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Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals

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Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals

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Executive Summary

All organizations that fund or have regulatory responsibility for stream management projects have an inherent responsibility to evaluate projects and measure their success relative to stated goals and objectives. While a number of guidelines and manuals exist for developing specific elements of stream management projects, their focus typically is the engineering or design of construction projects—without providing a context for watershed processes or management. No accepted standard of guidance exists for stream management projects, and all existing guidelines are limited in scope with respect to the specific needs and considerations of the regulatory services in their project consultation programs and funding entities in their granting programs. Furthermore, resources are needed that direct, organize, and inform the review of stream management practices in a watershed context. This document addresses these needs by providing the tools and scientific basis to evaluate common stream management practices.

This widely vetted and peer-reviewed document serves as an educational reference and training aid for evaluating stream management practices, with an emphasis on physical processes related to river system habitats. The review of stream management projects is facilitated by three integrated tools, which we present at the outset of this document since these tools are the lead resource for reviewers. The tools, all online at www.restorationreview.com, are:

1. **Project Screening Matrix:** This tool assists in evaluating the potential risks posed by a project to species or habitat, and in prioritizing staff resources for review.
2. **Project Information Checklist:** This tool assists in evaluating whether a project proposal includes all the information necessary to allow critical and thorough project evaluation.
3. **River Restoration Analysis Tool (RiverRAT):** This tool promotes consistent and comprehensive project planning and review. It is available as a Web-based application.

Training in the use of RiverRAT was developed parallel to writing of this document, and training sessions for reviewers begin with a presentation on watershed and stream processes as they relate to river habitat. Additionally, the checklist and RiverRAT have built-in reporting features to facilitate efficient tracking and reporting back of project reviews. While an emphasis on salmonid recovery and the Endangered Species Act context in the Pacific Northwest and California is inherent in RiverRAT, the resources and tools have broader utility and could easily be adapted to other agencies, regions, or resources.

This document next presents a synthesis of science relevant to stream management, focusing on the processes that determine the physical characteristics of stream habitat. Fully understanding and evaluating stream management actions often require technical understanding that integrates the sciences of aquatic ecology, hydrology, geomorphology, and engineering. Understanding the principles of these sciences is a prerequisite to interpreting channel changes and predicting potential responses to proposed stream management actions.

Following the scientific synthesis, the document leads the reader through a detailed and logical project development process that includes problem identification, consideration of watershed and social contexts, critical review of project goals and objectives, evaluation of alternatives, project design and implementation, and postproject monitoring. This account of project development is presented in the context of evaluating proposed projects, thereby providing a framework for reviewing a variety of relatively common management actions and stream projects, including channel and bank stabilization, rehabilitation, habitat enhancement, and restoration.

The resources presented herein will help services staff (e.g., National Marine Fisheries Service and U.S. Fish and Wildlife Service) evaluate whether proposed management actions may help or harm the biological and physical processes that comprise sustainable stream ecosystems. If broadly applied, these resources will foster consistency in project review within and among agencies. Consistent application of the tools will also promote the development of projects that minimize risk to protected species and habitat, and foster reporting practices that can streamline the review process and improve future projects by learning from doing.

The goals of the resources presented herein are to enable reviewers to:

1. Understand the connections between physical processes and aquatic habitat.
2. Understand the connection between common management actions, effects, and associated risks to protected species and habitat.
3. Understand alternatives that can minimize project-related risks to protected species and habitat.
4. Provide science and understanding that promote the design of sustainable projects, resilient to physical processes and changing environmental conditions.
5. Document and streamline project review and foster consistency among project reviewers.
6. Promote effective postproject appraisals, leading to more effective future river management.

To facilitate reviews that may require deeper assessments of project designs and design analyses, the document includes appendices that detail design considerations, approaches, and analyses. Appendix A details investigative analyses that form the basis for evaluating existing and proposed conditions and for conducting design analyses. Appendix B describes approaches and the application of criteria for developing specific design elements as well as specific monitoring metrics. Appendix C presents a suite of additional management alternatives for river systems. Appendix D provides an annotated bibliography of existing guidelines and manuals for stream management and restoration design.

Acknowledgments

This document and its associated tools were developed by a team of National Marine Fisheries Service and U.S. Fish and Wildlife Service staff together with their contractors. In addition to the author team, a panel of experts was convened in December 2007 for brainstorming the project and giving guidance; the panel also later reviewed drafts of the document. Interviews with services managers and workshops with more than 50 potential end users from a wide range of state and federal resource agencies were conducted to solicit input, guidance, and feedback on draft products.

The expert review panel included William Dietrich and Matt Kondolf, University of California Berkeley; Peter Downs, Stillwater Sciences; Greg Koonce, InterFluve Inc.; and Douglas Shields, U.S. Department of Agriculture National Sedimentation Laboratory.

NOAA managers interviewed included Dale Brege, Dan Guy, Spencer Hovekamp, Vince Kosakiewicz, Ken Phippen, Penny Ruvelas, and Ken Troyer.

LaGrande, Oregon, workshop attendees included Ken Bronec, Rick Christian, Chad Fealko, Mary Headley-Hoffman, Scott Hofer, Spencer Hovekamp, Christian Jilek, Lyle Kukenbecker, Vance McGowan, Coby Menton, D'Ann Reid, Dan Rife, Shelly Schmidt, John Stephenson, Randy Tweten, Gary Wade, and Justin Yeager.

Portland, Oregon, workshop attendees included Chris Allen, Megan Callahan-Grant, Alex Cyril, Christy Fellas, Brad Goehring, Kevin Herkamp, Jess Jordan, Marc Liverman, Larry Swenson, Mike Turaski, Jody Walters, and Brianna Blaud.

Santa Rosa, California, workshop attendees included Stephen Bargsten, Darren Brumback, Kit Crump, Brian Ellrott, Peter LaCivita, Serge Glushkoff, John McKeon, Gillian O'Doherty, Bob Pagliuco, Jeremiah Puget, Erin Strange, Kris Vyverberg, and Leslie Wolff.

Other contributors included Karin Boyd, Applied Geomorphology Inc.; Scott Gillilan, Gillilan Associates Inc.; Ginger Birkeland, scientific editor; Ed Quimby, NWFSC editorial project leader; and Bert Tarrant, NWFSC technical editor.

1. Introduction

Management actions within stream corridors span a wide range of intended outcomes, including reconstruction or renovation of structural assets, channel rehabilitation, stabilization of eroding streambanks, management or diversion of in-channel and overbank flows, sediment management, river restoration, and habitat enhancement to promote a single species or overall biodiversity. Because streams are complex and dynamic systems, projects undertaken with the best of intentions still cause unintended outcomes that often pose risks to fisheries or habitat, either directly or through introducing additional constraints on natural processes.

In this source document, we begin by providing the tools for the evaluