale installation guidelines. The limitations on siting are the same as for silt fences, but straw bales are typically less durable and might need to be replaced.

Where the scope of a project is so small that no official erosion control plans have been prepared, control measures should be appropriate to the site, installed promptly, and maintained appropriately.

Proper restoration implementation requires managers to prepare for "unexpected" failure of erosion control measures. By the time moderate to heavy rains can be expected, the follow-

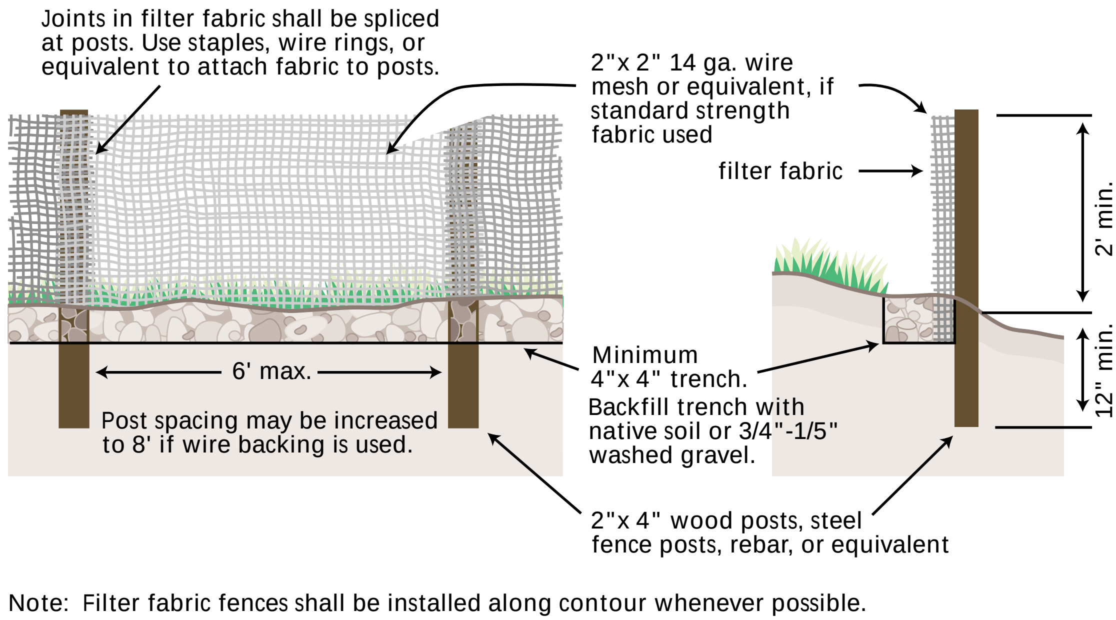


Figure 9.3: Silt fence installation guidelines. *Erosion control measures must be installed properly.*
Source: King County, Washington.

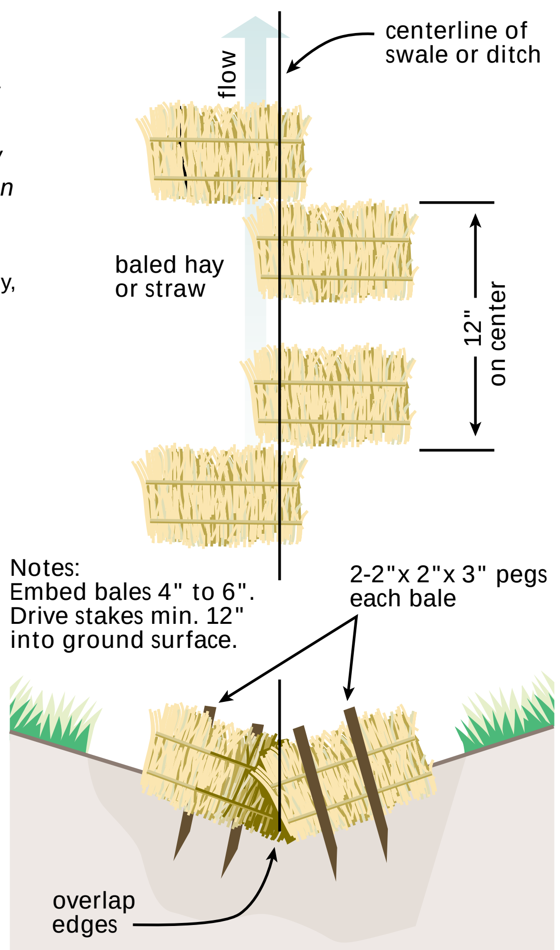


Figure 9.4: Straw bale installation guidelines. *Straw bales are common sediment control measures.*
Source: King County, Washington.

ing preparations should have been made:

- Additional erosion control materials should be stockpiled on site, including straw bales, filter fabric and wire backing, posts, sand and burlap bags, and channel lining materials (rock, geotextile fabric or grids, jute netting, coconut fabric material, etc.).
- Inspection of the construction site should occur during or immediately after a rain storm or other significant runoff event to determine the effectiveness of sediment control measures.
- A telephone number for the site superintendent or project manager should be made available to neighboring residents if they witness any problems on or coming from the site. Residents should be educated on what to watch for, such as sediment-laden runoff or failed structures.

Water Quality

Although sediment is the major source of water quality impairment on construction sites, it is not the only source. Motorized vehicles and equipment or improperly stored containers can leak petroleum products. Vehicles should be steam-cleaned off site on a regular basis and checked for antifreeze leaks and repaired. (Wildlife can be attracted to the sweet taste of most antifreeze and poisoned.) Various other chemicals such as fertilizers and pesticides can be washed off by rain. Most of these problems can be minimized or avoided entirely by thoughtful siting storage areas for chemicals and equipment and staging areas. Gradients should not favor rapid overland flow from these areas into adjacent streams and wetlands. Distances should be as great as possible and the intervening vegetation as dense as site traffic will allow.

Occasionally, implementation activities will require the entry or crossing of heavy equipment into the stream channel (**Figure 9.5**). Construction site planning and layout should always seek to avoid these intrusions. When these intrusions are absolutely necessary, they should be infrequent. Gravelly streambeds are best able to receive traffic; finer substrates should be reinforced with a geoweb network backfilled with gravel. In addition, any equipment used in these activities should be thoroughly steam-cleaned prior to stream entry.

Application of fertilizers and pesticides can also be a source of pollution into water bodies, and their use may be closely regulated in restoration settings. Where their use is permitted, the site manager should closely monitor the quantity applied, the local wind conditions, and the likelihood of rainfall. Potential water quality impacts are a function of the characteristics of the selected pesticide, its form, mode of application, and soil conditions. Pesticides and fertilizers must be stored in a locked and protected storage unit that provides adequate protection from leaks and spills. Pesticides must be prepared or mixed far from streams and, where possible, off site. All containers should be rinsed and disposed of properly.

Figure 9.5: Heavy equipment. *Avoid heavy equipment in stream channels unless absolutely necessary.*

Air Quality

Air quality in the vicinity of a restoration site can be affected by vehicle emissions and dust. Rarely, however, will either be a major concern during implementation activities. Vehicle emissions are regulated at the source (the vehicle), and dust is usually associated primarily with haul roads or major earthmoving during dry periods. The need for dust control should be evaluated during initial restoration implementation and road planning (if not previously determined during the planning phase of the restoration initiative). Site conditions, duration of construction activities, prevailing winds, and proximity to neighbors should be considered when making decisions on dust control. Temporary road surfaces or periodic water spraying of the road surface are both effective in controlling dust. Covered loads and speed limits on all temporary roads will also reduce the potential for construction-related dust and debris leaving the site (Hunt 1993). Where appropriate, use of volunteer labor in lieu of diesel-powered equipment will help to protect air quality in and surrounding the site. Due to safety concerns, it is recommended that volunteers not be used on a site where heavy equipment will also be used.

Cultural Resources

Since stream corridors have been a powerful magnet for human settlement throughout history, it is not uncommon for historic and prehistoric resources to be buried by sediment or obscured by vegetation along stream corridors. It is quite possible to discover cultural resources during restoration implementation (particularly during restoration that requires earth-disturbing activities). (See **Figure 9.6.**)

Prior to implementation, any potential cultural resources should be identified in compliance with section 106 of the National Historic Preservation Act. An archaeological record search should be conducted during the planning process in accordance with the State Historic Preservation Officer (SHPO). If a site is uncovered unexpectedly, all activity that might adversely affect the historic property must cease, and the responsible agency official must notify the U.S. Department of the Interior (USDI) National Park Service and the SHPO. Upon notification, the SHPO determines whether the activity will cause an irreparable loss or degradation of significant data. This might require on-site consultation with a 48-hour response time for determining significance and appropriate mitigation actions so as not to delay implementation activities inordinately.

If the property is determined not to be significant or the action will not be adverse, implementation activities may continue after documenting consultation findings. If the resource is significant and the on-site activity is determined to be an adverse action that cannot be avoided, implementation activities are delayed until appropriate actions can be taken (i.e., detailed survey, recovery, protection, or preservation of the cultural resources). Under the Historical and Archaeological Data Preservation Act of 1974, USDI may assume liability for delays in implementation.

Figure 9.6: Archaeological site. *Cultural resources, such as those at this site in South Dakota, are commonly found near streams.*

Noise

Noise from restoration sites is regulated at the state or local level. Although criteria can vary widely, most establish reasonable and fairly consistent standards.

The U.S. Housing and Urban Development (HUD) agency has set a maximum acceptable construction noise emission of 65 A-weighted decibels (dBA) at the property line. Numerous studies conducted since the late 1960s suggest that community complaints rise dramatically above 55 dBA (Thumann and Miller 1986). Meeting the HUD standard (65 dBA) requires that typical construction equipment be over 300 feet away from the listener; avoiding the chance of any significant complaints requires about 500 feet of separation or more. The project manager should contact surrounding neighbors prior to restoration implementation. Public awareness of and appreciation for the project goals help improve tolerance for off-site noise impacts. (Impacts from noise on equipment operators is usually not significant since most construction equipment meets the noise standards imposed by the U.S. General Services Administration of 75 dBA at 50 feet.)

High noise levels might be a concern to wildlife as well, particularly during the breeding season. Any sensitive species that inhabit the project vicinity should be identified and appropriate actions taken to reduce noise levels that could adversely affect these species.

Solid Waste Disposal

Debris is an inevitable by-product of implementation activities. The management of debris is a matter of job site safety, function, and aesthetics. From the first day, the locations of equipment storage, vehicle unloading, stockpiled materials, and waste should be identified. At the end of each workday, all scattered construction debris, plant materials, soil, and tools should be gathered up and brought to their respective holding areas. The site should be left as neat and well organized as possible at the end of each day. Even during the workday, sites in close proximity to business or residential districts should be kept as well organized and “sightly” as possible to avoid complaints and delays initiated by unhappy neighbors.

The importance of these measures to the safety and efficiency of the restoration effort as a whole is sometimes evident only to the project manager. Under such conditions, achieving adequate job site cleanliness is almost impossible because the manager alone does not have time to tidy up trash and debris. Meetings with work crews to emphasize this element of the work should occur early in the construction process and be repeated as often as required. People working on site, whether contractors, volunteers, or government personnel, need to be reminded of these needs as an unavoidable part of doing their jobs.

Worksite Sanitation

Sanitation facilities for work crews should be identified before construction begins. Particularly in remote areas, the temptation to allow ad hoc arrangements will be high. In urban areas, the existing facilities of a neighboring business might be offered. In most settings, however, one or more portable toilets should be provided and might be required by local building or grading permits. Although normally self-contained, any facilities should be located to minimize the risk of contamination of surface water bodies by leakage or overflow.

Obtaining Appropriate Equipment

Standard earthmoving and planting equipment is appropriate for most restoration work. Small channels or wetland pool areas can be excavated with backhoes or track-mounted excavators or trackhoes. Trackhoes are mobile over rough or steep terrain (**Figure 9.7**). They have adequate reach and power to work at a distance from the stream channel; with an opposing “thumb” on the bucket, they can maneuver individual rocks and logs with remarkable precision. Logs can also be

Figure 9.7: Backhoe in operation at a restoration site. *Backhoes are mobile in rough terrain and can move rocks and logs with remarkable precision.*
Source: M. Landin.

placed by a helicopter's cable. Although the hourly rate is about that of the daily cost of ground-based equipment, the ability to reach a stream channel without use of an access road is sometimes indispensable.

Where access is good but the riparian corridor is intact, instream modifications can be made with a telescoping crane. This equipment comes in a variety of sizes. A fairly large, fully mobile unit can extend across a riparian zone 100 feet wide to deliver construction materials to a waiting crew without disturbing the intervening ground or vegetation. Where operational constraints permit their use, bulldozers and scrapers can be very useful, particularly for earthmoving activities that are absolutely necessary to get the job done. In addition, loaders are excellent tools for transporting rocks, transplanting large plants, and digging and placing sod.

For planting, standard farm equipment, such as tractors with mounted disks or harrows, are generally suitable unless the ground is extremely wet and soft. Under these circumstances, light-tracking equipment with low-pressure tires or rubber tracks might work. Seeds planted on restoration sites are commonly broadcast by hydroseeding, requiring a special tank truck with a pump and nozzle for spraying the mixture of seeds, fertilizer, binder, and water (**Figure 9.8**). A wider range of seed species can be planted more effectively with a seed drill towed behind a tractor (e.g., Haferkamp et al. 1985). Where access is limited, hand planting or aerial spreading of seeds might be feasible.

Site Clearing

Once the appropriate construction equipment has been acquired and site preparation has been completed, any necessary site clearing can begin. Site clearing involves setting the geographic limits, removing undesirable plant species, addressing site drainage issues, and protecting and managing desirable existing vegetation.

Geographic Limits

Site clearing should not proceed unless the limits of activity have been clearly marked in the field. Where large trees are present, each should be marked with colored and labeled flagging to ensure that the field crew understands what is to be cut and what is to remain and be protected from damage.

Removal of Undesirable Plant Species

Undesirable plant species include non-native and invasive species that might threaten the survival of native species. Undesirable plants are normally removed by mechanical means, but the specific method should be tailored to the species of concern if possible. For example, simply cutting the top growth

Figure 9.8: Hydroseeding of a streambank. *Special tank trucks carrying seed, water, and fertilizer can be used in revegetation efforts.*

might be adequate management for some plants, but others might resprout rapidly. Where herbicides are selected (and permitted), their use might need to precede clearing of the top growth by up to 2 weeks to allow full absorption of certain chemicals used for this purpose.

For initial brush removal, a variety of track-mounted and towed equipment is available. Bulldozers are most commonly used because of their ready availability, but other equipment can often work more rapidly or more effectively with minimal site disturbance.

Hand clearing with portable tools might be the only appropriate method in some sensitive or difficult areas.

Drainage

Sites that are very wet and poorly drained might require extra preparation. However, many of the traditional efforts to improve drainage are in partial or direct conflict with wetland-protection regulations and might conflict with the restoration goals of the project as a whole. Standard engineering approaches should be reviewed for appropriateness, as well as the timing and schedule of the restoration activities.

Specific techniques for improving the workability of a wet construction site depend on the particular access, storage needs, and site characteristics. Load-bearing mats can provide stable areas for equipment and the unloading of plant materials. Surface water may be intercepted above the working area by a shallow ditch and temporarily routed around the construction area. Subsurface water can sometimes be intercepted by a perforated pipe set in a shallow trench, such as a French drain, but the topography must be favorable to allow positive drainage of the pipe to a surface outlet.

Protection and Management of Existing Vegetation

Protecting existing vegetation on a restoration site requires a certain degree of attention and advanced planning. An area on a site plan that is far from all earthmoving activity might appear to the site foreman as the ideal location for parking idle equipment or stockpiling excess soil. Only a careless minute with heavy equipment, however, can reduce a vegetated area to churned earth (**Figure 9.9**). Vegetation designed for a protection zone should be clearly marked in the field.

Existing vegetation might also require temporary protection if it occupies a part of the site that will be worked, but only late in the implementation sequence. Before that time, it is best left undisturbed to improve the level of overall erosion control. To save mobilization costs, most earthmoving contractors normally begin construction by clearing every part of the site that will eventually require it. If clearing is to be phased instead, this requirement must be specified in the contract documents and discussed at a preimplementation meeting.

*Figure 9.9: **Lessons to be learned.** Heavy equipment can quickly reduce a vegetated area to churned earth.*

When identifying and marking vegetation protection zones, the rooting extent of the vegetation should be respected. Fencing and flagging of protected vegetation should be sturdy and maintained. Despite the cool shade and fencing, vegetation protection zones are neither a picnic area nor a storage/staging area. They are zones of no disturbance.

When working in riparian corridors with mature conifers, it is especially important to protect them from mechanical operations which can cause severe damage.

Installation and Construction

Following site preparation and clearing, restoration installation activities such as earthmoving, diversion of flow, and the installation of plant materials can proceed.

Earthmoving

Fill Placement and Disposal

How and where fill is placed on a site should be determined by the final placement of restoration measures. Fills adjacent to retaining walls or similar structures need to meet the criteria for structural fill.

Where plants will be the final treatment of a fill slope, the requirements for soil materials and compaction are not as severe. Loose soil on a steep slope is still prone to erosion or landsliding, however. Where fill is to be placed on slopes steeper than about 2:1, a soils engineer should determine whether any special measures are appropriate (**Figure 9.10**). Even on gentler slopes, surface runoff from above should not be allowed to saturate the new material

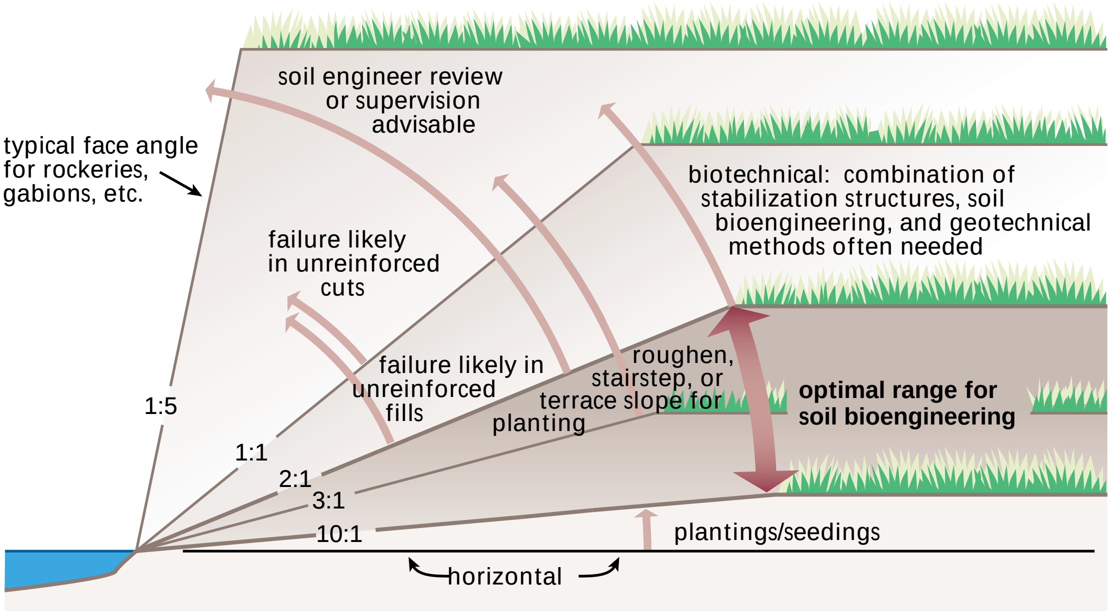


Figure 9.10: Treatment of cuts and fills. *Slope gradient is an important factor in determining appropriate restoration measures.*

since the stability of noncompacted fills is generally quite low.

To reduce grading expenses, the cut and fill should be balanced so no material needs to be transported to or from the site. If the volume of material resulting from cuts exceeds that from fills, some of the soil must be disposed of off-site. Disposal sites can be difficult to locate and might require an additional grading permit from the local jurisdiction. These possibilities should be planned for far enough in advance to avoid unanticipated delays during implementation.

As a general rule, topsoil removed from the site should be properly stockpiled for reuse during the final stages of implementation. Even if undesirable species are present, the topsoil will provide a growth medium suitable for the plant community appropriate to the site. It will also be a source of native species that can reestablish the desired diversity most rapidly (Liebrand and Sykora 1992). Stockpiled soil also can be vegetated with species that will be used at the restoration site to protect the soil from erosion and noxious weeds.

Contouring

The erosive power of water flowing down a slope should be recognized during earthmoving. The steepest direction down a hillside is also the direction of greatest erosion by overland or channelized flow. The overall topography of the graded surface should be designed to minimize the uncontrolled flow of runoff in this direction. Channelized flow should be diverted to ditches cut into the soil that more closely follow the level contours of the land. Dispersed sheet flow should be broken up by terraces or benches along the slope that also follow topographic contours. On a fine scale, the ground surface can be roughened by the tracks of a bulldozer driven up and down the slope, or by a rake or harrow pulled perpendicularly to the slope. In either case, the result is a set of parallel ridges, spaced only a few inches apart, that follow the contours of the land surface and greatly reduce on-site erosion.

Earthmoving should result in a slope that is stable, minimizes surface erosion by virtue of length and gradient, and provides a favorable environment for plant growth.

Final Grading

Earthmoving should result in a slope that is stable, minimizes surface erosion by virtue of length and gradient, and provides a favorable environment for plant growth. The first two criteria are generally determined by plans and can be modified only minimally by variations in grading techniques. Where plans specify a final slope gradient steeper than about 1:1, however, vegetation reestablishment will be very difficult, and a combination of stabilization structures, soil bioengineering, and geotechnical methods will probably be necessary. The shape at the top of the slope is also important: if it forms a straight abrupt edge, plant regrowth will be nearly impossible. A rounded edge that forms a gradual transition between upland and slope will be much more suitable for growth (Animoto 1978).

Providing a favorable environment for plant growth requires attention to the small-scale features of the slope. Rough-textured slopes, resulting from vehicle tracks or serrated blades, provide a much better environment for seedlings than do smooth-packed surfaces (**Figure 9.11**). Small terraces should be cut into slopes steeper than about 3:1 to create sites of moisture accumulation and enhanced plant growth. Compaction by excessive reworking from earthmoving equipment can result in a lower rate of rainfall infiltrating the soil and, consequently, a higher rate of erosive surface runoff. The result is a loss of the topsoil needed to support plant growth and less moisture available for the plants that remain.

Figure 9.11: Track-roughened area. *Rough-textured slopes provide a much better environment for seedlings than do smooth-packed surfaces.*

Diversion of Flow

Channelized flow (from stream channels, ditches, ravines, or swales) might need to be diverted, impounded, or otherwise controlled during implementation of restoration measures. In some cases, this need might be temporary, until final grading is complete or plantings have become established. In other cases, the diversion is a permanent part of the restoration. Permanent facilities frequently replace temporary measures at the same location but are often constructed of different materials.

Temporary dikes, lined or grassed waterways, or pipes can be used to divert channelized flow. Runoff can also be impounded in ponds or sediment basins to allow sediment to settle out.

Most temporary measures are not engineered and are constructed from materials at hand. Dikes (ridges of soil up to a few feet high) are compacted to achieve some stability and are sometimes armored to resist erosion. They are used to keep water from washing over a newly graded or planted slope where erosion is otherwise likely, and to divert runoff into a natural or artificial channel. The loosened soil from swales can be readily compacted into an adjacent dike, improving the efficiency and capacity of the runoff diversion. Pipes or rock-lined ditches can carry channelized water down a slope that is steep enough to otherwise suffer erosion; they can also be used to halt erosion that has already occurred from uncontrolled discharges. Flexible plastic pipe is most commonly used in these situations, although the outlet must be carefully located or well armored with rocks or sandbags to avoid merely shifting the point of erosion farther downslope.

Sediment ponds and traps are basins either dug into the soil with a rock-armored overflow or impounded by an embankment with an outlet. A fraction of the sediment carried by the site runoff will settle out in the trap, depending on the ratio of surface area or storage volume to inflow rate. The utility of sediment ponds may be limited depending on the sediment-trapping efficiency. A sediment pond can also release nearly as much sediment as is ultimately trapped if the pond is not built to handle maximum surface water flows or is not maintained properly.

Several techniques are available where the active streamflow must be temporarily isolated from installation activities. Most common are temporary dams, constructed of sandbags, geotextile fences, water control structures, or sheet piles. All may be suitable in certain situations, but have drawbacks. Sandbags are inexpensive, but submerged burlap sacks rot quickly and the sand used to fill them might not be appropriate for the stream. Fabric fences can be used in conjunction with sandbags, but they will not withstand high flows. Water control structures, such as long water-filled tubes available commercially, can be very effective, but need ample lateral space and carry a high initial cost. They also can be swept away by high flows. Sheet piles are effective if heavy equipment is already on site, but their installation and removal can mobilize much fine sediment.

Alternatively, water can be diverted into a bypass pipe, normally made of large flexible plastic (unless anticipated discharges are very great), and the construction area can be kept totally and reliably dry. A dam must be constructed at the pipe inlet to shunt the water, and an adequate apron of nonerosive material must be provided at the discharge. Both of these structures can themselves lead to instream damage, but with care the problems are only temporary. Since fish passage and migration are generally precluded with such a diversion, its applicability is limited.

In some situations unexpectedly erosive conditions will demand better outlet or channel protection than that originally specified in the plans. Erosion control in these settings might require a thick blanket of angular rocks and geotextiles (cloth, plastic grids, or netting) used with plantings. New types of geotextiles are becoming widely available and can serve a wide range of flow conditions. Where possible, channels and spillways should be stabilized using soil bioengineering or other appropriate techniques.

Installation of Plant Materials

Plant establishment is an important part of most restoration initiatives that require active restoration. Detailed local standards and specifications that describe planting techniques and establishment procedures should be developed. Native species should be used where possible to achieve the restoration goals. Vegetation can be installed by seeding; planting vegetative cuttings; or using nursery-grown bare-rooted, potted, and burlap-wrapped specimens. If natural colonization and succession is appropriate, techniques may include controlling exotic species and establishing an initial plant community to hasten succession.

Plant establishment is an important part of most restoration initiatives that require active restoration.

Timing

The optimum conditions for successful plant installations are broad and vary from region to region. As a general rule, temperature, moisture, and sunlight must be adequate for germination and establishment. In the eastern and midwestern United States, these conditions are met beginning in late winter or early spring, after ground thawing, and continuing through mid-autumn. In the West, the typical summertime dryness normally limits successful seedings to late summer or early autumn. Where arid conditions persist through most of the year, plants and seedings must take advantage of whatever rainfall occurs, typically in late autumn or winter, or supplemental irrigation must be provided. Because the requirements can vary so much for different species, the local supplier or a comprehensive reference text (e.g., Schopmeyer 1974, Fordham and Spraker 1977, Hartmann and Kester 1983, Dirr and Heuser 1987) should be consulted early in the restoration design phase. If rooted stock is to be propagated from seed before it is planted at the restoration site, 1 to 2 years (including seed-collection time) should be allowed.

Plants should be installed when dormant for the highest rate of survival. Survival is further influenced by species used and how well they are matched to site conditions, available moisture, and time of installation. In mild climates, the growth of roots occurs throughout the winter, improving survival of fall plantings. Where high wintertime flows are anticipated, however, first-season cuttings might not survive unless given some physical protection from scour. Alternatively, planting can occur in the spring before dormancy ends, but supplemental irrigation might be needed even in areas of abundant summertime rainfall. Irrigation might be necessary in some regions of the country to ensure successful establishment of vegetation.

Acquisition

Native plant species are preferred over exotic ones, which might result in unforeseen problems. Some plant materials can be obtained from commercial sources, but many will need to be collected. When attempting to restore native plant communities, it is desirable to use appropriate genotypes. This requires the collection of seeds and plants from local sources. Early contact with selected sources of rooted stock and seed can ensure that appropriate species in adequate quantities will be available when needed.

The site itself might also be a good source of salvageable plants. Live cuttings can be collected from healthy native vegetation at the donor site. Sharp, clean equipment must be used to harvest the plant material. Vegetation is normally cut at a 40 to 50 degree angle using loppers, pruners, or saws. If the whole plant is being used, the cut is made about 10 inches above the ground, which encourages rapid regeneration in most species. Cuttings typically range from 0.4 to 2 inches in diameter and 2 to 7 feet long.

After harvesting, the donor site should be left in a clean condition. This will avoid the potential for landowner complaints and facilitate potential reuse of the site at some time in the future. Large unused material can be cut for firewood, piled for wildlife cover, or scattered to hasten decomposition. Any diseased material should be burned, per local ordinances.

Transportation and Storage

The requirements for the transport and storage of plant materials vary, depending on the type of material being used. Depending on species, seeds may require a minimum period of dormancy of several weeks or months, with specific temperature requirements during that time. Some seeds may also require scarifying or other special treatment. Nurseries that specialize in native plants are recommended because they should be cognizant of any special requirements. Although the necessary information for any chosen species should be readily available from local seed sources or agricultural extension offices, this interval must be recognized and accounted for in the overall implementation schedule.

Live cuttings present rather severe limitations on holding time. In most cases, they should be installed on the day they are harvested, unless refrigerated storage areas are secured. Thus, donor sites must be close to the restoration site, and access and transportation must be orchestrated to coincide with the correct stage of construction. Live cuttings should be tied in manageable bundles, with the cut ends all lying in the same direction. Since drying is the major threat to survival at this stage, cuttings should be covered with damp burlap during transport and storage (**Figure 9.12**). They should always be shaded from direct sun. On days with low humidity and temperatures above 60 degrees Fahrenheit, the need for care and speed is particularly great. Where temperatures are below this level, “day-after” installation is acceptable, although not optimal. Any greater delay in installation will require refrigeration, reliably cold weather on site, or storage in water.

***Figure 9.12*: Live cuttings covered with damp burlap to prevent drying during transport.** *Drying is a major threat to survival of live cuttings during transport and storage.*

Rooted stock is also prone to drying, particularly if pots or burlap-wrapped roots are exposed to direct sun. Submergence of the roots in water is not recommended for long periods, but 1 to 2 hours of immersion immediately prior to planting is a common practice to ensure the plant begins its in-place growth without a moisture deficit. Onsite storage areas should be chosen with ample shade for pots. Bare-rooted or burlap-wrapped stock should be heeled into damp ground or mulch while awaiting final installation.

Planting Principles

The specific types of plants and plant installations are generally specified in the construction plans and therefore will have been determined long before implementation. A project manager or site foreman should also know the basic installation principles and techniques for the area.

The type of soil used should be determined by the types of plants to be supported. Ideally, the plants have been chosen to match existing site conditions, so stockpiled topsoil can be used to cover the plant material following layout. However, part of the rehabilitation of a severely disturbed site might require the removal of unsuitable topsoil or the import of new topsoil. In these situations, the requirements of the chosen plant species should be determined carefully and the soil procured from suitable commercial or field sites that have no residual chemicals and undesirable plant species.

When using seeds, planting should be preceded by elimination of competing plants and by preparation of the seedbed (McGinnies 1984). The most common methods of seeding in a restoration setting are hand broadcasting and hydroseeding. Hydroseeding and other methods of mechanical seeding might be limited by vehicular access to the restoration site.

When using either cuttings or rooted stock, the soil and the roots must make good contact. This requires compaction of the soil, either by foot or by equipment, to avoid air pockets. It also requires that the soil be at the right moisture content. If it is too dry (a rare condition), the soil particles cannot "slip" past each other to fill in voids. If it is too wet (far more common, especially in wetland or riparian environments), the water cannot squeeze out of the soil rapidly enough to allow compaction to occur.

Another aspect to consider is that quite frequently after planting, the resulting soil is too rough and loose to support vigorous seed growth. The roughness promotes rapid drying, and the looseness yields poor seed-to-soil contact and also erratic planting depths where mechanical seed drills are used. As a result, some means of compaction should be employed to return the soil to an acceptable state for planting.

Special problems may be encountered in arid or semiarid areas (Anderson et al. 1984). The salt content of the soil in these settings is critical and should be tested before planting. Deep tillage is advisable, with holes augured for saplings extended to the water table if at all possible. First-year irrigation is mandatory; ongoing fertilization and weeding will also improve survival.

Competing Plants

Although a well-chosen and established plant community should require no human assistance to maintain vigor and function, competition from other plants during establishment might be a problem. Competing plants commonly do not provide the same long-term benefits for stability, erosion control, wildlife habitat, or food supply. The restoration plan therefore must include some means to suppress or eliminate them during the first year or two after construction.

Competing plants may be controlled adequately by mechanical means. Cutting the top growth of competing plants can slow their development long enough for the desired plants to become established. Hand weeding is also very effective, although it is usually feasible only for small sites or those with an ongoing source of volunteer labor.

Unfortunately, some species can survive even the most extreme mechanical treatment. They will continue to reemerge until heavily shaded or crowded out by dense competing stands. In such cases the alternatives are limited. The soil containing the roots of the undesired vegetation can be excavated and screened or removed from the site, relatively mature trees can be planted to achieve near-instantaneous shading, or chemical fertilizers or herbicides can be applied.

Use of Chemicals

In situations where mechanical controls are not enough, the application of fertilizers and the use of herbicides to suppress undesirable competing species may be necessary.

Herbicides can eliminate undesirable species more reliably, but they may eliminate desirable species. Their use near watercourses may also be severely curtailed by local, state, and federal permit requirements. Several herbicides are approved for near-stream use and degrade quickly, but their use should be considered a last resort and the effects of excessive spray or overspray carefully controlled.

If herbicide use is both advisable and permitted, the specific choice is based first on whether the herbicide is absorbed by the leaves or by the roots (e.g., Jacoby 1987). The most common foliar-absorbed herbicide is 2,4-D, manufactured by numerous companies and particularly effective on broadleaf weeds and some shrubs. Other foliar herbicides have become available more recently and are commonly mixed with 2,4-D for broad-spectrum control. Root-absorbed herbicides are either sprayed (commonly mixed with dye to show the area of application) or spread in granular form. They persist longer than most foliar herbicides, and some are formulated to kill newly sprouted weeds for some time after application.

Since herbicides and fertilizers may be problematic near surface water, they should be used only if other alternatives are not available.

Mulches

Mulching limits surface erosion, suppresses weeds, retains soil moisture, and can add some organic material to the soil following decomposition. A variety of mulches are available with different benefits and limitations, as shown in **Table 9.1**.

Organic mulches, particularly those based on wood (chips or sawdust), have a high nitrogen demand because of the chemical reactions of decomposition. If nitrogen is not supplied by fertilizers, it will be extracted from the soil, which can have detrimental effects on the vegetation that is mulched. Certain species of wood, such as redwood and cedar, are toxic to certain species of seedlings and should not be used for mulch.

Straw is a common mulch applied on construction and revegetation sites because it is inexpensive, available, and effective for erosion control. Appropriate application rates range from about 3,000 to 8,000 lb/acre. Straw can be spread by hand or broadcast by machine, although uniform application is difficult in windy conditions. Straw must be anchored for the same reason: it is easily transported by wind. It can be punched or crimped into the soil mechanically, which is rapid and inexpensive, but requires high application rates. It can be covered with jute or plastic netting, or it can be covered with a sprayed tackifier (usually asphalt emulsion at rates of about 400 gal/acre). Straw or hay can also be a source of un-

Since herbicides and fertilizers may be problematic near surface-water, they should be used only if other alternatives are not available.

Mulch	Benefits	Limitations
Chipped wood	Readily available; inexpensive; judged attractive by most	High nitrogen demand; may inhibit seedlings; may float offsite in surface runoff
Rock	May be locally available and inexpensive	Can inhibit plant growth; adds no nutrients; suppresses diverse plant community; high cost where locally unsuitable or unavailable
Straw or hay	Available and inexpensive; may add undesirable seeds	May need anchoring; may include undesirable seeds
Hydraulic mulches	Blankets soil rapidly and inexpensively	Provides only shallow-rooted grasses, but may out compete woody vegetation
Fabric mats	Relatively (organic) or very (inorganic) durable; works on steep slopes	High costs; suppresses most plant growth; inorganic materials harmful to wildlife
Commercial compost	Excellent soil amendment at moderate cost	Limited erosion-control effectiveness; expensive over large areas

Table 9.1: Types of mulches.

desirable weed seed and should be inspected prior to application.

Wood fibers provide the primary mechanical protection in hydraulic mulches (usually applied during hydroseeding). Rates of 1 to 1.5 tons/acre are most effective. They can also be applied as the tackifier over straw at about one-third the above rate. Hydraulic mulches are adequate, but not as effective as straw, for controlling erosion in most settings. However, they can be applied on slopes steeper than 2:1, at distances of 100 feet or more, and in the wind. On typical earthmoving and construction projects, they are favored because of the speed at which they can be applied and the appearance of the resulting slope—tidy, smooth, and faintly green. The potential drawbacks—introducing fertilizers and foreign grasses that are frequently mixed into hydraulic mulches—should be carefully evaluated.

The value of an effective mulch to the final success of an initiative is generally well in excess of its cost, even when the most expensive treatment is used.

An appropriate mulch in many restoration settings is a combination of straw and organic netting, such as jute or coconut fibers (**Figure 9.13**). It is the most costly of the commonly used systems, but erosion control and moisture retention are highly effective, and the problems with undesirable seeds and excess fertilizers are reduced. The value of an effective mulch to the final success of an initiative is generally well in excess of its cost, even when the most expensive treatment is used.

Irrigation

In any restoration that involves replanting, the need for irrigation should be carefully evaluated. Irrigation might not be needed in wetland and near-stream riparian sites or where rainfall is well distributed throughout the year. Irrigation may be essential to ensure success on upland sites, in riparian zones where seasonal construction periods limit installation to dry months, or where a wet-weather planting may have to endure a first-year drought. Initial costs are lowest with a simple overhead spraying system. Spray systems, however, have inefficient water delivery and have heightened potential for vandalism. Drip-irrigation systems are therefore more suitable at many sites (Goldner 1984). There is also a greater potential for undesirable species with spray irrigation since the area between individual plants receives moisture.

Fencing

If the plant species chosen for the site are suitable, little or no special effort will be necessary for survival and establishment. During the initial construction and postconstruction phases, however, plants will commonly need some measure of physical protection. Construction equipment, work crews, onlookers, grazing horses and cattle, and browsing deer and other herbivores can reduce a new plant installation to barren or crushed twigs in very short order. Vandalism is also a potential problem in populated areas. Fencing is an effective, low-cost method to provide

Figure 9.13: A well-mulched site. *Mulching is an effective method for improving the final outcome of stream corridor restoration.*

physical protection from these types of hazards and should be included in virtually any restoration.

The type of fencing should be chosen for the type of hazard anticipated. Inexpensive, fluorescent orange plastic fencing is very effective for controlling people and equipment during construction, but it rarely makes a suitable long-term barrier. Domestic cattle can be controlled by a variety of wood and wire fences (**Figure 9.14**). Depending on the density of grazing animals, these fences are best assumed to be permanent installations and their design chosen accordingly. Electric fences can also be effective, and the higher cost of the electrification equipment can be offset by lower costs for materials and installation. Where deer are a known problem, fencing must be robust, but it probably will not need to remain in place permanently after well-chosen plants have matured. Damage from small mammals may be halted with chicken wire alone, surrounding individual saplings, or below-ground collars. Individual wire cages or other control devices might be necessary to protect trees.

Inspection

Frequent, periodic inspection of work, whether done by a landowner, contractor, volunteer group, or government personnel, is mandatory. Defects such as poor planting methods, stressed plant materials, inadequate soil compaction, or sloppy erosion control, may become evident only weeks or months after completion of work unless the activities on the site are regularly reviewed. Some of those activities may require specialized testing, such as the degree of compaction of a fill slope. Most require little more than observations by an inspector familiar with all elements of the design.

Figure 9.14: A permanent livestock fence. *Fencing is an effective, low-cost method of providing physical protection to restoration sites.*

In the case of contracted work, it is the responsibility of the construction inspector to monitor installation activities to ensure that the contractor completes work according to the contract plans and specifications. At key points during construction, the inspector should consult with clients and design team(s) for assistance. The inspector should create comprehensive documentation of the construction history in anticipation of any future audit or quantity dispute. All inspections should result in a written record that includes at least the information shown in **Figure 9.15**.

Daily and weekly reports are invaluable to maintain clear communication about billable days, progress, and anticipated problems. These written reports establish the authority to release payment to the contractor and provide the main documentation in case of a dispute between the client and contractor. Completeness, timeliness, and clarity of documentation are critical.

Inspection of restoration elements that involve management actions (i.e., land-use controls, grazing restrictions, etc.) require follow-up communication with the resource manager or landowner. A

Inspector's Daily Report

Date:

Project:

Contractor:

Inspector:

Temperature: H____ L____ Precip:____ Hours: Workable____
Nonworkable____

Work Done ____

Contractor Equipment On-Site ____

Personnel On-Site ____

Materials Used and Location ____

Remarks ____

Inspection Time ____________
Inspector's Signature ________________

Figure 9.15: Sample of an inspector's daily report. *Frequent, periodic inspection is a mandatory part of restoration implementation.*

review of the action against the plan and applicable standards should be conducted. For example, rotational grazing may be a critical plan element to achieve restoration of the stream corridor. Inspection of this plan element would involve a review of the rotation scheme, condition of individual pastures or ranges, and condition of fencing and related watering devices.

Keep in mind that although plans and specifications should be specific to the conditions of the site, they might have been developed from generic sets or from those implemented elsewhere.

On-Site Inspection Following Installation

The final inspection after installation determines the conditions under which the contractor(s) can be paid and the contract finalized. It must occur promptly and should determine whether all elements of the contract have been fulfilled satisfactorily. Before scheduling this final inspection, the project manager and inspector, together with any other necessary members of the restoration team, inspect the work and prepare a list of all items requiring completion by the contractor. This "pre-final" inspection is in fact the most comprehensive review of the work that will occur, so it must be conducted with care and after nearly all of the work has been completed. The final inspection should occur with representatives of both the client and the contractor present after completion of all required work and after site cleanup, but before equipment is removed from the site to facilitate additional work if necessary. It must address removal of protection measures no longer needed, such as silt fences. These are an eyesore and might inhibit restoration. A written report should state the complete or provisional acceptance of the work, the basis on which that judgment has been made, and any additional work that is needed prior to final acceptance and payment.

Follow-up Inspections

Planning for successful implementation should always look beyond the period of installation to the much longer interval of plant establishment. Twelve or more additional site visits are advisable over a period of many months or years. Such inspections will generally require a separate budget item that must be anticipated during restoration planning. If they are included in the specifications, they may be the responsibility of the contractor. A sample inspection schedule is shown in **Table 9.2**. Although this level of activity after installation might seem beyond the scope of a project, any restoration work that depends on the growth of vegetation will benefit greatly from periodic review, particularly during the first two years.

Documentation of follow-up inspections is important, both to justify recommendations and to provide a record from which chronic problems can be identified. Documentation can include standard checklists, survey data, cross sections, data sheets, data summaries, and field notes. Sketches, maps, and permanent photo points can be used to document vegetation development. Videotape can be particularly useful to document the performance of structures during various flows, to illustrate wildlife use and floodplain storage of floodwaters, and otherwise to record the performance and functions of the corridor system.

Inspection reports are primarily intended to address maintenance issues. Problems discovered in the inspection process should be documented in a report that details deficiencies, recommends specific maintenance, and explains the consequences of not addressing the problems. Postplanting inspections to ensure survival require documentation and immediate action. Consequently, the reporting and response loop should be simple and direct so that inspections indicating the need for emergency structural repairs can be reported and resolved without delay.

General Inspection

To the extent feasible, the entire stream corridor should be inspected annually to detect areas of rapid bank erosion or debris accumulation (**Figure 9.16**). A general inspection can also identify inappropriate land uses, such as encroachments of roads near banks or uncontrolled irrigation water returns, that might jeopardize restoration measures, affect water quality, or otherwise interfere with restoration objectives. The integrity of fences, water access, crossings, and other livestock control measures should be inspected (**Figure 9.17**). Lack of compliance with agreed-upon best management practices should be noted as well. Aerial photos are particularly useful in the overview inspection, but inspections by boat or on foot can be more informative in many cases.

Table 9.2: Sample inspection schedule.

Time Since Installation	Inspection Interval
2 Months	2 weeks (4 total)
6 Months	1 month (5 total)
2 Years	6 months (3 total)

Bank and Channel Structures

Special inspections should be conducted following high flows, particularly after the first flood event following installation. Soil bioengineering measures should be assessed during prolonged drought and immediately after high flows during the first few years fol-

Figure 9.16: Flood debris. *The entire corridor should be inspected annually to detect areas of debris accumulation from flood flows.*

lowing installation until the system is well established.

Most routine inspections of bank and channel measures should be conducted during low-water conditions to allow viewing of the measure as well as channel bed changes that might threaten its future integrity. This is particularly true of bank stabilization works where the principal mechanism of bank failure is undermining at the toe. A low water inspection should involve looking for displaced rock, settling or tilting, undermining, and similar problems (Johnson and Stypula 1993).

In the past, bank stabilization measures were routinely cleared of vegetation to facilitate inspection and prevent damage such as displacement of rock by trees uprooted from a revetment during a flood. However, evidence that vegetation compromises revetment integrity has not been documented (Shields 1987, 1988). Leaving vegetation in place or planting vegetation through rock blankets has been encouraged to realize the environmental benefits of vegetated streambanks. Consequently, agencies have modified inspection and maintenance guidelines accordingly in some areas.

Figure 9.17: Fencing. *The integrity of fencing should be inspected periodically.*

Vegetation

Streambanks that have been stabilized using plantings alone or soil bioengineering techniques require inspections, especially in the first year or two after planting (**Figure 9.18**). It is important that the planted material be checked frequently to ensure that the material is alive and growing satisfactorily. Any dead material should be replaced and the cause of mortality determined and corrected if possible. If the site requires watering, rodent control, or other remedial actions, the problem must be detected and resolved immediately or the damage may become severe enough to require extensive or complete replanting. Competition from weeds should be noted if it is likely to suppress new plantings. If nonnative plants capable of invading and outcompeting native species are known to be present in the area, both plantings and existing native vegetation should be inspected. Any newly established nonnative populations should be eradicated quickly.

After the first growing season, semiannual to annual evaluations should be sufficient in most cases. At the end of a 2-year period, 50 percent or more of the originally installed plant material should be healthy and growing well (**Figure 9.19**). If not, determining the cause of die-off and subsequent replanting will probably be necessary. If the installation itself is determined to have been improper, any warranty or dispute-resolution clauses in the plant installation contract might need to be invoked.

The effectiveness of bank protection is based largely on the development of the plants and their ability to bind soils at moderate flow velocities. The bank protection measures should be inspected immediately after high-flow events in the first few years, particularly if the plantings have not fully established. Washouts, slumping of geogrids, and similar problems require detection and correction, since they might become the sites of further deterioration and complete failure if left uncorrected.

Floodplain and other off-channel plantings might be important components of the corridor restoration plan as well. Inspection requirements are similar to those on streambank sites but are less critical to the integrity of the project in terms of preventing additional damage. Nevertheless, several site visits are appropriate during the first growing season to detect problems due to browsing, insects, too much or too little water, and other causes. Inspection of plantings that require irrigation during establishment, as well as of the irrigation system, may be needed on a weekly or more frequent basis.

Techniques for inspecting vegetation survival are fairly straightforward. Satisfactory survival rates may be determined using stem counts within sample plots or estimates of cover percentages, depending on the purpose of the plantings. For example, Johnson and Stypula (1993) suggest that woody plantings established for streambank protection should not include open spaces more than 2 feet in dimension. In most cases, such criteria can be established in advance based on common-sense decisions regarding the adequacy of establishment relative to the objectives. Where more detailed monitoring is appropriate to document development of habitat quality or similar objectives, more rigorous monitoring techniques can be used. (See Section 9.B).

Urban Features

Stream corridor objectives may require periodic inspections of features other than the stream, streambank, and corridor vegetation. In urban areas, these features may be a major focus of the inspection program. Facilities, nest boxes, trails, roads, storm water systems, and similar features must be inspected to ensure they are in satisfactory condition and are not contributing to degradation of the stream corridor. Access points required to accomplish maintenance and emergency repairs should be checked for serviceability. Popular public use areas, particularly stream access points, should be evaluated to determine

Figure 9.18: Revegetation project. *It is important that the planted material be inspected frequently to ensure that it is alive and growing satisfactorily.*

Figure 9.19: Revegetation project, 1 to 2 years postconstruction. *At the end of a 2-year period, 50 percent or more of the original plantings should be healthy and growing well.*
Source: King County, Washington.

FAST FORWARD

Preview Section 9.B, Monitoring Techniques Appropriate for Evaluation Restoration.

whether measures are being damaged, erosion is being initiated, or project objectives are otherwise being impeded. Inspection should reveal whether signs, trail closures, and other traffic-control measures are in place and effective. Trash and debris dumping, off-road vehicle damage, vandalism, and a wide variety of other detrimental occurrences may be noted during routine inspections.

Maintenance

Maintenance encompasses those repairs to restoration measures which are based on problems noted in annual inspections, are part of regularly scheduled upkeep, or arise on an emergency basis.

- *Remedial maintenance* is triggered by the results of the annual inspection (**Figure 9.20**). The inspection report should identify and prioritize maintenance needs that are not emergencies, but that are unlikely to be addressed through normal scheduled maintenance.
- *Scheduled maintenance* is performed at intervals that are preestablished during the design phase or based on project-specific needs. Such maintenance activities as clearing culverts or regrading roads can be anticipated, scheduled, and funded well in advance. In many instances, the scheduled maintenance fund can be a tempting source for emergency funds, but this can result in neglect of routine maintenance, which may eventually produce a new, more costly, emergency.
- *Emergency maintenance* requires immediate mobilization to repair or prevent damage. It may include measures such as replacement of plants that fail to establish in a soil bioengineered bank stabilization, or repair of a failing revetment. Where there is a reasonable probability that repair or replacement might be required (e.g., anything that depends on vegetation establishment), sources of funding, labor, and materials should be identified in advance as part of the contingency planning process. However, there should be some general strategy for allowing rapid response to any emergency.

Figure 9.20: Remedial maintenance. *Soil bioengineering used to repair failing revetment.*

Many maintenance actions will require permits, and such requirements should be identified well in advance to accommodate permitting delays. Similarly, access to areas likely to require maintenance (e.g., bank stabilization structures) should be guaranteed at the time of construction, and the serviceability of access roads verified periodically.

Various agencies and utilities may have maintenance responsibilities that involve portions of the stream corridor, such as road and transmission line crossings. This work should be coordinated as necessary to ensure there are no conflicts with corridor objectives.

Channels and Floodplains

Corridor restoration that includes reconfiguration of the channel and floodplain may require remedial action if the system does not perform as expected in the first few years after work has been completed. Any repairs or redesign, however, should be based on a careful analysis of the failure. Some readjustment is to be expected, and a continuing dynamic behavior is fundamental to successful restoration. Because establishment of a dynamic equilibrium condition is usually the intent, maintenance should be limited to actions that promote self-sustainability.

Many traditional channel maintenance actions may be inappropriate in the context of stream corridor restoration. In particular, removal of woody debris may be contrary to restoration objectives (**Figure 9.21**). Appropriate levels of woody debris loading should be a design specification of the project, and the decision to remove or reposition particular pieces should be based on specific concerns, such as unacceptably accelerated bank erosion due to flow deflection, creation of ice jams causing an increased chance for flooding, or concerns about safety in streams with high recreational use. In cases where woody debris sources have been depleted, periodic addition of debris may be a prescribed maintenance activity. (See next page for story on engineered log jams.)

Protection/Enhancement Measures

Measures intended to enhance fish habitat, deflect flows, or protect banks are likely to require periodic maintenance. If failure occurs soon after installation, the purpose and design of the measure should be reevaluated before it is repaired, and the mechanism of failure should be identified. Early failure is an inherent risk of soil- bioengineered systems that are not fully effective until the plants are well rooted and the stems reach a particular size and density. Although a design weakness may be identifiable and should be corrected, more often the mechanism of failure will be that the measure has not yet developed

Figure 9.21: Accumulated woody debris. *Removal of woody debris may be contrary to restoration objectives.*

full resistance to high-flow velocities or saturation of bank soils. Replanting should be an anticipated potential maintenance need in this situation.

In many stream corridor restoration areas, the intent of streambank and channel measures is to provide temporary stabilization until riparian vegetation develops and assumes those functions. In such cases, maintenance of some structures might become less important over time, and they might eventually be allowed to deteriorate. They can be wholly or partially removed if they represent impediments to natural patterns of channel migration and configuration, or if some components (cables, stone, geofabrics) become hazards.

Vegetation

Routine maintenance of vegetation includes removal of hazardous trees and branches that threaten safety, buildings, fences, and other structures, as well as maintenance of vegetation along road shoulders, trails, and similar features.

Planted vegetation may require irrigation, fertilization, pest control, and similar measures during the first few years of establishment. In large-scale planting efforts, such as floodplain reforestation efforts, maintenance may be precluded. Occasionally, replanting will be needed because of theft.

Maintenance plans should anticipate the need to replant in case soil- bioengineered bank protection structures are subjected to prolonged high water or drought before the plants are fully established. Techniques using numerous cuttings establish successfully, it might be desirable to thin the dense brush that develops to allow particular trees to grow more rapidly, especially if channel shading is a restoration objective. Often, bank protection measures become popular points for people to access the stream (for fishing, etc.). Plantings can be physically removed or trampled. Replanting, fencing, posting signs, or taking other measures might be needed.

Other Features

A wide variety of other restoration features will require regular maintenance or repair. Rural restoration efforts might require regular maintenance and periodic major repair or replacement of fences and access roads for management and fire control. Public use areas and recreational facilities require upkeep of roads, trails, drainage systems, signs, and so forth (**Figure 9.22**). Maintenance of urban corridors may be intensive, requiring trash removal, lighting, and other steps. An administrative contact should be readily available to address problems as they develop. As the level of public use increases, contracting of maintenance services might become necessary, and administration of maintenance duties will become an increasingly important component of corridor management.

Restoration measures placed to benefit fish and wildlife (e.g., nest boxes and platforms, waterers) need annual cleaning and repair. These maintenance activities can be as time-consuming as the original installation, and structures that are in bad condition might draw public attention and criticism. The maintenance commitment should be recognized before such structures are installed. Special wildlife management units, such as moist-soil-management impoundments and green-tree reservoirs, require close attention to be managed effectively.

Flooding and drawdown schedules must be fine-tuned based on site-specific conditions (Fredrickson and Taylor 1982). Special equipment might be needed to maintain levees, to work on soft ground, to repair drainage structures, and to pump out facilities, all of which might incur substantial fuel costs. The maintenance needs in these kinds of situations require that professional resource managers be on site regularly. Not operating the restoration attentively can create nuisance or hazardous conditions, have severe detrimental effects on existing resources, and fail to produce the desired results.

Mosquito control may also be a maintenance concern near inhabited areas, particularly if the restoration encourages the development of slack-water areas, such as beaver ponds, backwaters, and floodplain depressions. In some cases, control techniques may directly interfere with restoration objectives, but threats to people and livestock might make them necessary.

Figure 9.22: Streamside trail. *Public use areas and recreational facilities require upkeep of roads, trails, and signs.*

9.B Monitoring Techniques Appropriate for Evaluating Restoration

As discussed in Chapter 6, the completion of implementation does not mark the end of the restoration process. Restoration practitioners must plan for and invest in the monitoring of stream corridor restoration. The type and extent of monitoring will depend on specific management objectives developed as a result of stream corridor characterization and condition analysis. Monitoring may be conducted for a number of different purposes including:

- *Performance evaluation:* Assessed in terms of project implementation and ecological effectiveness. Ecological relationships used in monitoring and assessment are validated through collection of field data.
- *Trend assessment:* Includes longer term sampling to evaluate changing ecological conditions at various spatial and temporal scales.
- *Risk assessment:* Used to identify causes and sources of impairment within ecosystems.
- *Baseline characterization:* Used to quantify ecological processes operating in a particular area.

This section examines monitoring from the perspective of evaluating the performance of a restoration initiative. Such initiatives seek to restore the structure and functions discussed in earlier chapters. Designing a monitoring program that directly relates to those valued functions requires careful planning to ensure that a sufficient amount of information is collected. Such monitoring uses measurements of physical, biological, and chemical parameters to evalu-

REVERSE

Review previous chapters for an introduction to the restoration of stream corridor structure and functions.

CASE STUDY

Engineered Log Jams for Bank Protection and Habitat Restoration

Most riverbank protection measures are not designed to improve aquatic or riparian habitat, and many restoration initiatives lack sufficient engineering and geomorphic analysis to effectively restore natural functions of riparian and aquatic ecosystems. The ecological importance of instream woody debris (WD) has been well documented. Woody debris within a stream can often influence the instream channel structure by increasing the occurrence of pools and riffles. As a result, streams with WD typically have less erosion, slower routing of organic detritus (the main food source for aquatic invertebrates), and greater habitat diversity than straight, even-gradient streams with no debris. Woody debris also provides habitat cover for aquatic species and characteristics ideally suited for fish spawning.

*Reintroduction of WD (or log jams) in many parts of the United States has been extensive, but limited understanding of WD stability has hampered many of these efforts. Engineered log jams (ELJs) can restore riverine habitat and in some situations can provide effective bank protection (**Figure 9.23**). Although WD is often considered a hazard because of its apparent mobility, research in Olympic National Park has documented that stable WD jams can occur throughout a drainage basin (Abbe et al. 1997). Even in large alluvial channels that migrate at rates of 30 ft./yr, jams can persist for centuries, creating a mosaic of stable sites that in turn host the large trees necessary to initiate stable jams. Engineered log jams are designed to emulate natural jams and can meet management or restoration objectives such as bank protection and debris retention.*

After learning about the uncertainty and potential risks of creating man-made log jams, landowners near Packwood, Washington, decided the potential environmental, economic, and aesthetic benefits outweighed the risks. An experimental project consisting of three ELJs was implemented to control severe erosion along 1,400 ft. of the upper Cowlitz River. The channel at the site was 645 ft. wide and had an average bank erosion rate of 50 ft./yr from 1990 to 1995. Five weeks after constructing the log jams, the project experienced a 20-year recurrence flow (30,000 $ft.^3/s$). Each ELJ remained intact and met design objectives by transforming an eroding shoreline into a local depositional environment (i.e., accreting shoreline). Approximately 93 tons of WD that was in transport during the flood was trapped by the ELJs, alleviating downstream hazards and enhancing structure stability. Improvements in physical habitat included creation of complex scour pools at each ELJ (Abbe et al. 1997).

Landowners have been delighted by the experiment. The ELJs have remained intact, increased in size, and reclaimed some of the formerly eroded property even after being subjected to major floods in February 1996 and March 1997. When compared to traditional bank stabilization methods, which typically employ the extensive use of exotic materials such as rock rarely found in low-gradient alluvial channels, ELJs can offer an effective and low-cost alternative for erosion control, flood control, and habitat enhancement. The cumulative effect of most traditional bank stabilization methods over time results in progressive channel confinement and detachment of the riparian environment from the channel (e.g., loss of streamside vegetation). In stark contrast, the cumulative effects of using ELJs include long-term protection of a significant floodplain, improvement of instream and riparian habitat, and bank stabilization (Abbe et al. 1997).

Comprehensive geomorphic and hydraulic engineering analysis is required to determine the type of WD needed and the appropriate size, position, spacing, and type of ELJ structure for the particular site(s) and project objectives. Inappropriate design and application of ELJs can result in negative impacts such as local accelerated bank erosion, unstable debris, or channel avulsion. Acknowledging the potential risks and uncertainties of ELJs, their use should be limited to well-documented experimental situations. Continued research and development of ELJs involving field application in a variety of physiographic and climatic conditions is needed. ELJs can provide a means to meet numerous objectives in the management and restoration of rivers and riparian corridors throughout the United States.

Figure 9.23: Engineered log jams. *Engineered log jams (ELJs) can restore riverine habitat and in some situations provide effective bank protection.*

REVERSE

Review Chapter 7D's section on analytical methods for evaluating biological attributes.

ate the effectiveness of the restoration and to facilitate adaptive management where needed. Sampling locations, measurements to be made, techniques to be used, and how the results will be analyzed are important considerations in monitoring.

Adaptive Management

The implementation, effectiveness, and validation components of performance monitoring provide a vehicle to determine the need for adaptive management. Adaptive management is the process of establishing checkpoints to determine whether proper actions have been taken and are effective in providing desired results. Adaptive management provides the opportunity for course correction through evaluation and action.

Adaptive management provides the opportunity for course correction through evaluation and action.

Implementation Monitoring

Implementation monitoring answers the question, "Were restoration measures done and done correctly?" Evaluating the effectiveness of restoration through physical, biological, and/or chemical monitoring can be time-consuming, expensive, and technically challenging. Time and partnerships are needed to build the capability for evaluating project effectiveness based on changes in ecological condition. Therefore, an important interim step to this goal is implementation monitoring. This comparatively simple process of documenting what was done and whether or not it was done properly can yield valuable information that promotes refinement of restoration practices.

Effectiveness Monitoring

Effective monitoring answers the question "Did restoration measures achieve the desired results?" or more simply "Did the restoration initiative work?" Effectiveness monitoring evaluates success by determining whether the restoration had the desired effect on the ecosystem. Monitoring variables focus on indicators that document achievement of desired conditions and are closely linked with project goals. It is important that indicators selected for effectiveness monitoring are sensitive enough to show change, are measurable, are detectable and have statistical validity. This level of monitoring is more time-consuming than implementation monitoring, making it more costly. To save time and money, monitoring at this level is usually performed on a sample population or portion of a project with results extrapolated to the whole population.

Validation Monitoring

Validation monitoring answers the question "Are the assumptions used in restoration design and cause-effect relationships correct?" Validation monitoring considers assumptions made during planning and execution of restoration measures. This level of monitoring is performed in response to nonachievement of desired results once proper implementation is confirmed. A restoration initiative that fails to achieve intended results could be the result of improper assumptions relative to ecological conditions or selection of invalid monitoring indicators. This level of monitoring is always costly and requires scientific expertise.

Evaluation Parameters

Physical Parameters

A variety of channel measurements are appropriate for performance evaluation (**Figure 9.24**). The parameters presented in **Table 9.3** should be considered for measurement of physical performance and stability. Stream pattern and morphology are a result of the interaction of eight measurable parameters—width, depth, channel slope, roughness of channel materials, discharge, velocity, sediment loads, and sediment size (Leopold et al. 1964). These parameters and several other dimensionless ratios (including entrenchment, width/depth ratio, sinuosity, and meander/width ratio) can be used to group stream systems with similar form and pattern. They have been used as delineative criteria in stream classification (Rosgen 1996). Natural streams are not random in their variation.

A change in any of the primary stream variables results in a series of channel adjustments, resulting in alterations of channel pattern and form, and attendant changes in riparian and aquatic habitat.

Figure 9.24: Measurement of a stream corridor. *Monitoring the physical aspects of the stream corridor system is important in evaluating the success of any restoration effort.*

REVERSE

Review Chapters 2 and 7 for information on chemical water parameters and their sampling. Also, review Chapter 8's section on reference reaches.

Biological Parameters

Biological monitoring can cover a broad range of organisms, riparian conditions, and sampling techniques. In most cases, budget and staff will limit the diversity and intensity of evaluation methods chosen. Analytical methods for evaluating biological attributes are discussed in Section 7.D of this document.

Table 9.4 provides examples of the biological attributes of stream ecosystems that may be related to restoration goals. Biological aspects of the stream corridor that may be monitored as part of performance goals include primary productivity, invertebrate and fish communities, riparian/terrestrial wildlife, and riparian vegetation. This may involve monitoring habitat or fauna to determine the degree of success of revegetation efforts or instream habitat improvements.

Biological monitoring programs can include the use of chemical measures. For example, if specific stressors within the stream system, such as high water temperatures and low dissolved oxygen, limit biological communities, direct monitoring of these attributes can provide an evaluation of the performance of more intensive remedial practices, including point source pollution reduction.

Chemical Parameters

Monitoring is necessary to determine if a restoration initiative has had the desired effect on water chemistry. The type and extent of chemical monitoring depends upon the goal of the monitoring program. Major chemical parameters of water and their sampling are discussed in Chapters 2 and 7.

A factor in designing a chemical monitoring approach is the amount of change expected in a system. If the

Table 9.3: Physical parameters to be considered in establishing evaluation criteria for measurement of physical performance and stability.

Plan view	Sinuosity, width, bars, riffles, pools, boulders, logs
Cross sectional profiles — by reach and features	Sketch of full cross section
	Bank response angle
	Depth bankfull
	Width
	Width/depth ratio
Longitudinal profile	Bed particle size distribution
	Water surface slope
	Bed slope
	Pool size/shape/profile
	Riffle size/shape/profile
	Bar features
Classification of existing streams (all reaches)	Varies with classification system
Assessment of hydrologic flow regimes through monitoring	2-, 5-, 10-year storm hydrographs
	Discharge and velocity of base flow
Channel evolutionary track determination	Decreased or increased runoff, flash flood flows
	Incisement/degradation
	Overwidening/aggradation
	Sinuosity trend—evolutionary state, lateral migration
	Increasing or decreasing sinuosity
	Bank erosion patterns
Corresponding riparian conditions	Saturated or ponded riparian terraces
	Alluvium terraces and fluvial levees
	upland/well-drained/sloped or terraced geomorphology
	Riparian vegetation composition, community patterns and successional changes
Corresponding watershed trends–past 20 years and future 20 years	Land use/land cover
	Land management
	Soil types
	Topography
	Regional climate/weather

restoration goal, for example, is to reduce the salinity in a stream by 5 percent, it would be much more difficult to detect than a goal of reducing salinity by 50 percent.

Chemical monitoring can often be used in conjunction with biological monitoring. There are pros and cons for using chemical and biological parameters when monitoring. Biological parameters are often good integrators of several water quality parameters. Biological indicators are especially useful when determining the bioaccumulation of a chemical.

Water chemistry samples are typically easier to replicate, can disclose slow changes over time, and be used to prevent catastrophic events when chemical characteristics are near toxic levels. For example, water quality monitoring might detect a slow decrease in pH over a period of time. Some aquatic organisms, such as trout, might not respond to this gradual change until the water becomes toxic. However, water quality monitoring could detect the change and thereby avoid a catastrophic event. An ideal monitoring program would include both biological and chemical parameters.

Important chemical and physical parameters that might have a significant influence on biological systems include the following:

- Temperature
- Turbidity
- Dissolved oxygen
- pH
- Natural toxics (mercury) and manufactured toxics
- Flow
- Nutrients
- Organic loading (BOD, TOC, etc.)
- Alkalinity/Acidity
- Hardness
- Dissolved and suspended solids
- Channel characteristics
- Spawning gravel
- Instream cover
- Shade
- Pool/riffle ratio
- Springs and ground water seeps
- Bed material load
- Amount and size distribution of large woody debris (i.e., fallen trees)

These parameters may be studied independently or in conjunction with biological measurements of the ecological community.

Reference Sites

Understanding the process of change requires periodic monitoring and mea-

Table 9.4: Examples of biological attributes and corresponding parameters that may be related to restoration goals and monitored as part of performance evaluation.

Biological Attribute	Parameter
Primary productivity	Periphyton
	Plankton
	Vascular and nonvascular macrophytes
Zooplankton/diatoms	
Invertebrate community	Species
	Numbers
	Diversity
	Biomass
	Macro/micro
	Aquatic/terrestrial
Fish community	Anadromous and resident species
	Specific populations or life stages
	Number of outmigrating smolts
	Number of returning adults
Riparian wildlife/ terrestrial community	Amphibians/reptiles
	Mammals
	Birds
Riparian vegetation	Structure
	Composition
	Condition
	Function
	Changes in time (succession, colonization, extirpation, etc.)

surement and scientific interpretation of the information as it relates to the stream corridor. In turn, an evaluation of the amount of change attributed to restoration must be based on established reference conditions developed by the monitoring of reference sites. The following are important considerations in reference site selection:

- What do we want to know about the stream corridor?
- Are identified sites minimally-disturbed?
- Are the identified sites representative of a given ecological region, and do they reflect the range of natural vari-

Performance Evaluation of Fish Barrier Modifications

Fish barrier modifications provide a good example of a technically difficult performance evaluation. The goal of the restoration is easily understood and stated. Barrier modification provides one of two options—to increase populations (increase upstream and downstream movement) or to decrease populations (restrict movement).

In all cases, the specific target species should be identified. If the goal is to restore historic runs of commercial fishes, data for commercial landings may be available to provide guidance. Habitat models are available for species such as Atlantic salmon and can provide insight into expected carrying capacities of nursery habitat. Existing runs in adjacent or nearby river(s) may be examined for population levels and trends that can provide insight into realistic goals. Barriers may be planned for only short-term protection of some species (e.g., protection against cannibalism) or for longer term exclusion of problematic or undesirable species.

*Methodologies to evaluate the success of fish barrier modifications can use a variety of field methods to count the number of adult spawners, to determine the abundance of fry, to estimate the size of the outmigrating juvenile population, or to monitor the travel time between specific points within a watershed (**Table 9.5**). However, consideration needs to be given to factors that may influence the success of the population outside the study area. Commercial fishing, disease, predation, limited food supply, or carrying capacity of juvenile or adult habitat may be more important controlling factors than access to spawning and nursery habitat.*

The performance evaluation must allow ample time for the species to complete its life cycle. Many anadromous species have life spans of 4 to 7 years; sturgeon live for decades. Adequate homing to natal areas may require several generations to build a significant migrating population and to fill all year classes. Floods or droughts can impact fry and juvenile life stages and do not become apparent in adult spawning populations until several years have elapsed. Restoration and monitoring goals need to be formulated to take these non-restoration-limiting factors into account. Examination of year-class structure of returning adults might be useful, or investigations that average the size of spawning runs for multiple years might be appropriate.

Table 9.5: Methods to evaluate effectiveness of fish barrier modifications.

Modification	Method
Fishway counts	Observation windows
	Hydroacoustics
	Fish traps/weirs
	Netting
Population estimates	Mark and recapture
	Snorkel counts
	Redd counts
	Creel census
	Direct counts of spawning adults
Timing of migration between observation points	Radio tagging
	Pit tags
	Dyes and other external marks
	Computer-coded tags

Performance evaluation study methodologies must use appropriate monitoring techniques. Collecting techniques need to be relatively nondestructive. Collecting weirs, traps, or nets need to be designed to limit injury or predation and should function over a wide range of flow and debris levels. Monitoring techniques should not extensively *limit movement. Weirs and traps should not cause excessive delays in migration, and fish tags should not encumber movement. Techniques are often species- and life stage-specific. Fish tags, including radio tags, may be appropriate for older, larger individuals, whereas chemical marks, dyes, fin clips, or internal microtags may be appropriate for smaller organisms. Certain fish, such as alosids (American shad and river herring), may be more difficult to handle than others, such as salmonids (trout and salmon), and appropriate handling techniques need to be used. Avoiding extreme environmental conditions (excessively high or low water temperature or flow) may be important. Nondestructive techniques, such as hydroacousitics and radio tags, have several advantages, but care needs to be taken to differentiate between background noise (mechanical, debris, entrained air, nonlaminar flow), other species, and target species.*

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ability associated with a given stream class?

- What is the least number of sites required to establish reference conditions?
- What are the impediments to reference site access?

Reference sites provide examples of a properly functioning ecosystem. It is from these reference sites that desired conditions are determined and levels of environmental indicators identified. Environmental indicators become the performance criteria to monitor the success of a initiative.

Human Interest Factors

Human activities requiring use of a healthy environment may often be important factors for evaluating stream corridor restorations (**Figure 9.25**). In these cases, the ability of the stream corridor to support the activity indicates benefits drawn from the stream corridor as well as adding insight into stream ecosystem condition. Many human interest-oriented criteria used in performance evaluations can serve the dual function of evaluating elements of human use and ecological condition together:

Figure 9.25: Human interest in the stream corridor. *Aesthetics are a highly valued benefit associated with a healthy stream corridor.*

Additional References for Monitoring

Averett, R.C., and L.J. Schroder. 1993. A guide to the design of surface-water-quality studies: US Geological Survey Open-File Report 93-105, U.S. Geological Survey.

Karr, J.R., and W. Chu. 1997. Biological monitoring and assessment: Using Multimetric Indexes Effectively. USEPA 235-R97-001. University of Washington, Seattle.

Kerchner, J.L. 1997. Setting Riparian/Aquatic Restoration Objectives Within a Watershed Context. In Restoration Ecology Vol. 5, No. 45.

Manley, P.A., et al. 1995. Sustaining Ecosystems: A Conceptual Framework. USDA Forest Service, Pacific Southwest Region, San Francisco, CA. 216 pp.

McDonald, L.H., et al. 1991. Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska. USEPA, Region 10, Seattle, WA. 166 pp.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983, Design of networks for monitoring water quality. Water Resources Publications, Littleton, CO., 328 p.

Stednick, J.D. 1991. Wildland water quality sampling and analysis. Academic Press, San Diego.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. Design of water quality monitoring systems. Van Nostrand Reinhold, New York.

- Human health (disease, toxic/fish consumption advisories)
- Aesthetics (odor, views, sound, litter)
- Non-consumptive recreation (hiking, birding, whitewater rafting, canoeing, outdoor photography)
- Consumptive recreation (fishing, hunting)
- Research and educational uses
- Protection of property (erosion control, floodwater retention)

Use surveys, which determine the success of the restoration in terms of human use, can provide additional biological data. Angler survey, creel census, birding questionnaires, and sign-in trail boxes that request observations of specific species can also provide biological data. Citizens' groups can participate effectively, providing valuable assistance at minimal cost.

9.C Restoration Management

Management is the long-term manipulation and protection of restoration resources to achieve objectives. Management priorities for the stream corridor ecosystem are set during the planning phase and refined during design. These priorities should also be subject to ongoing revision based on regular monitoring and analysis. Management needs can range from relatively passive approaches that involve removal of acute impacts to intensive efforts designed to restore ecosystem functions through active intervention. Whereas a preceding section described the need to provide adequate maintenance for the restoration elements, restoration management is the collective set of decisions made to guide the entire restoration effort to success.

> **anagement eeds can ange from rel- tively passive pproaches that nvolve removal f acute impacts o intensive fforts designed o restore cosystem func- ions through ctive inter- ention.**

The restoration setting and the priorities of participants can make management a fairly straightforward process or a complex process that involves numerous agencies, landowners, and interested citizens. Development of a management plan is less difficult when the corridor and watershed are under the control of a single owner or agency that can clearly state objectives and priorities. Some stream corridor restorations have, in fact, involved extensive land acquisition to achieve sufficient management control to make restoration feasible. Even then, competing interests can exist. Decisions must be made regarding which resource uses are compatible with the defined objectives.

More commonly, stream corridor management decisions will be made in an environment of conflicting interests, overlapping mandates and regulatory jurisdictions, and complex ownership patterns, both in the corridor and in the surrounding watershed. For example, in a Charles River corridor project in Massachusetts, the complex ownership pattern along the river requires direct active management in some areas and easements in others. In the remainder, management is largely a matter of encouraging appropriate use (Barron 1989). Many smaller restorations might be similarly diversified with management decisions involving a variety of participants. Participation and adherence to restoration best management practices (BMPs) may be encouraged through various programs, such as the NRCS's Conservation Reserve Program, multi-agency riparian buffer restoration initiatives, and cost-sharing opportunities available under the EPA Section 319 Program.

Programs intended to reduce nonpoint source pollution of waterways often encourage the use of practices to address problems such as agricultural runoff or sediment generated by timber harvest operations. Because many practices focus on activities within the stream corridor, existing practices should be reviewed to determine their applicability to the stream corridor restoration plan (**Figure 9.26**). Although the ecological restoration objectives for the corridor might require more restrictive management, existing practices can provide a good starting point and establish a rationale for minimum management prescriptions. In stream corridor restoration efforts involving numerous landowners, it might be appropriate to develop a revised set of practices specific to the restoration area. Participants should have the opportunity to participate in developing the practices and should be willing to commit to compliance before the restoration is implemented.

Regulatory controls influencing management options are increasingly complex and require regular review as management plans evolve and adapt. In some areas, regulatory oversight of activities in streamside areas and in the vicinity of wetlands involves fairly rigid rules that may conflict with specific proposed management actions (e.g., selective tree removals). Implementation of management actions in such cases will require coordination and approval from the regulating agencies. Many state and local jurisdictions vary their restrictions according to classification systems reflecting the condition of the streamside area or wetland in terms of "naturalness"; for example, sites with large trees might receive a higher level of protection than sites that have been heavily disturbed.

Restoration is intended specifically to improve the condition of the stream corridor; however, an activity that is allowable initially might be regulated as the corridor condition improves. These changes should be anticipated to the extent possible in developing long-term management and use plans.

Streams

In effect, stream corridor restoration and ongoing monitoring constitute stream management. Many problems detected during monitoring can be resolved by manipulation of the stream corridor vegetation (**Figure 9.27**), land uses, where possible, and only occasionally, by direct physical manipulation of the channel. If "resetting" of the channel system is necessary, it essentially becomes a redesign problem. Where lateral erosion occurs in unanticipated areas and poses an unacceptable threat to function, property, or infrastructure, another restoration approach might have to be initiated.

Figure 9.26: Livestock fences used as a BMP. *Reviewing existing BMPs can be useful in establishing management prescriptions.*

Figure 9.27: Pruning streamside vegetation. *Monitoring might detect the need for manipulation of streamside vegetation.*

In cases where streamflow control is an option, it likely will be a significant component of the management plan to maintain baseflows, water temperatures, and other attributes. However, appropriate flow patterns should have been defined during the design phase, with components of corridor management prescribed accordingly. If hydrologic patterns change after the restoration is established, significant redesign or management changes might be required for the entire corridor. Ultimately, a well-planned, prepared stream corridor restoration design predicts and addresses the potential for hydrologic change.

Forests

In forested environments, the planning and design phases of stream corridor restoration should set specific objectives for forest structure and composition within the corridor. If existing forests are developing in the desired direction, action may not be needed. In this case, forest management consists of protection rather than intervention. In degraded stream corridor forests, achieving desired goals requires active forest management. In many corridors economic return to private and public landowners is an important objective of the restoration plan. Stream corridor restoration may accommodate economic returns from forest management, but management within the stream corridor should be driven primarily by ecological objectives. If the basic goal is to restore and maintain ecological functions, silviculture should imitate natural processes that normally occur in the corridor.

Numerous forest management activities can promote ecological objectives. For example, some corridor forest types might benefit from prescribed fire or wildfire management programs that maintain natural patterns of structural and compositional diversity and regeneration. In other systems, fire might be inappropriate or might be precluded if the stream corridor is in an urban setting. In the latter case, silvicultural treatments might be needed to emulate the effects of fire.

Recovery of degraded streamside forests can be encouraged and accelerated through silvicultural efforts. Active intervention and management may be essential to maintain the character of native plant communities where river regulation has contributed to hydrology and sedimentation patterns that result in isolation from seed sources (Klimas 1991, Johnson 1994). Streamside forests used as buffers to prevent nutrients from reaching streams may require periodic harvests to remove biomass and maintain net uptake (Lowrance et al. 1984, Welsch 1991). However, buffers intended to intercept and degrade herbicides might be most effective if they are managed to achieve old-growth conditions (Entry et al. 1995).

Management of corridor forests should not proceed in isolation from management of adjacent upland systems (**Figure 9.28**). Upland harvests can result in raised water tables and tree mortality in riparian zones. Coordinated silvicultural activities can reduce timber losses as well as minimize the need for roads (Oliver and Hinckley 1987).

Forests managed by government agencies are usually subject to established restrictions on activities in riparian areas. Elsewhere, BMPs for forestry practices are designed to minimize nonpoint source pollution and protect water quality. BMPs typically include restrictions on road placement, equipment use, timber removal practices, and other similar considerations. Existing

Figure 9.28: Streamside forests and adjacent uplands. *Management of streamside forests should not proceed in isolation from management of adjacent upland systems.*

state BMP guidelines may be appropriate for application within the restoration area but often require some modification to reflect the objectives of the restoration or other pre-identified constraints on activities in the vicinity of streams and wetlands.

Grazed Lands

Livestock grazing is a very important stream corridor management issue in most nonforested rangelands and in many forested areas. Uncontrolled livestock grazing can have severe detrimental effects on streambanks, riparian vegetation, and water quality, particularly in arid and semiarid environments (Behnke and Raleigh 1978, Elmore and Beschta 1987, Chaney et al. 1990) (**Figure 9.29**). Livestock naturally concentrate in the vicinity of streams; therefore, special efforts must be made to control or prevent access if stream corridor restoration is to be achieved.

In some cases, livestock may act as an agent in restoration. Management of livestock access is critical to ensure their role is a positive one. Existing state BMPs might be sufficient to promote proper grazing, but might not be innovative or adaptive enough to meet the restoration objectives of a corridor management program.

Complete exclusion of livestock is an effective approach to restore and maintain riparian zones that have been badly degraded by grazing. In some cases, exclusion may be sufficient to reverse the damage without additional intervention. In some degraded systems, removal of livestock for a period of years followed by a planned management program may allow recovery with-

Figure 9.29: Livestock in stream. Uncontrolled livestock grazing can have severe detrimental effects on streambanks, riparian vegetation, and water quality.

CASE STUDY

Partners Working for the Big Spring Creek Watershed

The Big Spring Creek watershed occupies a diverse, primarily agricultural landscape in central Montana, where the nation's third largest freshwater spring (Big Springs) provides untreated drinking water for the 7,000 residents of Lewistown and is the source of one of Montana's best trout streams, Big Spring Creek.

Conservation work by federal, state, and local agencies, private organizations, and citizens in the 255,000-acre Big Spring Creek watershed is not new. Actually, various projects and developments have occurred over the last several decades. For example, the flood control project that protects the city of Lewistown has its roots in the 1960s when, after experiencing a series of floods, the city of Lewistown and community leaders decided to take action. The Fergus County Conservation District, Fergus County Commissioners, City of Lewistown, U.S. Natural Resources Conservation Service, and many community leaders all worked together on this project. The Big Spring Creek Flood Control Project now protects the city of Lewistown from recurrent flooding.

Conservation work now, though, goes beyond flood control. It involves working to solve resource problems on a watershed basis, recognizing that what happens upstream has an effect on the downstream resources. We should look beyond property boundaries at the whole watershed, considering the "cumulative effects" of all our actions. With that in mind, the Fergus County Conservation District, with assistance from its citizen committee, has been working the last few years to improve and protect the watershed. With funding from the Montana Department of Environmental Quality (Section 319), the Big Spring Creek Watershed Partnership was formed.

*This project helps agricultural producers and other landowners to plan and install conservation practices to prevent erosion and keep sediment and other pollutants out of streams and lakes. Area landowners are implementing conservation practices such as improving the riparian vegetation (**Figure 9.30**), treating streambank erosion, and developing water sources off the stream for livestock. Because the project has been well received by the agricultural producers, it has been possible for cooperating agencies to participate in additional watershed improvements. The U.S. Fish and Wildlife Service Partners for Wildlife program has provided funding for several stream restoration and riparian improvement projects. In addition, the Montana Department of Fish, Wildlife and Parks is actively participating in fisheries habitat projects, including the Brewery Flats Stream Restoration.*

Implementation of the Big Spring Creek Watershed Partnership has brought many positive changes to the predominantly agricultural Big Spring Creek watershed. Since most of the agricultural operations are livestock or grain, the major emphasis is on riparian/stream improvement and grazing management. Thus far, more than 30 landowners have participated in the project by installing conservation practices that include over 8 miles of fencing, and 13 off-stream water developments, with more than 10 miles of stream/riparian area protected.

Studies show that stream characteristics and water quality are the best indicators of watershed vitality. Thus, an active monitoring strategy in the watershed provides feedback to measure any improvements. Preproject and postproject fisheries (trout) surveys are conducted in cooperation with the Montana Department of Fish, Wildlife and Parks on selected streams. On East Fork Spring Creek, fencing and off-stream water development were implemented on a riparian/stream reach that was severely degraded from livestock use. Fish populations and size structure changed dramatically from preproject to postproject work. Salmonid numbers increased from 12 to 32 per 1,000 feet, and average size increased by 50 percent. In addition to *fisheries surveys, benthic macroinvertebrate communities are collected and analyzed on a number of streams. This analysis relates to the stream's biological health or integrity. Community structure, function, and sensitivity to impact are compared to baseline data. Habitat conditions on three of six monitoring sites on Big Spring Creek from 1990 to 1997 have shown improved conditions from a suboptimal to an optimal rating. Monitoring will continue on major streams in the watershed, which will help to provide important feedback as to the project's effectiveness.*

Although the major emphasis is on improving and protecting the riparian areas and streams in the watershed, other ongoing efforts include participating in the "Managing Community Growth" initiative, preserving agriculture and open space, and developing recreational and environmental resources. An active committee of the group is involved in one of the largest stream restoration initiatives ever to be undertaken in Montana, planned for 1998. Included in this project is an environmental education trial site being developed with the local schools.

Working with watersheds is a dynamic process, and as a result new activities and partners are continually incorporated into the Big Spring Creek Watershed Partnership. The following agencies and organizations are currently working together with the citizens of the watershed to protect this "very special place."

Fergus County Conservation District

M.S.U.-Extension Service, Fergus County

U.S. Natural Resources Conservation Service

U.S. Fish and Wildlife Service

Montana Department of Fish, Wildlife and Parks

Montana Department of Environmental Quality

Montana Department of Natural Resources and Conservation

(a)

(b)

Figure 9.30: The Big Spring Creek watershed. *(a) A heavily impacted tributary within the Big Spring Creek watershed and (b) the same tributary after restoration.*

U.S. Forest Service

City Of Lewistown

Fergus County Commissioners

Snowy Mountain Chapter Trout Unlimited

Central Montana Pheasants Forever

Lewistown School District No.1

Lewistown Visioning Group

Lewistown Area Chamber of Commerce

out permanent livestock exclusion (Elmore and Beschta 1987). Systems not badly damaged might respond to grazing management involving seasonal and herd size restrictions, off-channel or restricted-access watering, use of riparian pastures, herding, and similar techniques (Chaney et al. 1990). Response to grazing is specific to channel types and season.

In off-channel areas of the stream corridor, grazing may require less intensive management. Grazing might have limited potential to be used as a habitat manipulation tool in certain ecosystems, such as the Northern Plains, where native grazing animals formerly controlled ecosystem structure (Severson 1990). However, where grazing occurs within the stream corridor, it might conflict directly with ecosystem restoration objectives if not properly managed. Corridors that include grazing or have livestock in adjacent areas require vigilance to ensure that fences are maintained and herd management BMPs are followed.

Corridors that include grazing or have livestock in adjacent areas require vigilance to ensure that fences are maintained and herd management BMPs are followed.

Fish and Wildlife

Stream and vegetation care are the focus of many fish and wildlife management activities in the stream corridor. Hunting and fishing activities (**Figure 9.31**), nuisance animal control, and protection of particular species may be addressed in some restoration plans. Special management units, such as seasonally flooded impoundments specifically designed to benefit particular groups of species (Fredrickson and Taylor 1982), might be appropriate components of the stream corridor, requiring special maintenance and management. Numerous fish and wildlife management tools and techniques that address temporary deficiencies in habitat availability are available (e.g., Martin 1986). Inappropriate or haphazard use of some techniques can have unintended detrimental effects (for example, placing wood duck nest boxes in areas that lack brood habitat). Programs intended to manipulate fish and wildlife populations or habitats should be undertaken in consultation with the responsible state or federal resource agencies.

Restoration of a functional stream corridor can be expected to attract beaver in many areas. Where beaver control is warranted because of possible damage to private timberlands or roads, increased mosquito problems, and other concerns, controls should be placed as soon as possible and not after the damage is done. Techniques are available to prevent beaver from blocking culverts or drain pipes and destroying trees. In some cases, effective beaver control requires removal of problem animals (Olson and Hubert 1994).

Human Use

Stream corridors in urban areas are usually used heavily by people and require much attention to minimize, control, or repair human impacts. In some cases, human disturbance prevents some stream corridor functions from being restored. For example, depending on the amount of degradation that has occurred, urban streams might support relatively few, if any, native wildlife species. Other concerns, such as improved water quality, might be addressed effectively through proper restoration efforts. Addressing impacts from surrounding developed areas (such as uncontrolled storm water runoff and predation by pets) requires coordination with community agencies and citizen groups to minimize, prevent, or reverse damage. Management of urban corridors might tend to em-

CASE STUDY

A Creek Ran Through It

Portland, Oregon, sprang up along the Willamette River. As time went on and the city grew, it came to occupy a sequestered spot between the Willamette and Columbia Rivers and the higher reaches of the Sylvan Hills. But before the city expanded to this point, a creek ran through it—Tanner Creek.

The Tanner Creek watershed, comprising approximately 1,600 acres, extended from the forested hills through a canyon and across the valley floor to the Willamette River. During summer months, the creek was placid if not dry. But during the heavy winter rains, the creek became a raging torrent.

As the city of Portland expanded, the creek was diverted into the sewer system and the creek floodway was filled in to make way for development. These combined sewers drained directly to the Willamette River and the Columbia Slough until a series of interceptor pipes and a municipal sewage treatment plant were constructed in the 1940s and 1950s.

However, this new system did not have sufficient capacity to handle the combined sewage and storm water flows during periods of heavy rain, which frequently occur during the winter months. As a result, rather than flowing to the treatment plant for processing and disinfection, the combined sewage and storm water overflowed to outfalls along the Willamette River and the Columbia Slough. Tanner Creek became a part of the cause of combined sewer overflows (CSOs).

In the early 1990s, the city of Portland began to develop a plan to eliminate CSOs. The Tanner Creek Stream Diversion Project was identified early in the CSO planning process as a cornerstone project, a relatively inexpensive method of removing clean storm water from the combined system, thereby reducing CSOs. Nearly 10 miles of pipe ranging from 84 inches to 60 inches in diameter will be constructed to once again carry storm water directly to the river. In addition, best management practices for storm water management will be included. Finally, opportunities for water feature enhancements and educational and cultural opportunities will be explored in partnership with the community and other agencies.

Principal among these opportunities is daylighting a portion of the stream in the city's River District. In partnership with community leaders, special interest groups, a private developer, and other agencies, the city's Bureau of Environmental Services is leading a study of possible design alternatives. For more information contact: Nea Lynn Robinson, Project Manager, Tanner Creek Stream Diversion Project, City of Portland, Oregon.

Figure 9.31: Local fisherman. Fishing and other recreational activities must be considered in restoration management.

igure 9.32: Off-road ehicle. Low- and igh-impact use areas hould be clearly narked within public tream corridors.

phasize recreation, educational opportunities, and community activities more than ecosystem functions. Administrative concerns may focus heavily on local ordinances, zoning, and construction permit standards and limitations.

Community involvement can be an important aspect of urban stream corridor restoration and management. Community groups often initiate restoration and maintain a feeling of ownership that translates into monitoring input, management oversight, and volunteer labor to conduct maintenance and management activities. It is essential that community groups be provided with professional technical guidance including assistance in translating regulatory requirements. It is also important that proposed management actions in urban corridors be discussed in advance with interested groups affected by tree cutting or trail closures.

In nonurban areas, recreation can usually be accommodated without impairing ecological functions if all concerned parties consider ecosystem integrity to be the priority objective (Johnson and Carothers 1982). Strategies can be devised and techniques are available to minimize impacts from activities such as camping, hiking (trail erosion), and even the use of off-road vehicles (Cole and Marion 1988) (**Figure 9.32**). Recreationists should be educated on methods to minimize impacts on the ecosystem and on restoration structures and vegetation. Location of areas designated for low-impact use and areas off-limits to certain high-impact activities (such as off-road vehicles, biking, horseback riding, etc.) should be clearly marked. Access should be restricted to areas where new vegetation has not yet been fully established or where vegetation could be damaged beyond the point of survival.

All the flowers of all the tomorrows are in the seeds of today.

—Chinese proverb

There will come a time when you believe everything is finished. That will be the beginning.

—Louis L'Amour

Appendixes

Appendix A

"The outstanding scientific discovery of the twentieth century is not television, or radio, but rather the complexity of the land organism. Only those who know the most about it can appreciate how little we know about it. The last word in ignorance is the man who says of an animal or plant: "What good is it?" If the land mechanism as a whole is good, then every part is good, whether we understand it nor not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering."

—Aldo Leopold 1953, pp. 145-146

Introduction

The user of this document is cautioned not to attempt to replicate or apply any of the techniques displayed without determining their appropriateness as an integral part of the restoration plan.

The following are presented as examples of the many techniques that are being used in support of stream corridor restoration. Only a limited number of techniques by broad category are shown as examples. Neither the number of examples nor their descriptions are intended to be exhaustive. The examples are conceptual and contain little design guidance. All restoration techniques, however, should be designed; often through an interdisciplinary approach discussed in Part II of this document. Limited guidance is provided on applications, but local standards, criteria, and specifications should always be used.

These and other techniques have specific ranges of applicability in terms of physical and climate adaptation, as well as for different physiographic regions of the country. Techniques that are selected must be components of a system designed to restore specific functions and values to the stream corridor. The use of any single technique, without consideration of system functions and values, may become a short-lived, ineffective fix laid on a system-wide problem. All restoration techniques are most effective when included as an integral part of a restoration plan. Typically a combination of techniques are prescribed to address prevailing conditions and desired goals. Effective restoration will respond to goals and objectives that are determined locally through the planning process described in Chapters 4 though 6.

The restoration plan may prescribe a variety of approaches depending on the condition of the stream corridor and the restoration goals:

- *No action*. Simply remove disturbance factors and "let nature heal itself."
- *Management*. Modify disturbance factors to allow continued use of the corridor, while the system recovers.
- *Manipulation*. Change watershed, corridor, or stream conditions through land use changes, intervention, and designed systems ranging from installing practices to altering flow conditions, to changing stream morphology and alignment.

Regardless of the techniques applied, they should restore the desired functions and achieve the goals of the restoration plan. The following are general considerations that apply to many or all of the techniques in this appendix:

- The potential adverse impacts from failure of these and other techniques should be assessed before they are used.
- Techniques that change the channel slope or cross section have a high potential for causing channel instability upstream and downstream. They should therefore be analyzed and designed by an interdisciplinary team of professionals. These techniques include: weirs, sills, grade control measures, channel realignment, and meander reconstruction.
- The potential impact on flood elevations should be analyzed before these and other techniques are used.
- Many techniques will not endure on streams subject to headcuts or general bed degradation.
- Some form of toe protection will be required for many bank treatment techniques to endure where scour of the streambank toe is anticipated.
- Any restoration technique installed in or in contact with streams, wetlands, floodplains, or other water bodies are subject to various federal, state, and local regulatory programs and requirements. Most techniques presented in this appendix would require the issuance of permits by federal, state, and local agencies prior to installation.

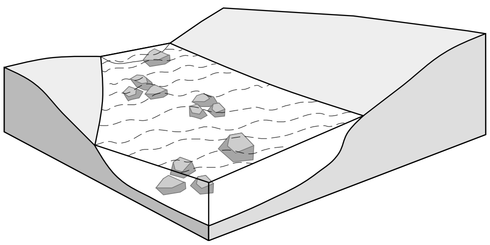
Appendix A: Contents

WATERSHED MANAGEMENT PRACTICES

Appendix A: Techniques

INSTREAM PRACTICES

Boulder Clusters



Groups of boulders placed in the base flow channel to provide cover, create scour holes, or areas of reduced velocity.

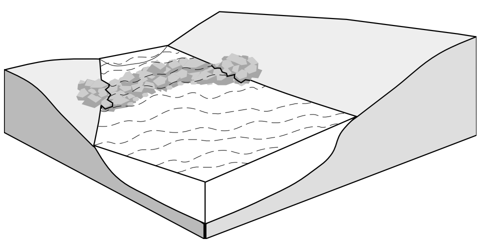
Applications and Effectiveness

- Can be used in most stream habitat types including riffles, runs, flats, glides and open pools.
- Greatest benefits are realized in streams with average flows exceeding 2 feet per second.
- Group placements are most desirable. Individual boulder placement might be effective in very small streams.
- Most effective in wide, shallow streams with gravel or rubble beds.
- Also useful in deeper streams for providing cover and improving sub-strate.
- Not recommended for sand bed (and smaller bed materials) streams because they tend to get buried.
- Added erosive forces might cause channel and bank failures.
- Not recommended for streams which are aggrading or degrading.
- May promote bar formation in streams with high bed material load.

For More Information

- Consult the following references: Nos. 11, 13, 21, 34, 39, 55, 60, 65, 69.

Weirs or Sills



Log, boulder, or quarrystone structures placed across the channel and anchored to the streambank and/or bed to create pool habitat, control bed erosion, or collect and retain gravel.

Applications and Effectiveness

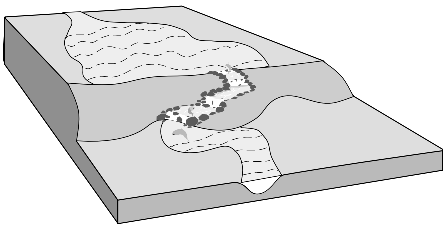
- Create structural and hydraulic diversity in uniform channels.
- If placed in series, they should not be so close together that all riffle and run habitat is eliminated.
- Pools will rapidly fill with sediment in streams transporting heavy bed material loads.
- Riffles often are created in downstream deposition areas.
- Weirs placed in sand bed streams are subject to failure by undermining.
- Potential to become low flow migration barriers.
- Selection of material is important.
  - Boulder weirs are generally more permeable than other materials and might not perform well for funneling low flows. Voids between boulders may be chinked with smaller rock and cobbles to maintain flow over the crest.
  - Large, angular boulders are most desirable to prevent movement during high flows.
  - Log weirs will eventually decompose.
- Design cross channel shape to meet specific need(s).
  - Weirs placed perpendicular to flow work well for creating backwater.
  - Diagonal orientations tend to redistribute scour and deposition patterns immediately downstream.
  - Downstream “V’s” and “U’s” can serve specific functions but caution should be exercised to prevent failures.
  - Upstream “V’s” or “U’s” provide mid-channel, scour pools below the weir for fish habitat, resting, and acceleration maneuvers during fish passage.
  - Center at lower elevation than sides will maintain a concentrated low flow channel.

For More Information

- Consult the following references: Nos. 11, 13, 44, 55, 58, 60, 69.

INSTREAM PRACTICES

Fish Passages



Any one of a number of instream changes which enhance the opportunity for target fish species to freely move to upstream areas for spawning, habitat utilization, and other life functions.

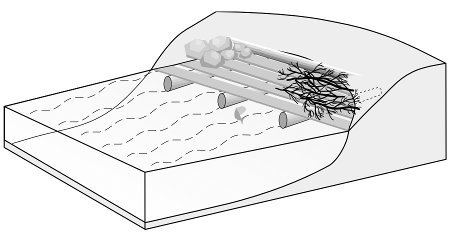
Applications and Effectiveness

- Can be appropriate in streams where natural or human placed obstructions such as waterfalls, chutes, logs, debris accumulations, beaver dams, dams, sills, and culverts interfere with fish migration.
- The aquatic ecosystem must be carefully evaluated to assure that fish passages do not adversely impact other aquatic biota and stream corridor functions.
- Slopes, depths and relative positions of the flow profile for various flow ranges are important considerations. Salmonids, for example, can easily negotiate through vertical water drops where the approach pool depth is 1.25 times the height of the (drop subject to an overall species-specific limit on height) (CA Dept. of Fish and Game, 1994).
- The consequences of obstruction removal for fish passage must be carefully evaluated. In some streams, obstructions act as barriers to undesirable exotics (e.g. sea lamprey) and are useful for scouring and sorting of materials, create important backwater habitat, enhance organic material input, serve as refuge for assorted species, help regulate water temperature, oxygenate water, and provide cultural resources.
- Designs vary from simple to complex depending on the site and the target species.

For More Information

- Consult the following references: Nos., 11, 69, 81.

Log/Brush/Rock Shelters



Logs, brush, and rock structures installed in the lower portion of streambanks to enhance fish habitat, encourage food web dynamics, prevent streambank erosion, and provide shading.

Applications and Effectiveness

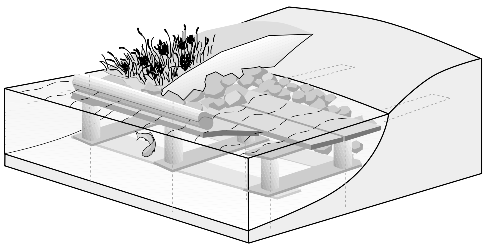
- Most effective in low gradient stream bends and meanders where open pools are already present and overhead cover is needed.
- Create an environment for insects and other organisms to provide an additional food source.
- Can be constructed from readily available materials found near the site.
- Not appropriate for unstable streams which are experiencing severe bank erosion and/or bed degradation unless integrated with other stabilization measures.
- Important in streams where aquatic habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Not generally as effective on the inside of bendways.

For More Information

- Consult the following references: Nos. 11, 13, 39, 55, 65.

INSTREAM PRACTICES

Lunker Structures



Cells constructed of heavy wooden planks and blocks which are imbedded into the toe of streambanks at channel bed level to provide covered compartments for fish shelter, habitat, and prevention of streambank erosion.

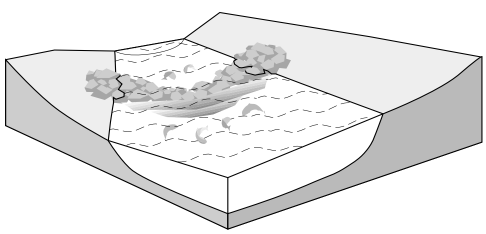
Applications and Effectiveness

- Appropriate along outside bends of streams where water depths can be maintained at or above the top of the structure.
- Suited to streams where fish habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Are often used in conjunction with wing deflectors and weirs to direct and manipulate flows.
- Are not recommended for streams with heavy bed material loads.
- Most commonly used in streams with gravel-cobble beds.
- Heavy equipment may be necessary for excavating and installing the materials.
- Can be expensive.

For More Information

- Consult the following references: Nos. 10, 60, 65, 85.

Migration Barriers



Obstacles placed at strategic locations along streams to prevent undesirable species from accessing upstream areas.

Applications and Effectiveness

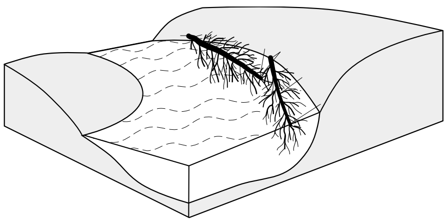
- Effective for specific fishery management needs such as separating species or controlling nuisance species by creating a barrier to migration.
- Must be carefully evaluated to assure migration barriers do not adversely impact other aquatic biota and stream corridor functions.
- Both physical structures or electronic measures can be used as barriers.
  - Structures can be installed across most streams, but in general they are most practical in streams with baseflows depths under two feet and widths under thirty feet.
  - Temporary measures such as seines can also be used under the above conditions.
  - Electronic barriers can be installed in deeper channels to discourage passage. Electronic barrier employs lights, electrical pulses or sound frequencies to discourage fish from entering the area. This technique has the advantage of not disturbing the stream and providing a solution for control in deep water.
- Barriers should be designed so that flood flows will not flank them and cause failures.

For More Information

- Consult the following references: Nos. 11, 55.

INSTREAM PRACTICES

Tree Cover



Felled trees placed along the streambank to provide overhead cover, aquatic organism substrate and habitat, stream current deflection, scouring, deposition, and drift catchment.

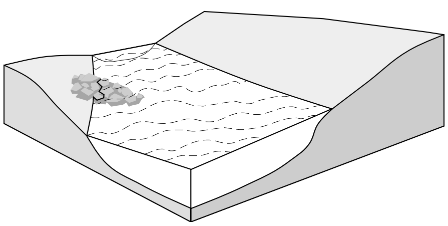
Applications and Effectiveness

- Can provide benefits at a low installation cost.
- Particularly advantageous in streams where the bed is unstable and felled trees can be secured from the top of bank.
- Channels must be large enough to accommodate trees without threatening bank erosion and limiting needed channel flow capacity.
- Design of adequate anchoring systems is necessary.
- Not recommended if debris jams on downstream bridges might cause subsequent problems.
- Require frequent maintenance.
- Susceptible to ice damage.

For More Information

- Consult the following references: Nos. 11, 55, 69.

Wing Deflectors



Structures that protrude from either streambank but do not extend entirely across a channel. They deflect flows away from the bank, and scour pools by constricting the channel and accelerating flow.

Applications and Effectiveness

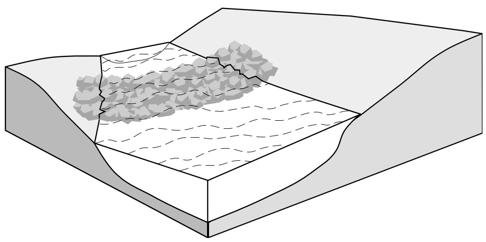
- Should be designed and located far enough downstream from riffle areas to avoid backwater effects that would drown out or otherwise damage the riffle.
- Should be sized based on anticipated scour.
- The material washed out of scour holes is usually deposited a short distance downstream to form a bar or riffle area. These areas of deposition are often composed of clean gravels that provide excellent habitat for certain species.
- Can be installed in series on alternative streambanks to produce a meandering thalweg and associated structural diversity.
- Rock and rock-filled log crib deflector structures are most common.
- Should be used in channels with low physical habitat diversity, particularly those with a lack of stable pool habitat.
- Deflectors placed in sand bed streams may settle or fail due to erosion of sand, and in these areas a filter layer or geotextile might be needed underneath the deflector.

For More Information

- Consult the following references: Nos. 10, 11, 18, 21, 34, 48, 55, 59, 65, 69, 77.

INSTREAM PRACTICES

Grade Control Measures



Rock, wood, earth, and other material structures placed across the channel and anchored in the streambanks to provide a "hard point" in the streambed that resists the erosion forces of the degradational zone, and/or to reduce the upstream energy slope to prevent bed scour.

Applications and Effectiveness

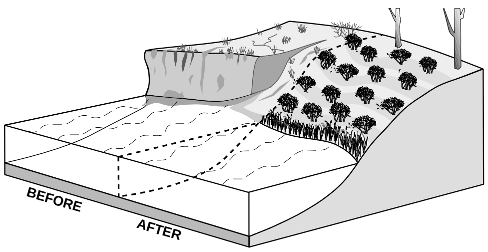
- If a stable channel bed is essential to the design, grade control should be considered as a first step before any restoration measures are implemented (if degradational processes exist in channel system).
- Used to stop headcutting in degrading channels.
- Used to build bed of incised stream to higher elevation.
- Can improve bank stability in an incised channel by reducing bank heights.
- Man-made scour holes downstream of structures can provide improved aquatic habitat.
- Upstream pool areas created by structures provide increased low water depths for aquatic habitat.
- Potential to become low flow migration barrier.
- Can be designed to allow fish passage.
- If significant filling occurs upstream of structure, then downstream channel degradation may result.
- Upstream sediment deposition may cause increased meandering tendencies.
- Siting of structures is critical component of design process, including soil mechanics and geotechnical engineering.
- Design of grade control structures should be accomplished by an experienced river engineer.

For More Information

- Consult the following references: Nos. 1, 4, 5, 6, 7, 12, 17, 18, 25, 26, 31, 37, 40, 63, 66, 84.

STREAMBANK TREATMENT

Bank Shaping and Planting



Regrading streambanks to a stable slope, placing topsoil and other materials needed for sustaining plant growth, and selecting, installing and establishing appropriate plant species.

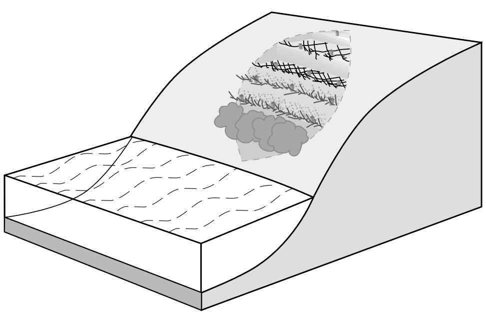
Applications and Effectiveness

- Most successful on streambanks where moderate erosion and channel migration are anticipated.
- Reinforcement at the toe of the embankment is often needed.
- Enhances conditions for colonization of native species.
- Used in conjunction with other protective practices where flow velocities exceed the tolerance range for available plants, and where erosion occurs below base flows.
- Streambank soil materials, probable groundwater fluctuation, and bank loading conditions are factors for determining appropriate slope conditions.
- Slope stability analyses are recommended.

For More Information

- Consult the following references: Nos. 11, 14, 56, 61, 65, 67, 68, 77, 79.

Branch Packing



Alternate layers of live branches and compacted backfill which stabilize and revegetate slumps and holes in streambanks.

Applications and Effectiveness

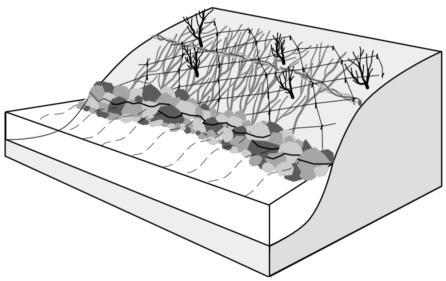
- Commonly used where patches of streambank have been scoured out or have slumped leaving a void.
- Appropriate after stresses causing the slump have been removed.
- Less commonly used on eroded slopes where excavation is required to install the branches.
- Produces a filter barrier that prevents erosion and scouring from streambank or overbank flows.
- Rapidly establishes a vegetated streambank.
- Enhances conditions for colonization of native species.
- Provides immediate soil reinforcement.
- Live branches serve as tensile inclusions for reinforcement once installed.
- Typically not effective in slump areas greater than four feet deep or four feet wide.

For More Information

- Consult the following references: Nos. 14, 21, 34, 79, 81.

STREAMBANK TREATMENT

Brush Mattresses



Combination of live stakes, live facines, and branch cuttings installed to cover and physically protect streambanks; eventually to sprout and establish numerous individual plants.

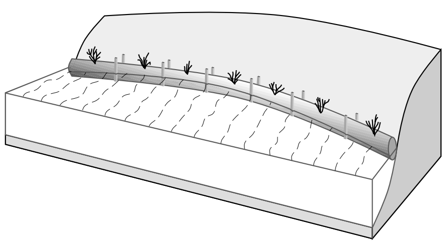
Applications and Effectiveness

- Form an immediate protective cover over the streambank.
- Capture sediment during flood flows.
- Provide opportunities for rooting of the cuttings over the streambank.
- Rapidly restores riparian vegetation and streamside habitat.
- Enhance conditions for colonization of native vegetation.
- Limited to the slope above base flow levels.
- Toe protection is required where toe scour is anticipated.
- Appropriate where exposed streambanks are threatened by high flows prior to vegetation establishment.
- Should not be used on slopes which are experiencing mass movement or other slope instability.

For More Information

- Consult the following references: Nos. 14, 21, 34, 56, 65, 77, 79, 81.

Coconut Fiber Roll



Cylindrical structures composed of coconut husk fibers bound together with twine woven from coconut material to protect slopes from erosion while trapping sediment which encourages plant growth within the fiber roll.

Applications and Effectiveness

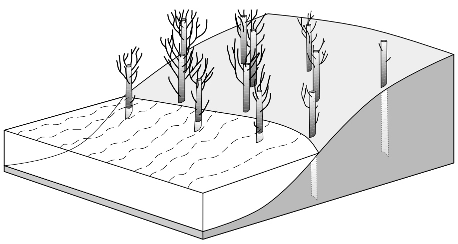
- Most commonly available in 12 inch diameter by 20 foot lengths.
- Typically staked near the toe of the streambank with dormant cuttings and rooted plants inserted into slits cut into the rolls.
- Appropriate where moderate toe stabilization is required in conjunction with restoration of the streambank and the sensitivity of the site allows for only minor disturbance.
- Provide an excellent medium for promoting plant growth at the water's edge.
- Not appropriate for sites with high velocity flows or large ice build up.
- Flexibility for molding to the existing curvature of the streambank.
- Requires little site disturbance.
- The rolls are buoyant and require secure anchoring.
- Can be expensive.
- An effective life of 6 to 10 years.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streamside vegetation.
- Enhances conditions for colonization of native vegetation.

For More Information

- Consult the following references: Nos. 65, 77.

STREAMBANK TREATMENT

Dormant Post Plantings



Plantings of cottonwood, willow, poplar, or other species embedded vertically into streambanks to increase channel roughness, reduce flow velocities near the slope face, and trap sediment.

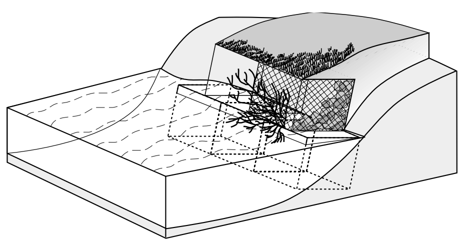
Applications and Effectiveness

- Can be used as live piling to stabilize rotational failures on streambanks where minor bank sloughing is occurring.
- Useful for quickly establishing riparian vegetation, especially in arid regions where water tables are deep.
- Will reduce near bank stream velocities and cause sediment deposition in treated areas.
- Reduce streambank erosion by decreasing the near-bank flow velocities.
- Generally self-repairing and will restem if attacked by beaver or livestock; however, provisions should be made to exclude such herbivores where possible.
- Best suited to non-gravely streams where ice damage is not a problem.
- Will enhance conditions for colonization of native species.
- Are less likely to be removed by erosion than live stakes or smaller cuttings.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streamside vegetation.
- Unlike smaller cuttings, post harvesting can be very destructive to the donor stand, therefore, they should be gathered as 'salvage' from sites designated for clearing, or thinned from dense stands.

For More Information

- Consult the following references: Nos. 65, 77, 79.

Vegetated Gabions



Wire-mesh, rectangular baskets filled with small to medium size rock and soil and laced together to form a structural toe or sidewall. Live branch cuttings are placed on each consecutive layer between the rock filled baskets to take root, consolidate the structure, and bind it to the slope.

Applications and Effectiveness

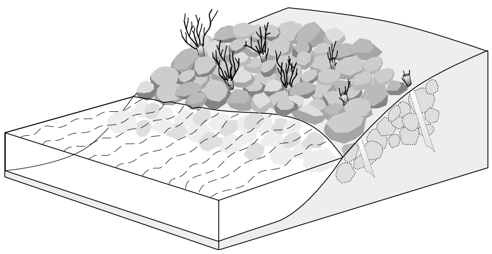
- Useful for protecting steep slopes where scouring or undercutting is occurring or there are heavy loading conditions.
- Can be a cost effective solution where some form of structural solution is needed and other materials are not readily available or must be brought in from distant sources.
- Useful when design requires rock size greater than what is locally available.
- Effective where bank slope is steep and requires moderate structural support.
- Appropriate at the base of a slope where a low toe wall is needed to stabilize the slope and reduce slope steepness.
- Will not resist large, lateral earth stresses.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Require a stable foundation.
- Are expensive to install and replace.
- Appropriate where channel side slopes must be steeper than appropriate for riprap or other material, or where channel toe protection is needed, but rock riprap of the desired size is not readily available.
- Are available in vinyl coated wire as well as galvanized steel to improve durability.
- Not appropriate in heavy bedload streams or those with severe ice action because of serious abrasion damage potential.

For More Information

- Consult the following references: Nos. 11, 18, 34, 56, 77.

STREAMBANK TREATMENT

Joint Plantings



Live stakes tamped into joints or openings between rock which have previously been installed on a slope or while rock is being placed on the slope face.

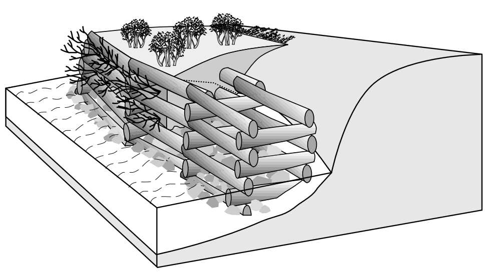
Applications and Effectiveness

- Appropriate where there is a lack of desired vegetative cover on the face of existing or required rock riprap.
- Root systems provide a mat upon which the rock riprap rests and prevents loss of fines from the underlying soil base.
- Root systems also improve drainage in the soil base.
- Will quickly establish riparian vegetation.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Have few limitations and can be installed from base flow levels to top of slope, if live stakes are installed to reach ground water.
- Survival rates can be low due to damage to the cambium or lack of soil/stake interface.
- Thick rock riprap layers may require special tools for establishing pilot holes.

For More Information

- Consult the following references: Nos. 21, 34, 65, 77, 81.

Live Cribwalls



Hollow, box-like interlocking arrangements of untreated log or timber members filled above baseflow with alternate layers of soil material and live branch cuttings that root and gradually take over the structural functions of the wood members.

Applications and Effectiveness

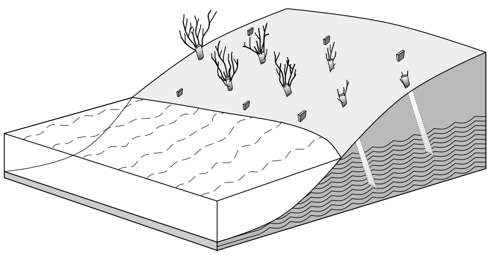
- Provide protection to the streambank in areas with near vertical banks where bank sloping options are limited.
- Afford a natural appearance, immediate protection and accelerate the establishment of woody species.
- Effective on outside of bends of streams where high velocities are present.
- Appropriate at the base of a slope where a low wall might be required to stabilize the toe and reduce slope steepness.
- Appropriate above and below water level where stable streambeds exist.
- Don't adjust to toe scour.
- Can be complex and expensive.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.

For More Information

- Consult the following references: Nos. 11, 14, 21, 34, 56, 65, 77, 81.

STREAMBANK TREATMENT

Live Stakes



Live, woody cuttings which are tamped into the soil to root, grow and create a living root mat that stabilizes the soil by reinforcing and binding soil particles together, and by extracting excess soil moisture.

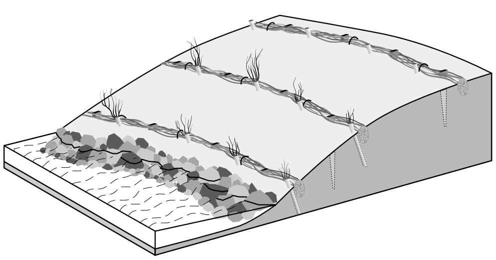
Applications and Effectiveness

- Effective where site conditions are uncomplicated, construction time is limited, and an inexpensive method is needed.
- Appropriate for repair of small earth slips and slumps that are frequently wet.
- Can be used to stake down surface erosion control materials.
- Stabilize intervening areas between other soil bioengineering techniques.
- Rapidly restores riparian vegetation and streamside habitat.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings.
- Enhance conditions for colonization of vegetation from the surrounding plant community.
- Requires toe protection where toe scour is anticipated.

For More Information

- Consult the following references: Nos. 14, 21, 34, 56, 65, 67, 77, 79, 81.

Live Fascines



Dormant branch cuttings bound together into long sausage-like, cylindrical bundles and placed in shallow trenches on slopes to reduce erosion and shallow sliding.

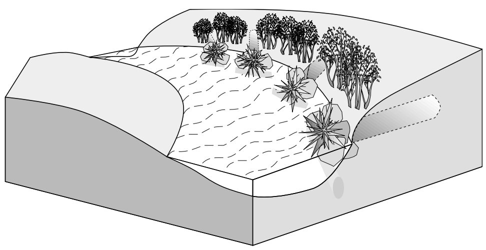
Applications and Effectiveness

- Can trap and hold soil on streambank by creating small dam-like structures and reducing the slope length into a series of shorter slopes.
- Facilitate drainage when installed at an angle on the slope.
- Enhance conditions for colonization of native vegetation.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings.
- Requires toe protection where toe scour is anticipated.
- Effective stabilization technique for streambanks, requiring a minimum amount of site disturbance.
- Not appropriate for treatment of slopes undergoing mass movement.

For More Information

- Consult the following references: Nos. 14, 21, 34, 65, 77, 81.

Log, Rootwad, and Boulder Revetments



Boulders and logs with root masses attached placed in and on streambanks to provide streambank erosion, trap sediment, and improve habitat diversity.

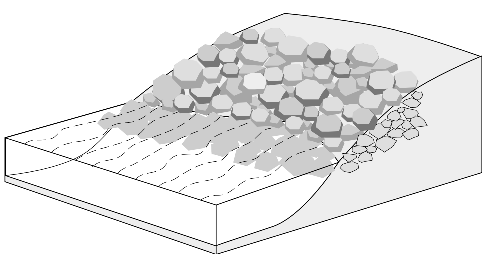
Applications and Effectiveness

- Will tolerate high boundary shear stress if logs and rootwads are well anchored.
- Suited to streams where fish habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Will enhance diversity in riparian areas when used with soil bioengineering systems.
- Will have limited life depending on climate and tree species used. Some species, such as cottonwood or willow, often sprout and accelerate colonization.
- Might need eventual replacement if colonization does not take place or soil bioengineering systems are not used.
- Use of native materials can sequester sediment and woody debris, restore streambanks in high velocity streams, and improve fish rearing and spawning habitat.
- Site must be accessible to heavy equipment.
- Materials might not be readily available at some locations.
- Can create local scour and erosion.
- Can be expensive.

For More Information

- Consult the following references: Nos. 11, 34, 77.

Riprap



A blanket of appropriately sized stones extending from the toe of slope to a height needed for long term durability.

Applications and Effectiveness

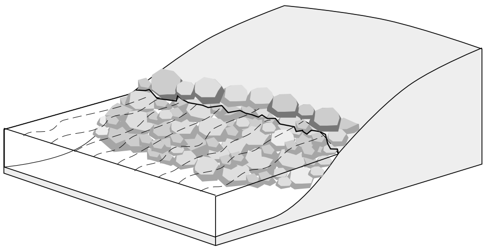
- Can be vegetated (see joint plantings).
- Appropriate where long term durability is needed, design discharge are high, there is a significant threat to life or high value property, or there is no practical way to otherwise incorporate vegetation into the design.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Flexible and not impaired by slight movement from settlement or other adjustments.
- Should not be placed to an elevation above which vegetative or soil bioengineering systems are an appropriate alternative.
- Commonly used form of bank protection.
- Can be expensive if materials are not locally available.

For More Information

- Consult the following references: Nos. 11, 14, 18, 34, 39, 56, 67, 70, 77.

STREAMBANK TREATMENT

Stone Toe Protection



A ridge of quarried rock or stream cobble placed at the toe of the streambank as an armor to deflect flow from the bank, stabilize the slope and promote sediment deposition.

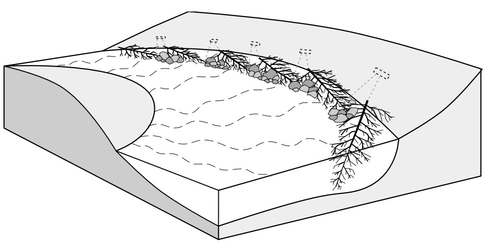
Applications and Effectiveness

- Should be used on streams where banks are being undermined by toe scour, and where vegetation cannot be used.
- Stone prevents removal of the failed streambank material that collects at the toe, allows revegetation and stabilizes the streambank.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerated source of streamside vegetation.
- Can be placed with minimal disturbance to existing slope, habitat, and vegetation.

For More Information

- Consult the following references: Nos. 10, 21, 56, 67, 77, 81.

Tree Revetments



A row of interconnected trees attached to the toe of the streambank or to deadmen in the streambank to reduce flow velocities along eroding streambanks, trap sediment, and provide a substrate for plant establishment and erosion control.

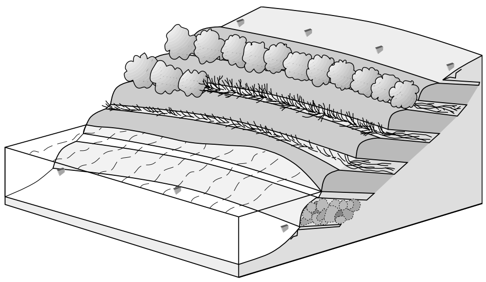
Applications and Effectiveness

- Design of adequate anchoring systems is necessary.
- Wire anchoring systems can present safety hazards.
- Work best on streams with streambank heights under 12 feet and bankfull velocities under 6 feet per second.
- Use inexpensive, readily available materials.
- Capture sediment and enhances conditions for colonization of native species particularly on streams with high bed material loads.
- Limited life and must be replaced periodically.
- Might be severely damaged by ice flows.
- Not appropriate for installation directly upstream of bridges and other channel constrictions because of the potential for downstream damages should the revetment dislodge.
- Should not be used if they occupy more than 15 percent of the channel's cross sectional area at bankfull level.
- Not recommended if debris jams on downstream bridges might cause subsequent problems.
- Species that are resistant to decay are best because they extend the establishment period for planted or volunteer species that succeed them.
- Requires toe protection where toe scour is anticipated.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerated source of streamside vegetation.

For More Information

- Consult the following references: Nos. 11, 21, 34, 56, 60, 77, 79.

Vegetated Geogrids



Alternating layers of live branch cuttings and compacted soil with natural or synthetic geotextile materials wrapped around each soil lift to rebuild and vegetate eroded streambanks.

Applications and Effectiveness

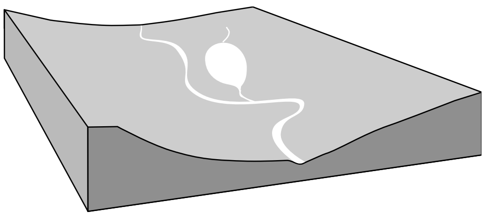
- Quickly establish riparian vegetation if properly designed and installed.
- Can be installed on a steeper and higher slope and has a higher initial tolerance of flow velocity than brush layering.
- Can be complex and expensive.
- Produce a newly constructed, well-reinforced streambank.
- Useful in restoring outside bends where erosion is a problem.
- Capture sediment and enhances conditions for colonization of native species.
- Slope stability analyses are recommended.
- Can be expensive.
- Require a stable foundation.

For More Information

- Consult the following references: Nos. 10, 11, 14, 21, 34, 56, 65, 77.

WATER MANAGEMENT

Sediment Basins



Barriers, often employed in conjunction with excavated pools, constructed across a drainage way or off-stream and connected to the stream by a flow diversion channel to trap and store waterborne sediment and debris.

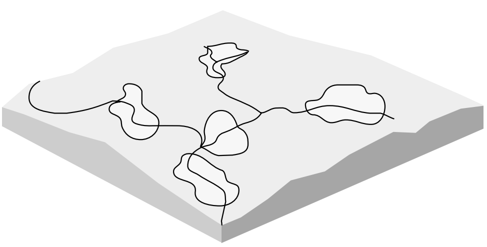
Applications and Effectiveness

- Provide an interim means of reducing the sediment load from a stream.
- Used occasionally to sort sediment sizes.
- Temporarily reduce excessive sediment loads until the upstream watershed can be protected from accelerated erosion.
- Can also be used to separate out sediment which may be causing damages downstream along reaches which are incapable of transporting the sediment sizes.
- Can be integrated with more permanent stormwater management ponds.
- Can only trap the upper range of particle sizes (sand and gravel) and allow finer particles (silt and clay) to pass through.
- Require a high level of analysis.
- Require periodic dredging and other maintenance.

For More Information

- Consult the following references: Nos. 10, 13, 29, 45, 49, 69, 74, 80.

Water Level Control



Managing water levels within the channel and adjoining riparian zone to control aquatic plants and restore desired functions, including aquatic habitat.

Applications and Effectiveness

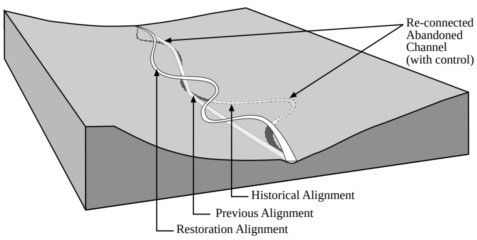
- Appropriate where flow depth in the stream, adjoining wetland, or the interdependent saturation zone in the adjoining riparian area is insufficient to provide desired functions.
- Need will often vary by season and requires flexible control devices which can be managed accordingly.
- The complexities of maintaining sediment balances, temperature elevation, change in channel substrate, changes in flow regime, and a host of other considerations must be factored into planning and design.
- Requires a high level of analysis.

For More Information

- Consult the following references: Nos. 11, 13, 15, 69, 75.

CHANNEL RECONSTRUCTION

Maintenance of Hydraulic Connections



Maintenance of hydraulic connectivity to allow movement of water and biota between the stream and abandoned channel reaches.

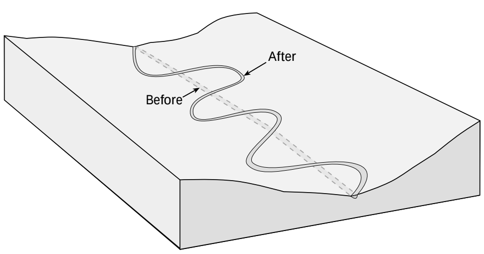
Applications and Effectiveness

- Used to prevent losses of aquatic habitat area and diversity.
- Slackwater areas adjoining the main channel have potential for spawning and rearing areas for many fish species and are a key component of habitat for wildlife species that live in or migrate through the riparian corridor.
- Recreation value can be enhanced if connecting channels are deep enough for small boats or canoes.
- Effective along reaches of realigned channel where cutoffs have been made.
- Not effective in streams with insufficient stages or discharges to maintain satisfactory hydraulic connections to the abandoned channel reaches.
- May require maintenance if sedimentation is a problem.
- May have limited life.
- Require a high level of analysis.

For More Information

- Consult the following references: Nos. 15, 56, 69, 75.

Stream Meander Restoration



Transformation of a straightened stream into a meandering one to reintroduce natural dynamics improve channel stability, habitat quality, aesthetics, and other stream corridor functions or values.

Applications and Effectiveness

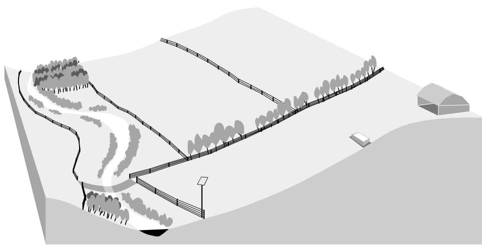
- Used to create a more stable stream with more habitat diversity.
- Requires adequate area where adjacent land uses may constrain locations.
- May not be feasible in watersheds experiencing rapid changes in land uses.
- Streambank protection might be required on the outside of bends.
- Significant risk of failure.
- Requires a high level of analysis.
- May cause significant increases in flood elevations.
- Effective discharge should be computed for both existing and future conditions, particularly in urbanized watersheds.

For More Information

- Consult the following references: Nos. 13, 16, 22, 23, 24, 46, 47, 52, 53, 54, 56, 61, 72, 75, 77, 78, 79, 86.

STREAM CORRIDOR MEASURES

Livestock Exclusion or Management



Fencing, alternate sources of water and shelter, and managed grazing to protect, maintain, or improve riparian flora and fauna and water quality.

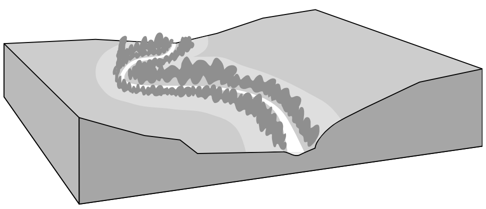
Applications and Effectiveness

- Appropriate where livestock grazing is negatively impacting the stream corridor by reducing growth of woody vegetation, decreasing water quality, or contributing to the instability of streambanks.
- Once the system has recovered, rotational grazing may be incorporated into the management plan.
- Must be coordinated with an overall grazing plan.

For More Information

- Consult the following references: Nos. 18, 39, 73.

Riparian Forest Buffers



Streamside vegetation to lower water temperatures, provide a source of detritus and large woody debris, improve habitat, and to reduce sediment, organic material, nutrients, pesticides and other pollutants migrating to the stream.

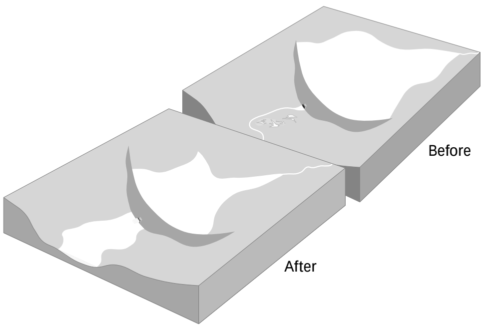
Applications and Effectiveness

- Applicable on stable areas adjacent to permanent or intermittent streams, lakes, ponds, wetlands and areas with ground water recharge.
- Unstable areas such as those with high surface erosion rates, mass soil movement, or active gullies will require stabilization prior to establishment of riparian forest buffers.
- Tolerant plant species and supplemental watering may be needed in some areas.
- Sites in arid and semi-arid regions may not have sufficient soil moisture throughout the growing season to support woody plants.
- Concentrated flow erosion, excessive sheet and rill erosion, or mass soil movement must be controlled in upland areas prior to establishment of riparian forest buffers.

For More Information

- Consult the following references: Nos. 20, 34, 49, 51, 70, 78, 79, 81, 82, 88, 89.

Flushing for Habitat Restoration



A high-magnitude, short duration release from a reservoir to scour fine-grained sediments from the streambed and restore suitable instream habitat.

Applications and Effectiveness

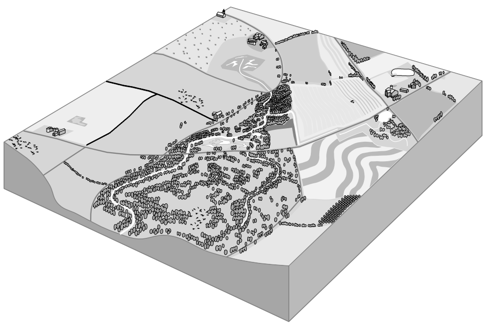
- Appropriate as part of an overall watershed management plan.
- May cause flooding of old floodplains below dams, depletion of gravel substrates, and significant changes in channel geometry.
- Flushing of fine sediments at one location may only move the problem further downstream.
- Seasonal discharge limits, rate of change of flow, and river stages downstream of impoundment should be considered to avoid undesirable impacts to instream and riparian habitat.
- Can be effective in improving gradation of streambed materials, suppression of aquatic vegetation, and maintenance of stream channel geometry necessary for desired instream habitat.
- Can induce floodplain scouring to provide suitable growing conditions for riparian vegetation.
- Requires high level of analysis to determine necessary release schedule.
- May not be feasible in areas where water rights are fully allocated.

For More Information

- Consult the following references: Nos. 11, 13, 32, 35, 41, 45, 57, 61, 73, 74, 81.

WATERSHED MANAGEMENT

Best Management Practices: Agriculture



Individual and systematic approaches aimed at mitigating non-point source pollution from agricultural land.

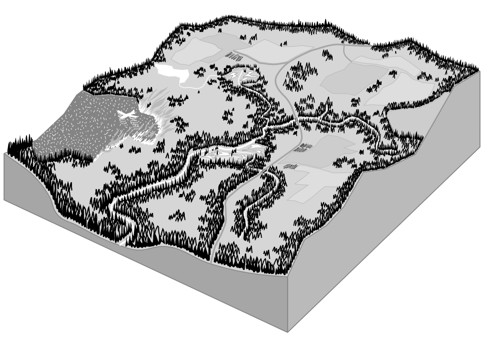
Applications and Effectiveness

- Used where current management systems are causing problems on-site or within farm or field boundaries and have a high potential to impact the stream corridor.
- Also applied where watershed management plans are being implemented to improve environmental conditions.
- Must fit within a comprehensive farm management plan, a watershed action plan, or a stream corridor restoration plan.
- Should consider the four season conservation of the soil, water, and microbial resources base.
- Tillage, seeding, fertility, pest management, and harvest operations should consider environmental qualities and the potential to use adjacent lands in water and soil conservation and management and pest management.
- Grazing land management should protect environmental attributes, including native species protection, while achieving optimum, long-term resource use.
- Where crops are raised and the land class allows, pastures should be managed with crop rotation sequences to provide vigorous forage cover while building soil and protecting water and wildlife qualities.
- Orchards and nursery production should actively monitor pest and water management techniques to protect ecosystem quality and diversity.
- Farm woodlots, wetlands, and field borders should be part of an overall farm plan that conserves, protects, and enhances native plants and animals, soil, water, and scenic qualities.
- BMPs may include: contour farming, conservation tillage, terracing, critical area planting, nutrient management, sediment basins, filter strips, waste storage management, and integrated pest management.

For More Information

- Consult the following references: Nos. 73, 78, 81.

Best Management Practices: Forestland



Individual and systematic approaches for mitigating non-point source pollution from forestland.

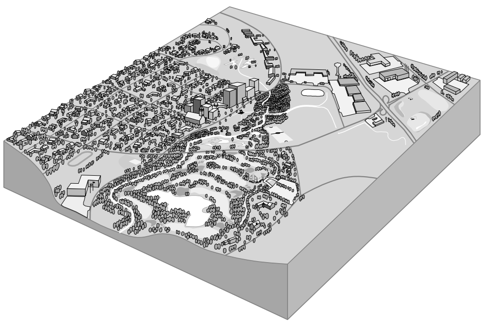
Applications and Effectiveness

- Used where current management systems are causing problems in the watershed and have a high potential to impact the stream corridor.
- Also applied where management plans are being implemented to restore one or more natural resource functions in a watershed.
- Must consider how it fits within a comprehensive forestland management plan, a watershed action plan, or a stream corridor restoration plan.
- BMPs may include: preharvest planning, streamside management measures, road construction or reconstruction, road management, timber harvesting, site preparation and forest generation, fire management, revegetation of disturbed areas, forest chemical management, and forest wetland management.

For More Information

- Consult the following references: Nos. 9, 20, 27, 30, 34, 42, 49, 51, 70, 78, 79, 81, 82, 83, 88, 89.

Best Management Practices: Urban Areas



Individual or systematic approaches designed to offset, reduce, or protect against the impacts of urban development and urban activities on the stream corridor.

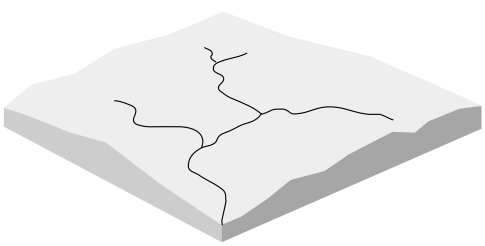
Applications and Effectiveness

- Used to improve and/or restore ecological functions which have been impaired by urban activities.
- Needs to be integrated with BMPs on other lands in the landscape to assure that stream restoration is applied along the entire stream corridor to the extent possible.
- The use of individual urban BMPs should be coordinated with an overall plan for restoring the stream system.
- Urban sites are highly variable and have a high potential for disturbance.
- Applicability of the treatment to the site situation in terms of physical layout, relationship to the overall system, arrangements for maintenance, and protection from disturbances are often critical considerations.
- BMPs may include: extended detention dry basins, wet ponds, constructed wetlands, oil-water separators, vegetated swales, filter strips, infiltration basins and trenches, porous pavement, and urban forestry.

For More Information

- Consult the following references: Nos. 29, 34, 43, 49, 78, 80, 81, 83.

Flow Regime Enhancement



Manipulation of watershed features (such as changes in land use or construction of impoundments) for the purpose of controlling streamflow and improving physical, chemical and biological functions.

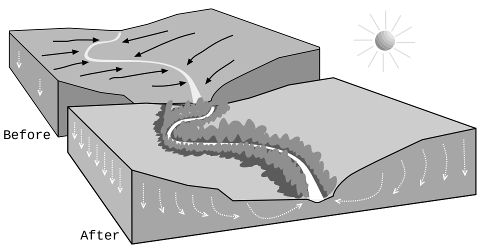
Applications and Effectiveness

- Appropriate where human-induced changes have altered stream flow characteristics to the extent that streams no longer support their former functions.
- Can restore or improve threatened functions (e.g., substrate materials or distribution of flow velocities to support the natural food web).
- Can require extensive changes over broad areas involving many land users.
- Can be expensive.
- Has been used for remediation of depleted dissolved oxygen levels, reduction in salinity levels, or to maintain a minimum flow level for downstream users.
- Must determine what impacts from historical changes in the flow regime over time can be mitigated using flow enhancement techniques.

For More Information

- Consult the following references: Nos. 32, 39, 45, 57, 75, 81.

Streamflow Temperature Management



Streamside vegetation and upland practices to reduce elevated streamflow temperatures.

Applications and Effectiveness

- Effective for smaller streams where bank vegetation can provide substantial shading of the channel and on which much of the canopy has been removed.
- Appropriate practices are those that establish streamside vegetation, increase vegetative cover, increase infiltration and subsurface flow, maintain base flow, and reduce erosion.
- Turbid water absorbs more solar radiation than clear; therefore, erosion control in watersheds can help in reducing thermal pollution.
- Flow releases from cooler strata of reservoirs must be exercised with caution. Although cooler, water from this source is generally low in dissolved oxygen and must be aerated before discharging downstream. Selective mixing of the reservoir withdrawal can moderate temperature as may be required.
- There might be opportunities in irrigated areas to cool return flows prior to discharge to streams.

For More Information

- Consult the following references: Nos. 32, 39, 45, 73, 80, 81, 88, 89.

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Appendix B

INCH-POUND / METRIC CONVERSION FACTORS

Length

Unit of measure	Abbreviation	mm	cm	m	km	in	ft	mi
millimeter	mm	1	0.1	0.001	—	0.0394	0.003	—
centimeter	cm	10	1	0.01	—	0.394	0.033	—
meter	m	1000	100	1	0.001	39.37	3.281	—
kilometer	km	—	—	1000	1	—	3281	0.621
inch	in	25.4	2.54	0.0254	—	1	0.083	—
foot	ft	304.8	30.48	0.305	—	12	1	—
mile	mi	—	—	1609	1.609	—	5280	1

Area

Unit of measure	Abbreviation	m^2	ha	km^2	ft^2	acre	mi^2
square meter	m^2	1	—	—	10.76	—	—
hectare	ha	10000	1	0.01	107600	2.47	0.00386
square kilometer	km^2	$1x10^6$	100	1	—	247	0.386
square foot	ft^2	0.093	—	—	1	—	—
acre	acre	4050	0.405	—	43560	1	0.00156
square mile	mi^2	—	259	2.59	—	640	1

Volume

Unit of measure	Abbreviation	km^3	m^3	L	Mgal	acre-ft	ft^3	gal
cubic kilometer	km^3	1	$1x10^9$	—	—	811000	—	—
cubic meter	m^3	—	1	1000	—	—	35.3	264
liter	L	—	0.001	1	—	—	0.0353	0.264
million U.S. gallons	Mgal	—	—	—	1	3.07	134000	$1x10^6$
acre-foot	acre-ft	—	1233	—	0.3259	1	43560	325848
cubic foot	ft^3	—	0.0283	28.3	—	—	1	7.48
gallon	gal	—	—	3.785	—	—	0.134	1

Flow Rate

Unit of measure	Abbreviation	km^3/yr	m^3/s	L/s	mgd	gpm	cfs	acre-ft/day
cubic kilometers/year	km^3/yr	1	31.7	—	723	—	1119	2220
cubic meters/second	m^3/s (m^3/sec)	0.0316	1	1000	22.8	15800	35.3	70.1
liters/second	L/s (L/sec)	—	0.001	1	0.0228	15.8	0.0353	0.070
million U.S. gallons/day	mgd (Mgal/d)	—	0.044	43.8	1	694	1.547	3.07
U.S. gallons/minute	gpm (gal/min)	—	—	0.063	—	1	0.0022	0.0044
cubic feet/second	cfs (ft^3/s)	—	0.0283	28.3	0.647	449	1	1.985
acre-feet/day	acre-ft/day	—	—	14.26	0.326	226.3	0.504	1

Temperature

Unit of measure	Abbreviation	F	C
Fahrenheit	F	—	.56 (after subtracting 32)
Celsius	C	1.8 (then add 32)	—

Index

Stream Corridor Restoration

Principles, Processes, and Practices

Stream Corridor Restoration Handbook

ADDENDA

The following edits have been made to the document, as of 08/07/2001. Let us know of other edits.

Download all revised pages (total 60 pages, 2Mbytes) or selected ones below.

Page number	Figure or table number	Edits made	Download revised pages
1-13,14	text	"Channel Size" section edited for clarity. Fig. 1.13 caption edited.	Download
1-18	Fig. 1.20	Added "bankfull width" to hydrologic floodplain label.	Download
1-31	Fig. 1.34	In graphic, "course" changed to "coarse"	Download
2-19	text	"higher" depths changed to "greater" depths.	Download
2-20	Fig. 2.15	sediment load is	Download
2-22	equation, text	Fourth equation should be "$Q_w^- Q_s^+ =$", not "$Q_w^+ Q_s^+ =$". Streams are "concave in upstream direction."	Download
2-24	text	Last sentence changed to "figure on following page" not "preceeding".	Download
2-31	text	First sent., "water" changed to "acid."	Download
2-54	Fig. 2.30	In graphic, "alder-walnut" changed to "alder-willow"	Download
2-64	Fig. 2.33	In graphic, "course" changed to "coarse."	Download
2-72	text	"Hyphorheic" changed to "hyporheic." Inorganic substrates tend to be "of larger size upstream"...	Download
2-73	text and Fig. 2.35	"Hyphorheic" changed to "hyporheic"	Download
2-84	text	Deleted 2-83 col. 1.	Download
2-86	text	Col. 2, bull. 3 revised.	Download
4-25	Fig. 4.13	Caption is for Hoover Dam, not Glen Canyon Dam.	Download
7-45	Fig. 7.20	X axis should be "Drainage Area - Square Miles", not Mean Annual Discharge.	Download
7-58	Fig. 7.29	Downloadable images corrected "sandy impervious" to pervious.	-
7-85	Table 7.9	References corrected. Poff corrected. "Simon and" Hupp.	Download
8-39	Table 8.3	Footnote for "k sub 4***" should be 0.0418, not 0.2418	Download
8-51	text	Equation exponent should be -0.872, not -0.0872	Download
Appendix A 25-30	numbering	Techniques appendix references numbers have been resolved.	Download
References	-	References added for text citations. 32 pages.	Download

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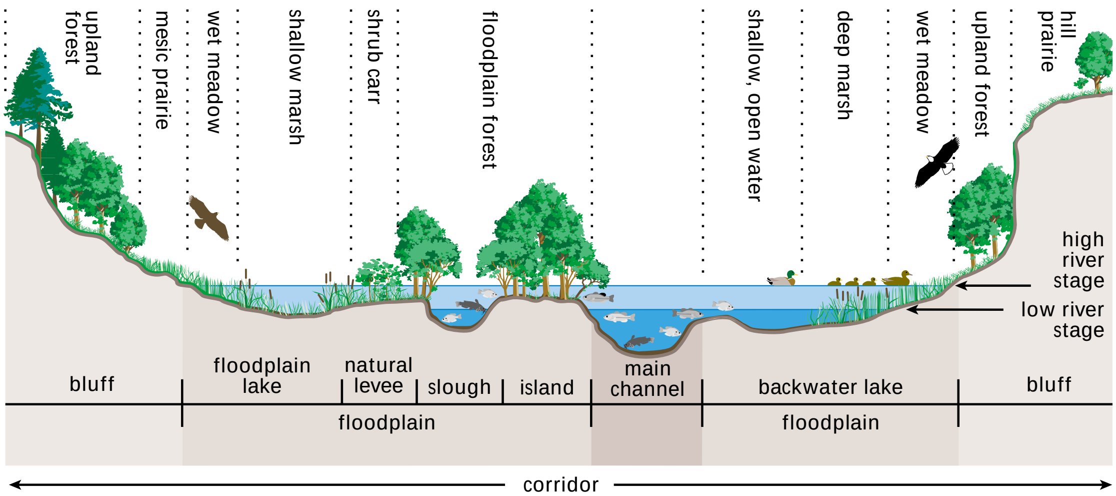


Figure 1.11: A cross section of a river corridor. *The three main components of the river corridor can be subdivided by structural features and plant communities. (Vertical scale and channel width are greatly exaggerated.)*

Source: Sparks, Bioscience, vol. 45, p. 170, March 1995. ©1995 American Institute of Biological Science.

pass through without spilling over the banks. Two attributes of the channel are of particular interest to practitioners, channel equilibrium and streamflow.

Lane's Alluvial Channel Equilibrium

Channel equilibirum involves the interplay of four basic factors:

- Sediment discharge (Q_s)
- Sediment particle size (D_{50})
- Streamflow (Q_w)
- Stream slope (S)

Lane (1955) showed this relationship qualitatively as:

$$Q_s \bullet D_{50} \propto Q_w \bullet S$$

This equation is shown here as a balance with sediment load on one weighing pan and streamflow on the other (**Figure 1.13**). The hook holding the sediment pan can slide along the horizontal arm according to sediment size. The hook holding the streamflow side slides according to stream slope.

Channel equilibrium occurs when all four variables are in balance. If a change occurs, the balance will temporarily be tipped and equilibrium lost. If one variable changes, one or more of the other variables must increase or decrease proportionally if equilibrium is to be maintained. For example, if slope is increased and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased (e.g., by an interbasin transfer) and the slope stays the same, sediment load or sediment particle size has to increase to maintain channel equilibrium. A stream seeking a new equilibrium tends to erode more sediment and of larger particle size.

Alluvial streams that are free to adjust to changes in these four variables generally do so and reestablish new equilibrium conditions. Non-alluvial streams such as bedrock or artificial, concrete channels are unable to follow Lane's relationship because of their inability to

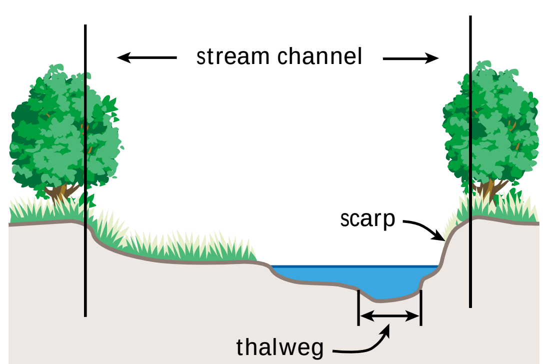


Figure 1.12: Cross section of a stream channel. *The scarp is the sloped bank and the thalweg is the lowest part of the channel.*

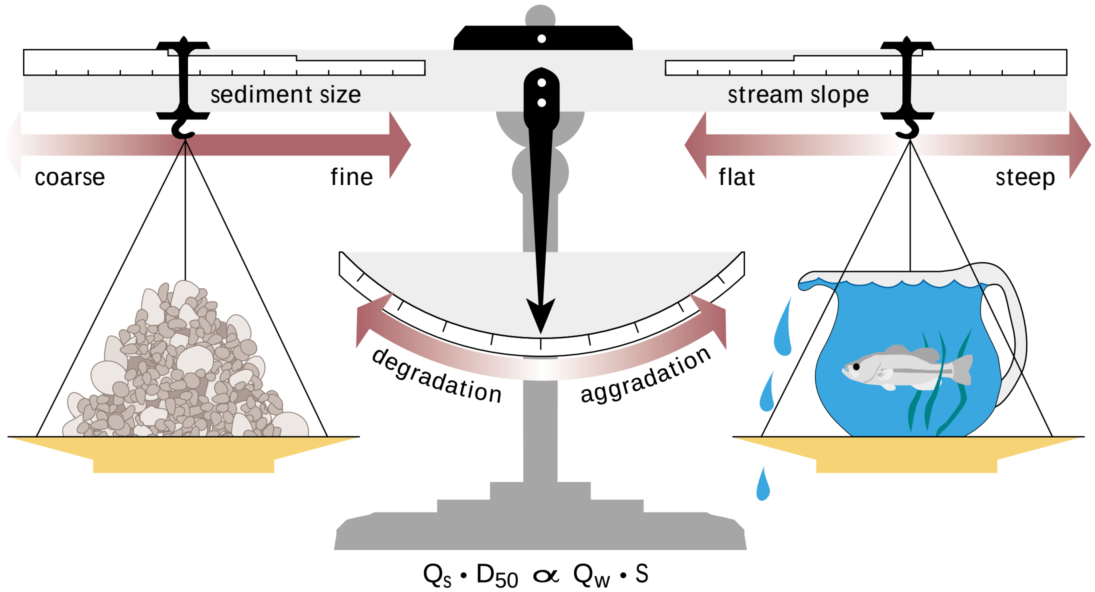


Figure 1.13: Factors affecting channel equilibrium. *At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.*

Source: Rosgen (1996), from Lane, ***Proceedings***, 1955. Published with the permission of American Society of Civil Engineers.

FAST FORWARD

Preview Chapter 2, Section B for more discussion on the stream balance equation. Preview Chapter 7, Section B for nformation on measuring and analyzing these variables and the use of sediment transport equations.

adjust the sediment size and quantity variables.

The stream balance equation is useful for making qualitative predictions concerning channel impacts due to changes in runoff or sediment loads from the watershed. Quantitative predictions, however, require the use of more complex equations.

Sediment transport equations, for example, are used to compare sediment load and energy in the stream. If excess energy is left over after the load is moved, channel adjustment occurs as the stream picks up more load by eroding its banks or scouring its bed. No matter how much complexity is built into these and other equations of this type, however, they all relate back to the basic balance relationships described by Lane.

Streamflow

A distinguishing feature of the channel is streamflow. As part of the water cycle, the ultimate source of all flow is precipitation. The pathways precipitation takes after it falls to earth, however, affect many aspects of streamflow including its quantity, quality, and timing. Practitioners usually find it useful to divide flow into components based on these pathways.

The two basic components are:

- *Stormflow*, precipitation that reaches the channel over a short time frame through overland or underground routes.
- *Baseflow*, precipitation that percolates to the ground water and moves slowly through substrate before reaching the channel. It sustains streamflow during periods of little or no precipitation.

FAST FORWARD

Preview Chapter 7, Section B for a discussion of calculating effective discharge. This computation should be performed by a professional with a good background in hydrology, hydraulics, and sediment transport.

Floodplain

The floor of most stream valleys is relatively flat. This is because over time the stream moves back and forth across the valley floor in a process called lateral migration. In addition, periodic flooding causes sediments to move longitudinally and to be deposited on the valley floor near the channel. These two processes continually modify the floodplain.

Through time the channel reworks the entire valley floor. As the channel migrates, it maintains the same average size and shape if conditions upstream remain constant and the channel stays in equilibrium.

Two types of floodplains may be defined (**Figure 1.20**):

- *Hydrologic floodplain*, the land adjacent to the baseflow channel residing below bankfull elevation. It is inundated about two years out of three. Not every stream corridor has a hydrologic floodplain.
- *Topographic floodplain*, the land adjacent to the channel including the hydrologic floodplain and other lands up to an elevation based on the elevation reached by a flood peak of a given frequency (for example, the 100-year floodplain).

Professionals involved with flooding issues define the boundaries of a floodplain in terms of flood frequencies. Thus, 100-year and 500-year floodplains are commonly used in the development of planning and regulation standards.

Flood Storage

The floodplain provides temporary storage space for floodwaters and sediment produced by the watershed. This attribute serves to add to the *lag time* of a flood—the time between the middle of the rainfall event and the runoff peak.

If a stream's capacity for moving water and sediment is diminished, or if the sediment loads produced from the watershed become too great for the stream to transport, flooding will occur more frequently and the valley floor will begin to fill. Valley filling results in the temporary storage of sediment produced by the watershed.

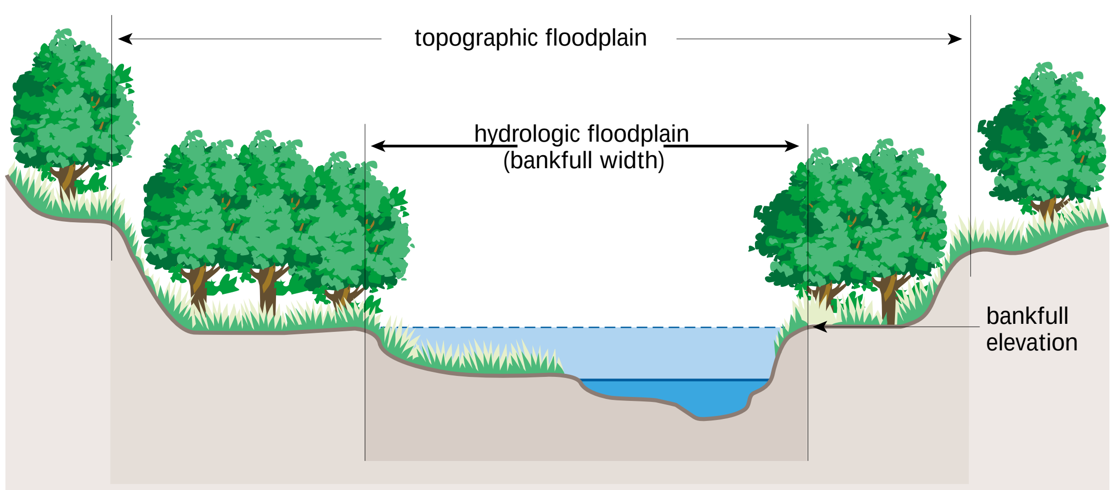


Figure 1.20: Hydrologic and topographic floodplains. *The hydrologic floodplain is defined by bankfull elevation. The topographic floodplain includes the hydrologic floodplain and other lands up to a defined elevation.*

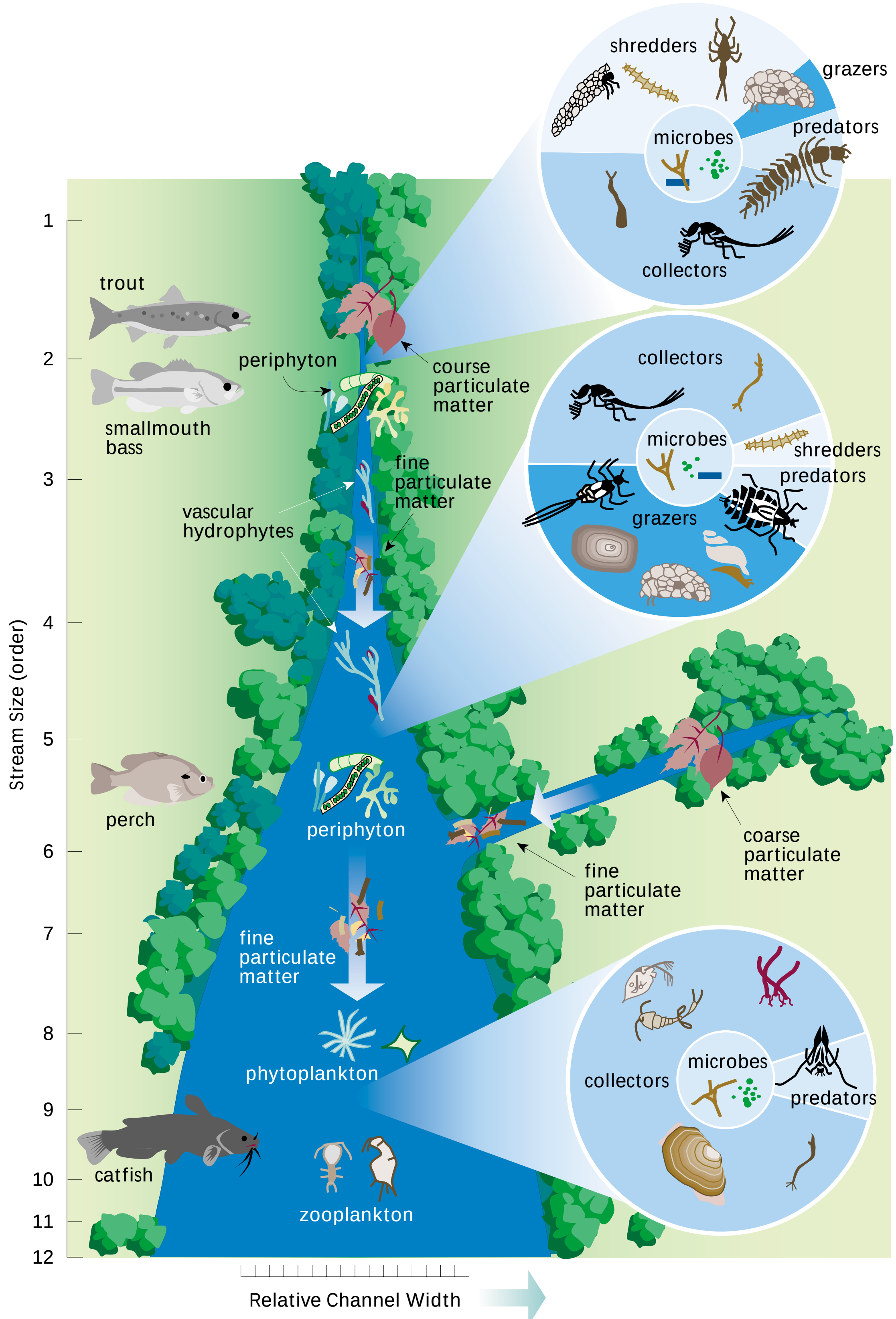


Figure 1.34: The River Continuum Concept. *The concept proposes a relationship between stream size and the progressive shift in structural and functional attributes.*
Source: Vannote et al. (1980). Published with the permission of NRC Research Press.

- *Measured load*, portion of the total sediment load that is obtained by the sampler in the sampling zone.
- *Unmeasured load*, portion of the total sediment load that passes beneath the sampler, both in suspension and on the bed. With typical suspended sediment samplers this is the lower 0.3 to 0.4 feet of the vertical.

The above terms can be combined in a number of ways to give the total sediment load in a stream (**Table 2.4**). However, it is important not to combine terms that are not compatible. For example, the suspended load and the bed material load are not complimentary terms because the suspended load may include a portion of the bed material load, depending on the energy available for transport. The total sediment load is correctly defined by the combination of the following terms:

Total Sediment Load =

Bed Material Load + Wash Load

or

Bed Load + Suspended Load

or

Measured Load + Unmeasured Load

Sediment transport rates can be computed using various equations or models. These are discussed in the *Stream Channel Restoration* section of Chapter 8.

Table 2.4: Sediment load terms.

		Classification System	
		Based on Mechanism of Transport	Based on Particle Size
Total sediment load	Wash load	Suspended load	Wash load
	Suspended bed-material load		Bed-material load
	Bed load	Bed load	

Stream Power

One of the principal geomorphic tasks of a stream is to transport particles out of the watershed (**Figure 2.15**). In this manner, the stream functions as a transporting "machine;" and, as a machine, its rate of doing work can be calculated as the product of available power multiplied by efficiency.

Stream power can be calculated as:

$$\varphi = \gamma\, Q\, S$$

Where:

φ = Stream power (foot-lbs/second-foot)

γ = Specific weight of water (lbs/ft^3)

Q = Discharge (ft^3/second)

S = Slope (feet/feet)

Sediment transport rates are directly related to stream power; i.e., slope and discharge. Baseflow that follows the highly sinuous thalweg (the line that marks the deepest points along the stream channel) in a meandering stream generates little stream power; therefore, the stream's ability to move sediment, *sediment-transport capacity,* is limited. At greater depths, the flow follows a straighter course, which increases slope, causing increased sediment transport rates. The stream builds its cross section to obtain depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel.

Runoff can vary from a watershed, either due to natural causes or land use practices. These variations may change the size distribution of sediments delivered to the stream from the watershed by preferentially moving particular particle sizes into the stream. It is not uncommon to find a layer of sand on top of a cobble layer. This often happens when accelerated erosion of sandy soils

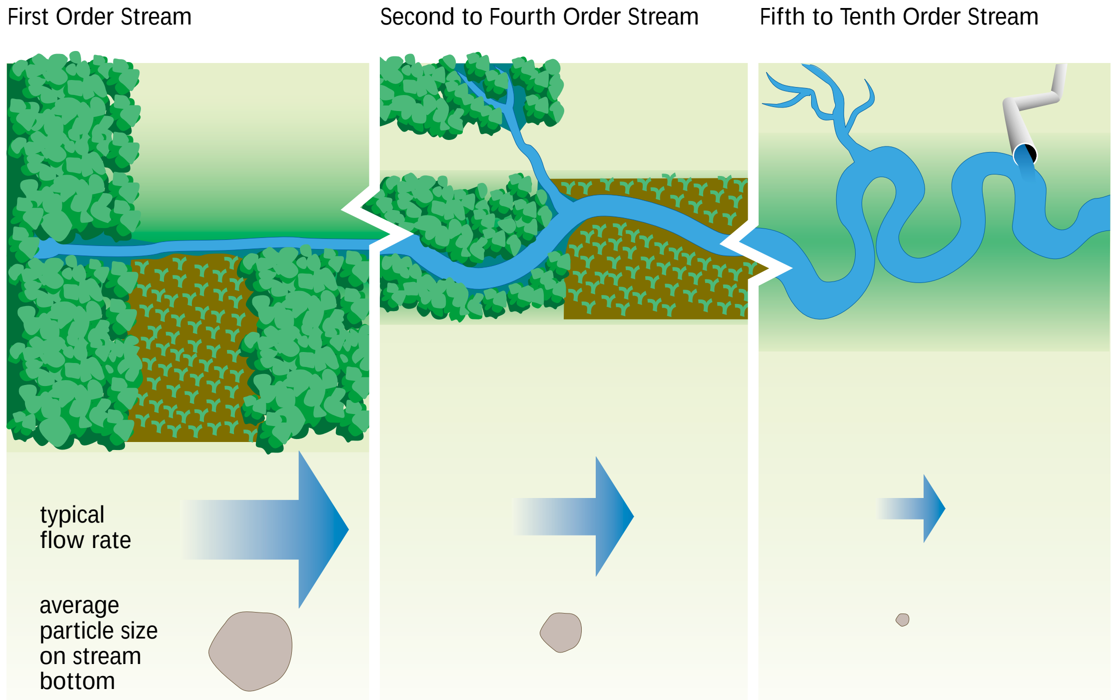


Figure 2.15: Particle transport. *A stream's total sediment load is the total of all sediment particles moving past a defined cross section over a specified time period. Transport rates vary according to the mechanism of transport.*

occurs in a watershed and the increased load of sand exceeds the transport capacity of the stream during events that move the sand into the channel.

Stream and Floodplain Stability

A question that normally arises when considering any stream restoration action is "Is it stable now and will it be stable after changes are made?" The answer may be likened to asking an opinion on a movie based on only a few frames from the reel. Although we often view streams based on a limited reference with respect to time, it is important that we consider the long-term changes and trends in channel cross section, longitudinal profile, and planform morphology to characterize channel stability.

Achieving channel stability requires that the average tractive stress maintains a stable streambed and streambanks. That is, the distribution of particle sizes in each section of the stream remains in equilibrium (i.e., new particles deposited are the same size and shape as particles displaced by tractive stress).

Yang (1971) adapted the basic theories described by Leopold to explain the longitudinal profile of rivers, the formation of stream networks, riffles, and pools, and river meandering. All these river characteristics and sediment transport are closely related. Yang (1971) developed the theory of average stream fall and the theory of least rate of energy expenditure, based on the entropy concept. These theories state that during the evolution toward an equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure per unit mass of flow along its course is a minimum.

Combining the four equations above yields additional predictive relationships for concurrent increases or decreases in streamflow and/or sediment discharge:

$$Q_w^+ Q_s^+ \sim b^+, d^{+/-}, L^+, S^{+/-}, P^-$$

$$Q_w^- Q_s^- \sim b^-, d^{+/-}, L^-, S^{+/-}, P^+$$

$$Q_w^+ Q_s^- \sim b^{+/-}, d^+, L^{+/-}, S^-, P^+$$

$$Q_w^- Q_s^+ \sim b^{+/-}, d^-, L^{+/-}, S^+, P^-$$

Channel Slope

Channel slope, a stream's longitudinal profile, is measured as the difference in elevation between two points in the stream divided by the stream length between the two points. Slope is one of the most critical pieces of design information required when channel modifications are considered. Channel slope directly impacts flow velocity, stream competence, and stream power. Since these attributes drive the geomorphic processes of erosion, sediment transport, and sediment deposition, channel slope becomes a controlling factor in channel shape and pattern.

(See Figs. 1-27 and 1-28)

Most longitudinal profiles of streams are concave upstream. As described previously in the discussion of dynamic equilibrium, streams adjust their profile and pattern to try to minimize the time rate of expenditure of potential energy, or stream power, present in flowing water. The concave upward shape of a stream's profile appears to be due to adjustments a river makes to help minimize stream power in a downstream direction. Yang (1983) applied the theory of minimum stream power to explain why most longitudinal streambed profiles are concave upward. In order to satisfy the theory of minimum stream power, which is a special case of the general theory of minimum energy dissipation rate (Yang and Song 1979), the following equation must be satisfied:

$$\frac{dP}{dx} = \gamma Q \frac{dS}{dx} + S \frac{dQ}{dx} = 0$$

Where:

P = QS = Stream power

x = Longitudinal distance

Q = Water discharge

S = Water surface or energy slope

γ = Specific weight of water

Stream power has been defined as the product of discharge and slope. Since stream discharge typically increases in a downstream direction, slope must decrease in order to minimize stream power. The decrease in slope in a downstream direction results in the concave-up longitudinal profile.

Sinuosity is not a profile feature, but it does affect stream slope. Sinuosity is the stream length between two points on a stream divided by the valley length between the two points. For example, if a stream is 2,200 feet long from point A to point B, and if a valley length distance between those two points is 1,000 feet, that stream has a sinuosity of 2.2. A stream can increase its length by increasing its sinuosity, resulting in a decrease in slope. This impact of sinuosity on channel slope must always be considered if channel reconstruction is part of a proposed restoration.

Pools and Riffles

The longitudinal profile is seldom constant, even over a short reach. Differences in geology, vegetation patterns, or human disturbances can result in flatter and steeper reaches within an overall profile. Riffles occur

Roughness plays an important r ole in streams. It helps determine the depth or stage of flow in a stream reach. As flow velocity slows in a stream reach due to roughness, the depth of flow has to increase to maintain the volume of flow that entered the upstream end of the reach (a concept known as flow continuity). Typical roughness along the boundaries of the stream includes the following:

- Sediment particles of different sizes.
- Bedforms.
- Bank irregularities.
- The type, amount, and distribution of living and dead vegetation.
- Other obstructions.

Roughness generally increases with increasing particle size. The shape and size of instream sediment deposits, or bedforms, also contribute to roughness.

Sand-bottom streams are good examples of how bedform roughness changes with discharge. At very low discharges, the bed of a sand stream may be dominated by ripple bedforms. As flow increases even more, sand dunes may begin to appear on the bed. Each of these bedforms increases the roughness of the stream bottom, which tends to slow velocity.

The depth of flow also increases due to increasing roughness. If discharge continues to increase, a point is reached when the flow velocity mobilizes the sand on the streambed and the entire bed converts again to a planar form. The depth of flow may actually decrease at this point due to the decreased roughness of the bed. If discharge increases further still, antidunes may form. These bedforms create enough friction to again cause the flow depth to increase. The depth of flow for a given discharge in sand-bed streams, therefore, depends on the bedforms present when that discharge occurs.

Vegetation can also contribute to roughness. In streams with boundaries consisting of cohesive soils, vegetation is usually the principal component of roughness. The type and distribution of vegetation in a stream corridor depends on hydrologic and geomorphic processes, but by creating roughness, vegetation can alter these processes and cause changes in a stream's form and pattern.

Meandering streams offer some resistance to flow relative to straight streams. Straight and meandering streams also have different distributions of flow velocity that are affected by the alignment of the stream, as shown in **Figure 2.17**. In straight reaches of a stream, the fastest flow occurs just below the surface near the center of the channel where flow resistance is lowest (see Figure 2.17 (a) Section G). In meanders, velocities are highest at the outside edge due to angular momentum (see Figure 2.17 (b) Section 3). The differences in flow velocity distribution in meandering streams result in both erosion and deposition at the meander bend. Erosion occurs at the outside of bends (cutbanks) from high velocity flows, while the slower velocities at the insides of bends cause deposition on the point bar (which also has been called the *slip-off slope*).

The angular momentum of flow through a meander bend increases the height or *super elevation* at the outside of the bend and sets up a secondary current of flow down the face of the cut bank and across the bottom of the pool toward the inside of the bend. This rotating flow is called *helical flow* and the direction of rotation is illustrated on the diagram on the following page by the arrows at the top and bottom of cross sections 3 and 4 in the figure.

minerals present in the watershed. For example, when an acid interacts with limestone, the following dissolution reaction occurs:

$$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$

This reaction consumes hydrogen ions, thus raising the pH of the water. Conversely, runoff may acidify when all alkalinity in the water is consumed by acids, a process often attributed to the input of strong mineral acids, such as sulfuric acid, from acid mine drainage, and weak organic acids, such as humic and fulvic acids, which are naturally produced in large quantities in some types of soils, such as those associated with coniferous forests, bogs, and wetlands. In some streams, pH levels can be increased by restoring degraded wetlands that intercept acid inputs, such as acid mine drainage, and help neutralize acidity by converting sulfates from sulfuric acid to insoluble nonacidic metal sulfides that remain trapped in wetland sediments.

pH, Alkalinity, and Acidity Along the Stream Corridor

Within a stream, similar reactions occur between acids in the water, atmospheric CO_2, alkalinity in the water column, and streambed material. An additional characteristic of pH in some poorly buffered waters is high daily variability in pH levels attributable to biological processes that affect the carbonate buffering system. In waters with large standing crops of aquatic plants, uptake of carbon dioxide by plants during photosynthesis removes carbonic acid from the water, which can increase pH by several units. Conversely, pH levels may fall by several units during the night when photosynthesis does not occur and plants give off carbon dioxide. Restoration techniques that decrease instream plant growth through increased shading or reduction in nutrient loads or that increase reaeration also tend to stabilize highly variable pH levels attributable to high rates of photosynthesis.

The pH within streams can have important consequences for toxic materials. High acidity or high alkalinity tend to convert insoluble metal sulfides to soluble forms and can increase the concentration of toxic metals. Conversely, high pH can promote ammonia toxicity. Ammonia is present in water in two forms, unionized (NH_3) and ionized (NH_4^+). Of these two forms of ammonia, un-ionized ammonia is relatively highly toxic to aquatic life, while ionized ammonia is relatively negligibly toxic. The proportion of un-ionized ammonia is determined by the pH and temperature of the water (Bowie et al. 1985)—as pH or temperature increases, the proportion of un-ionized ammonia and the toxicity also increase. For example, with a pH of 7 and a temperature of 68°F, only about 0.4 percent of the total ammonia is in the un-ionized form, while at a pH of 8.5 and a temperature of 78°F, 15 percent of the total ammonia is in the un-ionized form, representing 35 times greater potential toxicity to aquatic life.

Dissolved Oxygen

Dissolved oxygen (DO) is a basic requirement for a healthy aquatic ecosystem. Most fish and aquatic insects “breathe” oxygen dissolved in the water column. Some fish and aquatic organisms, such as carp and sludge worms, are adapted to low oxygen conditions, but most sport fish species, such as trout and salmon, suffer if DO concentrations fall below a concentration of 3 to 4 mg/L. Larvae and juvenile fish are more sensitive and require even higher concentrations of DO (USEPA 1997).

Many fish and other aquatic organisms can recover from short periods of low intra-riparian (longitudinal, elevational) gradient (Johnson and Lowe 1985). In the west, growth of riparian vegetation is increased by the “canyon effect” resulting when cool moist air spills downslope from higher elevations (**Figure 2.30**). This cooler air settles in canyons and creates a more moist microhabitat than occurs on the surrounding slopes. These canyons also serve as water courses. The combination of moist, cooler edaphic and atmospheric conditions is conducive to plant and animal species at lower than normal altitudes, often in disjunct populations or in regions where they would not otherwise occur (Lowe and Shannon 1954).

Plant Communities

The sensitivity of animal communities to vegetative characteristics is well recognized. Numerous animal species are associated with particular plant communities, many require particular developmental stages of those communities (e.g., old-growth), and some depend on particular habitat elements within those communities (e.g., snags). The structure of streamside plant communities also directly affects aquatic organisms by providing inputs of appropriate organic materials to the aquatic food web, by shading the water surface and providing cover along banks, and by influencing instream habitat structure through in-

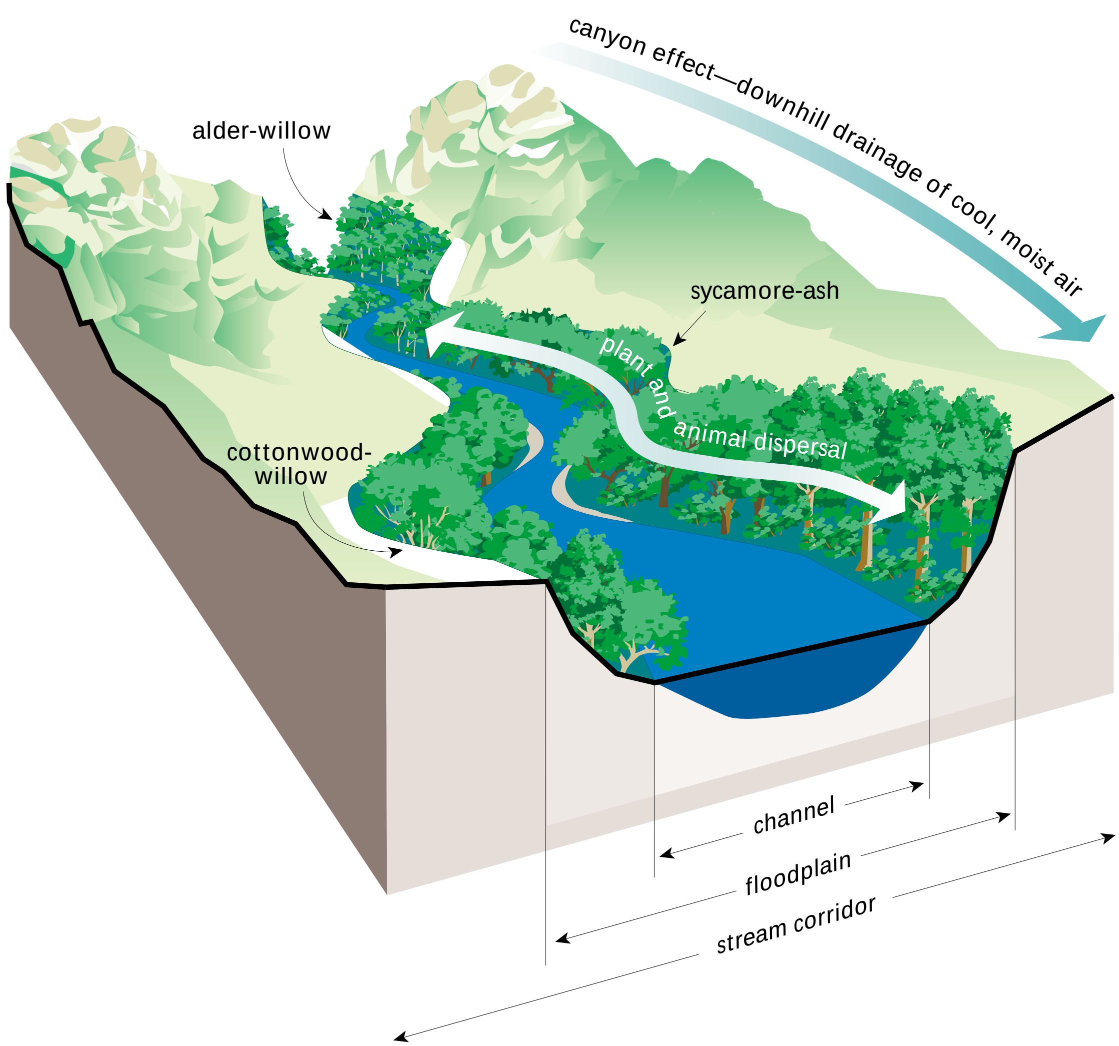


Figure 2.30: Canyon effect. *Cool moist air settles in canyons and creates microhabitat that occurs on surrounding slopes.*

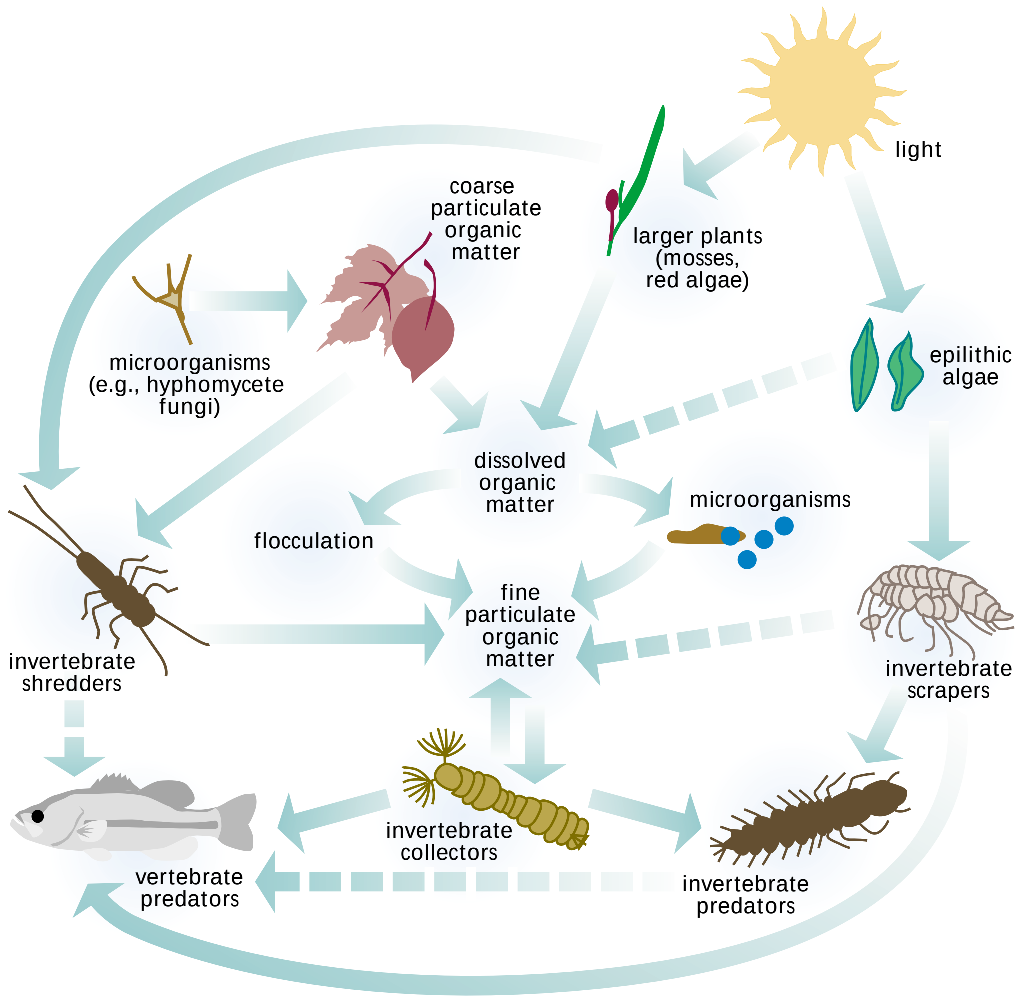


***Figure 2.33: Stream biota.** Food relationships typically found n streams.*

Bourassa and Morin 1995). Furthermore, the larger species often play important roles in determining community composition of other components of the ecosystem. For example, herbivorous feeding activities of caddisfly larvae (Lamberti and Resh 1983), snails (Steinman et al. 1987), and crayfish (Lodge 1991) can have a significant effect on the abundance and taxonomic composition of algae and periphyton in streams. Likewise, macroinvertebrate predators, such as stoneflies, can influence the abundance of other species within the invertebrate community (Peckarsky 1985).

Table 2.12: Ranges of densities commonly observed for selected groups of stream biota.

Biotic Component	Density (Individuals/Square Mile)
Algae	$10^9 – 10^{10}$
Bacteria	$10^{12} – 10^{13}$
Protists	$10^8 – 10^9$
Microinvertebrates	$10^3 – 10^5$
Macroinvertebrates	$10^4 – 10^5$
Vertebrates	$10^0 – 10^2$

Collectively, microorganisms (fungi and bacteria) and benthic invertebrates facilitate the breakdown of organic material, such as leaf litter, that enters the stream from external sources. Some invertebrates (insect larvae and amphipods) act as shredders whose feeding activities break down larger organic leaf litter to smaller particles. Other invertebrates filter smaller organic material from the water (blackfly larvae, some mayfly nymphs, and some caddisfly larvae), scrape material off surfaces species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach (Benke et al. 1984, Smock et al. 1985, Huryn and Wallace 1987). This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams (Hackney et al. 1992).

Stream substrates can be viewed in the same functional capacity as soils in the terrestrial system; that is, stream substrates constitute the interface between water and the hyporheic subsurface of the aquatic system. The *hyporheic zone* is the area of substrate which lies below the substrate/water interface, and may range from a layer extending only inches beneath and laterally from the stream channel, to a very large subsurface environment. Alluvial floodplains of the Flathead River, Montana, have a hyporheic zone with significant surface water/ground water interaction which is 2 miles wide and 33 feet deep (Stanford and Ward 1988). Naiman et al. (1994) discussed the extent and connectivity of hyporheic zones around streams in the Pacific Northwest. They hypothesized that as one moves from low-order (small) streams to high-order (large) streams, the degree of hyporheic importance and continuity first increases and then decreases. In small streams, the hyporheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock. The hyporheic zones are generally not continuous. In mid-order channels with more extensive floodplains, the spatial connectivity of the hyporheic zone increases. In large order streams, the spatial extent of the hyporheic zone is usually greatest, but it tends to be highly discontinuous because of features associated with fluvial activities such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems (Naiman et al. 1994) (**Figure 2.35**).

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes (Minshall 1984). Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms (Odum 1971). As previously described, substrate size, heterogeneity, stability with respect to high and baseflow, and durability vary within streams, depending on particle size, density, and kinetic energy of flow. Inorganic substrates tend to be of larger size upstream than downstream and tend to be larger in riffles than in pools (Leopold et al. 1964). Likewise, the distribution and role of woody debris varies with stream size (Maser and Sedell 1994).

In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris that falls into the stream can increase the quantity and diversity of substrate and aquatic habitat or range (Bisson et al. 1987, Dolloff et al. 1994). Debris dams trap sediment behind them and often create scour holes immediately downstream. Eroded banks commonly occur at the boundaries of debris blockages.

Organic Material

Metabolic activity within a stream reach depends on autochthonous, allochthonous, and upstream sources of food and nutrients (Minshall et al. 1985). Autochthonous materials, such as algae and aquatic macrophytes, originate within the stream channel, whereas allochthonous materials such as wood, leaves, and dissolved organic carbon, originate outside the stream channel. Upstream materials may be of autochthonous or allochthonous origin and are transported by streamflow to downstream locations. Seasonal flooding provides allochthonous input of organic material to the stream channel and also can significantly increase the rate of decomposition of organic material.

The role of primary productivity of streams can vary depending on geographic location, stream size, and season (Odum 1957, Minshall 1978). The river continuum concept (Vannote et al. 1980) (see *The River Continuum Concept* in section 1.E in Chapter 1) hypothesizes that primary productivity is of minimal importance in shaded headwater streams but increases in significance as stream size increases and riparian vegetation no longer limits the entry of light to stream periphyton. Numerous researchers have demonstrated that primary productivity is of greater importance in certain ecosystems, including streams in grassland and desert ecosystems. Flora of streams can range from diatoms in high mountain streams to dense stands of macrophytes in low gradient streams of the Southeast.

As discussed in Section 2.C, loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as *eutrophication*. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems in waterbodies.

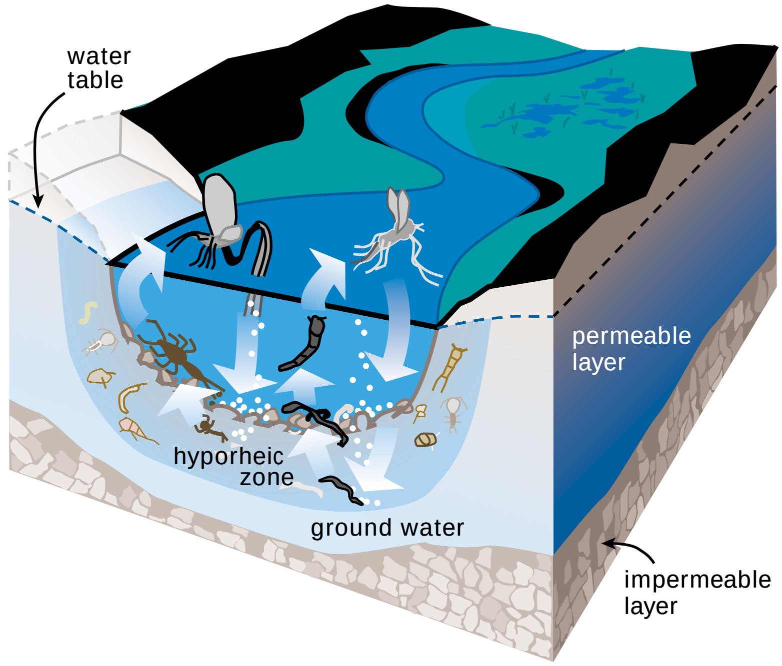


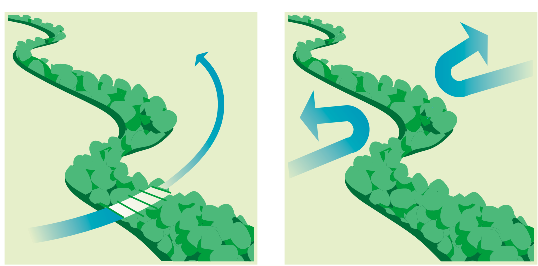
Figure 2.35: Hyporheic zone. *Summary of the different means of migration undergone by members of the stream benthic community.*

Eutrophication in lakes and reservoirs is indirectly measured as standing crops of phytoplankton biomass, usually represented by planktonic chlorophyll a concentration. However, phytoplankton biomass is usually not the dominant portion of plant biomass in smaller streams, due to periods of energetic flow and high substrate to volume ratios that favor the development of periphyton and macrophytes on the stream bottom. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures (**Figure 2.36**). Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

Local areas in the corridor are dependent on the flow of materials from one point to another. In the salmonid example, the local upland area adjacent to spawning grounds is dependent upon the nutrient transfer from the biomass of the fish into other terrestrial wildlife and off into the uplands. The local structure of the streambed and aquatic ecosystem are dependent upon the sediment and woody material from upstream and upslope to create a self-regulating and stable channel.

Stream corridor width is important where the upland is frequently a supplier of much of the natural load of sediment and biomass into the stream. A wide, contiguous corridor acts as a large conduit, allowing flow laterally and longitudinally along the corridor. Conduit functions are often more limited in narrow or fragmented corridors.

Filter and Barrier Functions



Stream corridors may serve as barriers that prevent movement or filters that allow selective penetration of energy, materials and organisms. In many ways, the entire stream corridor serves beneficially as a filter or barrier that reduces water pollution, minimizes sediment transport, and often provides a natural boundary to land uses, plant communities, and some less mobile wildlife species.

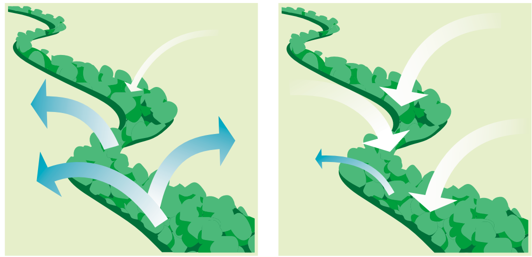
Materials, energy, and organisms which moved into and through the stream corridor may be filtered by structural attributes of the corridor. Attributes affecting barrier and filter functions include connectivity (gap frequency) and corridor width (**Figure 2.40**). Elements which are moving along a stream corridor edge may also be selectively filtered as they enter the stream corridor. In these circumstances it is the shape of the edge, whether it is straight or convoluted, which has the greatest effect on filtering functions. Still, it is most often movement perpendicular to the stream corridor which is most effectively filtered or halted.

Materials may be transported, filtered, or stopped altogether depending upon the width and connectedness of a stream corridor. Material movement across landscapes toward large river valleys may be intercepted and filtered by stream corridors. Attributes such as the structure of native plant communities can physically affect the amount of runoff entering a stream system through uptake, absorption, and interruption. Vegetation in the corridor can filter out much of the overland flow of nutrients, sediment, and water.

Siltation in larger streams can be reduced through a network of stream corridors functioning to filter excessive sediment. Stream corridors filter many of the upland materials from moving unimpeded across the landscape. Ground water and surface water flows are filtered by plant parts below and above ground. Chemical elements are intercepted by flora and fauna within stream corridors. A wider corridor provides more effective filtering, and a contiguous corridor functions as a filter along its entire length.

Breaks in a stream corridor can sometimes have the effect of funneling damaging processes into that area. For example, a gap in contiguous vegetation along a stream corridor can reduce the filtering function by focusing increased runoff into the area, leading to erosion,

Source and Sink Functions



Sources provide organisms, energy or materials to the surrounding landscape. Areas that function as sinks absorb organisms, energy, or materials from the surrounding landscape. Influent and effluent reaches, discussed in Section 1.B of Chapter 1, are classic examples of sources and sinks. The influent or "losing" reach is a source of water to the aquifer, and the effluent or "gaining" reach is a sink for ground water.

Stream corridors or features within them can act as a source or a sink of environmental materials. Some stream corridors act as both, depending on the time of year or location in the corridor. Streambanks most often act as a source, for example, of sediment to the stream. At times, however, they can function as sinks while flooding deposits new sediments there. At the landscape scale, corridors are connectors to various other patches of habitats in the landscape and as such they are sources and conduits of genetic material throughout the landscape.

Stream corridors can also act as a sink for storage of surface water, ground water, nutrients, energy, and sediment allowing for materials to be temporarily fixed in the corridor. Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter. Although these functions of source and sink are conceptually understood, they lack a suitable body of research and practical application guidelines.

Forman (1995) offers three source and sink functions resulting from floodplain vegetation:

- Decreased downstream flooding through floodwater moderation and/or uptake
- Containment of sediments and other materials during flood stage
- Source of soil organic matter and water-borne organic matter

Biotic and genetic source/sink relationships can be complex. Interior forest birds are vulnerable to nest parasitism by cowbirds when they try to nest in too small a forest patch. For these species, small forest patches can be considered sinks that reduce their population numbers and genetic diversity by causing failed reproduction. Large forest patches with sufficient interior habitat, in comparison, support successful reproduction and serve as sources of more individuals and new genetic combinations.

Dynamic Equilibrium

The first two chapters of this document have emphasized that, although stream corridors display consistent patterns in their structure, processes, and functions, these patterns change naturally and constantly, even in the absence of human disturbance. Despite frequent change, streams and their corridors exhibit a dynamic form of stability. In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

The maintenance of dynamic equilibrium requires that a series of self-correcting mechanisms be active in the stream corridor ecosystem. These mech-

n constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

number and size of gravel bars are significantly different from what is evident in historical photos, for example, the difference might be an indication that either aggradation or erosion has been enhanced. Care is needed when using the channel to interpret possible changes in watershed conditions since similar channel symptoms can also be caused by changes in conditions within the stream corridor itself or by natural variation of the hydrograph.

Stream Corridor and Reach Factors Affecting Stream Corridor Conditions

In addition to watershed factors affecting stream corridor conditions, it is important to consider disturbances at the stream corridor and reach scales. In general, stream corridor structural attributes and functions are greatly affected by several important categories of activities if they occur within the corridor. Chapter 3 explores these in more detail; the following are some of the activities that commonly impact corridor structure and function.

- Activities that alter or remove streambank and riparian vegetation (e.g., grazing, agriculture, logging, and urbanization), resulting in changes in the stability of streambanks, runoff and transport of contaminants, water quality, or habitat characteristics of riparian zones (**Figure 4.14**).
- Activities that physically alter the morphology of channels, banks, and riparian zones, resulting in effects such as the displacement of aquatic and riparian habitat and the disruption of the flow of energy and materials (e.g., channelization, levee construction, gravel mining, and access trails).
- Instream modifications that alter channel shape and dimensions, flow hydraulics, sediment-transport characteristics, aquatic habitat, and water quality (e.g., dams and grade stabilization measures, bank riprap, logs, bridge piers, and habitat “enhancement” measures) (**Figure 4.15**). In the case of logs, it might be the loss of such structures rather than their addition that alters flow hydraulics and channel structure.

Figure 4.13: Water releases below a dam.
Altering the flow regime of river below Hoover Dam altered the stream condition.

Altered riparian vegetation and physical modification of channels and floodplains are primary causes of impaired stream corridor structure and functions because their effects are both profound and direct. Addressing the causes of these changes might offer the best, most feasible opportunities for restoring stream corridors. However, the altered vegetation and physical modifications also may create some of the most significant challenges for stream corridor restoration by constraining the number or type of possible solutions.

It is important to remember that there are no simple analytical methods available for analyzing relationships

FAST FORWARD

Preview Chapters 7 and 8, Analytical and Empirical Tools section.

sions to drainage area (**Figure 7.20**). Using these curves, the width and depth of the bankfull channel can be approximated once the drainage area of a watershed within one of these regions is known. Obviously, more curves such as these are needed for regions that experience different topographic, geologic, and hydrologic regimes; therefore, additional regional relationships should be developed for specific areas of interest. Several hydraulic geometry formulas are presented in **Table 7.5**.

Regional curves should be used only as indicators to help identify the channel geometry at a restoration initiative site

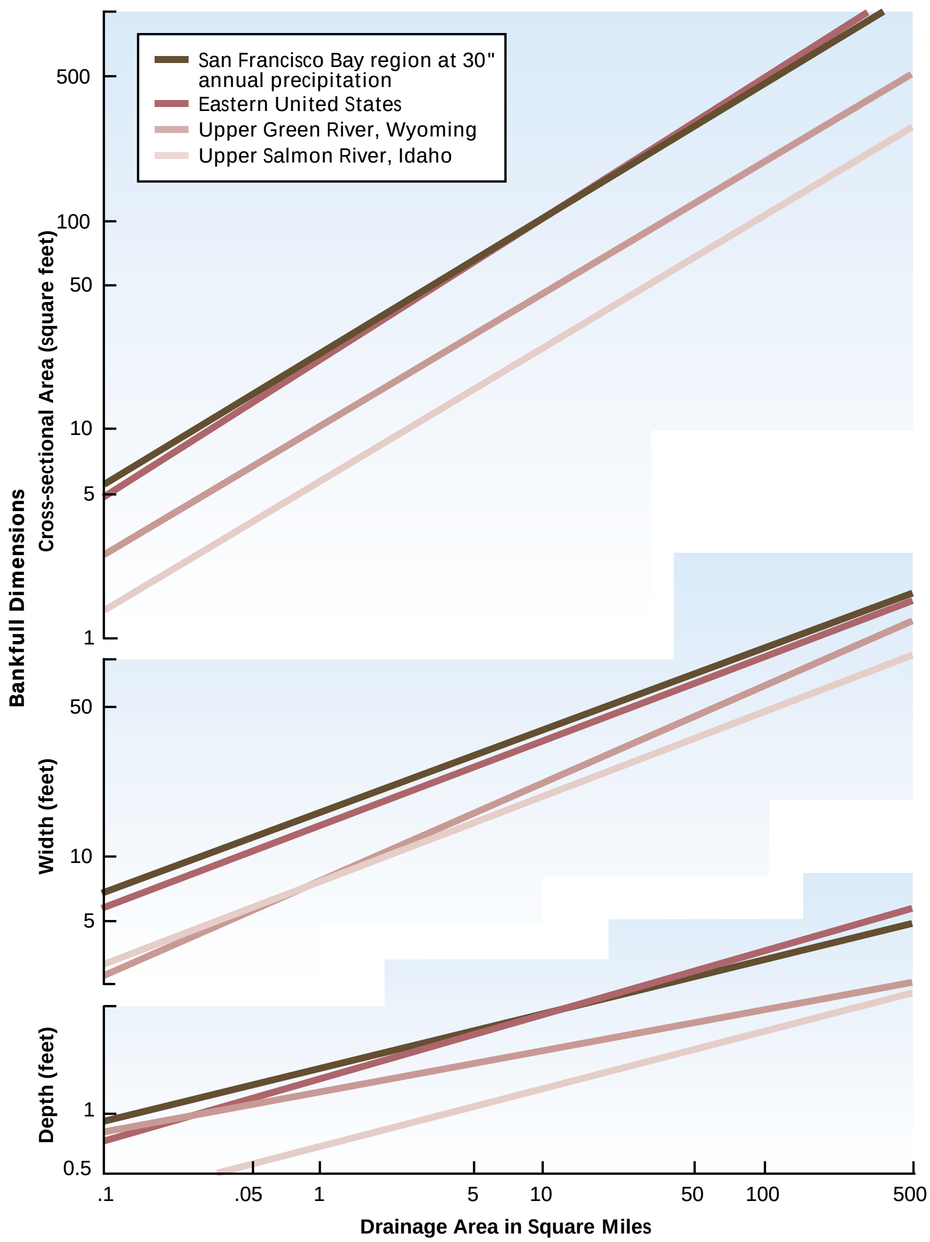


Figure 7.20: Regional curves for bankfull channel dimensions versus drainage area. *Curves showing channel dimensions relating to drainage area for a region of the country can be useful in determining departure from "normal" conditions. The use of such curves must be tempered with an understanding of the limitations of the specific data that produced the curves.*
Source: Dunne and Leopold 1978.

included to maximize amphibian richness. Examples of indirect methods to assess diversity include habitat models (Schroeder and Allen 1992, Adamus 1993) and cumulative impact assessment methods (Gosselink et al. 1990, Brooks et al. 1991).

Predicting diversity with a model is generally more rapid than directly measuring diversity. In addition, predictive methods provide a means to analyze alternative future conditions before implementing specific restoration plans. The reliability and accuracy of diversity models should be established before their use.

Classification Systems

Classification is an important component of many of the scientific disciplines relevant to stream corridors—hydrology, geomorphology, limnology, plant and animal ecology. **Table 7.9** lists some of the classification systems that might be useful in identifying and planning riverine restoration activities. It is not the intent of this section to exhaustively review all classification schemes or to present a single recommended classification system. Rather, we focus on some of the principal distinctions among classification systems and factors to consider in the use of classification systems for restoration planning, particularly in the use of a classification system as a measure of biological condition. It is likely that multiple systems will be useful in most actual riverine restoration programs.

The common goal of classification systems is to organize variation. Important dimensions in which riverine classification systems differ include the following:

- *Geographic domain*. The range of sites being classified varies from rivers of the world to local differences in the composition and characteristics of patches within one reach of a single river.
- *Variables considered*. Some classifications are restricted to abiotic vari-

Table 7.9: Selected riverine and riparian classification systems. *Classification systems are useful in characterizing biological conditions.*

Classification System	Subject	Geographic Domain	Citation
Riparian vegetation of Yampa, San Miguel/Dolores River Basins	Plant communities	Colorado	Kittel and Lederer (1993)
Riparian and scrubland communities of Arizona and New Mexico	Plant communities	Arizona and New Mexico	Szaro (1989)
Classification of Montana riparian and wetland sites	Plant communities	Montana	Hansen et al. (1995)
Integrated riparian evaluation guide	Hydrology, geomorphology, soils, vegetation	Intermountain	U.S. Forest Service (1992)
Streamflow cluster analysis	Hydrology with correlations to fish and invertebrates	National	Poff and Ward (1989)
River Continuum	Hydrology, stream order, water chemistry, aquatic communities	International, national	Vannote et al. (1980)
World-wide stream classification	Hydrology, water chemistry, substrate, vegetation	International	Pennak (1971)
Rosgen's river classification	Hydrology, geomorphology: stream and valley types	National	Rosgen (1996)
Hydrogeomorphic wetland classification	Hydrology, geomorphology, vegetation	National	Brinson (1993)
Recovery classes following channelization	Hydrology, geomorphology, vegetation	Tennessee	Simon and Hupp (1992)

posed by the two governing equations (e.g., sediment transport and flow resistance). Chang (1988) combined sediment transport and flow resistance formulas with flow continuity and minimization of stream power at each cross section and through a reach to generate a numerical model of flow and sediment transport. Special relationships for flow and transverse sediment transport in bends were also derived. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield d (bankfull depth) and w (bankfull width), given bankfull Q, S, and D_{50}. Separate sets of curves are provided for sand and gravel bed rivers. Regime-type formulas have been fit to the curves, as shown in **Table 8.3.** These relationships should be used with tractive stress analyses to develop converging data that increase the designer's confidence that the appropriate channel dimensions have been selected.

Subsequent work by Thorne et al. (1988) modified these formulas to account for effects of bank vegetation along gravel-bed rivers. The Thorne et al. (1988) formulas in Table 8.3 are based on the data presented by Hey and Thorne (1986) in Table 7.6.

Channels with Moving Beds and Known Sediment Concentration

White et al. (1982) present an analytical approach based on the Ackers and White sediment transport function, a companion flow resistance relationship, and maximization of sediment transport for a specified sediment concentration. Tables (White et al. 1981) are available to assist users in implementing this procedure. The tables contain entries for sediment sizes from 0.06 to 100 millimeters, discharges up to 35,000 cubic feet per second, and sedi-

Table 8.3: Equations for river width and depth.

Author	Year	Data	Domain	k_1	k_2	k_4	k_5
Chang	1988		Meandering or braided sand-bed rivers with:				
		Equiwidth point-bar streams and stable canals	$0.00238 < SD_{50}^{-0.5} Q^{-0.51}$ and $SD_{50}^{-0.5} Q^{-0.55} < 0.05$	$3.49k_1$*		$3.51k_4$*	0.47
		Straight braided streams	$0.05 < SD_{50}^{-0.5} Q^{-0.55}$ and $SD_{50}^{-0.5} Q^{-0.51} < 0.047$	Unknown and unusual			
		Braided point-bar and wide-bend point-bar streams; beyond upper limit lie steep, braided streams	$0.047 < SD_{50}^{-0.5} Q^{-0.51} <$ indefinite upper limit	$33.2k_1$**	0.93	$1.0k_4$**	0.45
Thorne et al.	1988	Same as for Thorne and Hey 1986	Gravel-bed rivers	$1.905 + k_1$***	0.47	$0.2077 + k_4$***	0.42
		Adjustments for bank vegetation[a]	Grassy banks with no trees or shrubs	$w = 1.46\, w_c - 0.8317$		$d = 0.8815\, d_c + 0.2106$	
			1-5% tree and shrub cover	$w = 1.306\, w_c - 8.7307$		$d = 0.5026\, d_c + 1.7553$	
			5-50% tree and shrub cover	$w = 1.161\, w_c - 16.8307$		$d = 0.5413\, d_c + 2.7159$	
			Greater than 50% tree and shrub cover, or incised into flood plain	$w = 0.9656\, w_c - 10.6102$		$d = 0.7648\, d_c + 1.4554$	

Chang equations for determining river width and depth. Coefficients for equations of the form $w = k_1 Q^{K_2}$; $d = K_4 Q^{K5}$; where w is mean bankfull width (ft), Q is the bankfull or dominant discharge ($ft^3/_s$), d is mean bankfull depth (ft), D_{50} is median bed-material size (mm), and S is slope (ft/ft).

[a] w_c and d_c in these equations are calculated using exponents and coefficients from the row labeled "gravel-bed rivers".

k_1* = $(S\, D_{50}^{-0.5} - 0.00238Q^{-0.51})^{0.02}$.

k_4* = $\exp[-0.38\, (420.17S\, D_{50}^{-0.5}Q^{-0.51} - 1)^{0.4}]$.

k_1** = $(S\, D_{50}^{-0.5})^{0.84}$.

k_4** = $0.015 - 0.025 \ln Q - 0.049 \ln (S\, D_{50}^{-0.5})$.

k_1*** = $0.2490[\ln(0.0010647 D_{50}^{1.15}/SQ^{0.42})]^2$.

k_4*** = $0.0418 \ln(0.0004419 D_{50}^{1.15}/SQ^{0.42})$.

tershed in northwest Mississippi should be stable with an average boundary shear stress at channel-forming (2-year) discharge of 0.4 to 0.9 lb/ft^2.

The value of the Shields constant also varies with bed material size distribution, particularly for paved or armored beds. Andrews (1983) derived a regression relationship that can be expressed as:

$$RS/[(S_s - 1)D_i] < 0.0834\ (D_i/D_{50})^{-0.872}$$

When the left side of the above expression equals the right, bed-sediment particles of size D_i are at the threshold of motion. The D_{50} value in the above expression is the median size of subsurface material. Therefore, if D_{50} = 30 mm, particles with a diameter of 100 mm will be entrained when the left side of the above equation exceeds 0.029. This equation is for self-formed rivers that have naturally sorted gravel and cobble bed material. The equation holds for values of D_i/D_{50} between 0.3 and 4.2. It should be noted that R and D_i on the left side of the above equation must be expressed in the same units.

Practical Guidance: Allowable Velocity and Shear Stress

Practical guidance for application of allowable velocity and shear stress approaches is provided by the Natural Resources Conservation Service (USDA-NRCS), formerly the U.S. Soil Conservation Service (SCS)(1977), and USACE (1994). See Figure 8.31.

Since form roughness due to sand dunes, vegetation, woody debris, and large geologic features in streams dissipates energy, allowable shear stress for bed stability may be higher than indicated by laboratory flume data or data from uniform channels. It is important to compute cross-sectional average velocities or shear stresses over a range of discharges and for seasonal changes in the erosion resistance of bank materials, rather than for a single design condition. Frequency and duration of discharges causing erosion are important factors in stability determination. In cobble- or boulder-bed streams, bed movement sometimes occurs only for discharges with return periods of several years.

Computing velocity or shear stress from discharge requires design cross sections, slope, and flow resistance data. If the design channel is not extremely uniform, typical or average conditions for rather short channel reaches should be considered. In channels with bends, variations in shear stress across the section can lead to scour and deposition even when average shear stress values are within allowable limits. The NRCS (formerly SCS) (1977) gives adjustment factors for channel curvature in graphical form that are based on very limited data (see Figure 8.31). Velocity distributions and stage-discharge relations for compound channels are complex (Williams and Julien 1989, Myers and Lyness 1994).

Allowable velocity or shear stress criteria should be applied to in-channel flow for a compound cross section with overbank flow, not cross-sectional average conditions (USACE 1994). Channel flow resistance predictors that allow for changing conditions with changing discharge and stage should be used rather than constant resistance values.

If the existing channel is stable, design channel slope, cross section, and roughness may be adjusted so that the current and proposed systems have matching curves of velocity versus discharge (USACE 1994). This approach, while based on allowable velocity concepts, releases the procedure from published empirical values collected in other rivers that might be intrinsically different from the one in question.

CASE STUDY

Careless Creek, Montana

In the Big Snowy Mountains of central Montana, Careless Creek begins to flow through rangelands and fields until it reaches the Musselshell River. At the beginning of the century, the stream was lined with a riparian cover, primarily of willow. This stream corridor was home to a diversity of wildlife such as pheasant, beaver, and deer.

In the 1930s, a large reservoir was constructed to the west with two outlets, one connected to Careless Creek. These channels were meant to carry irrigation water to the area fields and on to the Musselshell River. Heavy flows during the summer months began to erode the banks (Figure 8.39a). In the following years, ranchers began clearing more and more brush for pasture, sometimes burning it out along a stream.

"My Dad carried farmer's matches in his pocket. There was a worn spot on his pants where he would strike a match on his thigh," said Jessie Zeier, who was raised on a ranch near Careless Creek, recalling how his father often cleared brush.

This accelerated streambank erosion, and use of water for irrigation increased. Conflicts arose over the quality and quantity of water, as riparian vegetation continued to be cleared. Groups then began working together to resolve problems. A Technical Advisory Sterring Committee was developed to help the planning effort. Many organizations took part, including the Upper and Lower Musselshell Conservation Districts; Natural Resources Conservation Service; Montana Department of Natural Resources and Conservation; Montana Department of Fish; Wildlife and Parks; Deadman's Basin Water Users Association; U.S. Bureau of Reclamation; Central Montana RC&D; City of Roundup; Roundup Sportsmen; county commissioners; and local landowners.

As part of the planning effort, a geographic information system resource inventory was begun in 1993. The inventory revealed about 50 percent of the banks along the 18 miles of Careless Creek were eroding. The inventory helped to locate the areas causing the most problems. Priority was given to headquarters, corrals, and croplands, where stabilization of approximately 5,000 feet of streambank has taken place, funded by EPA monies.

Passive efforts have also begun to stabilize the banks. Irrigation flows in Careless Creek have been decreased for the past 5 years, enabling some areas, such as the one pictured, to begin to self-heal (Figure 8.39b). Vegetation has been given a chance to root as erosion has begun to stabilize. Other practices, such as fencing, are being implemented, and future treatments are planned to provide a long-term solution.

Figure 8.39: Careless Creek. *(a) Eroded streambank (May 1995) and (b) streambank in recovery (December 1997).*

(a)

(b)

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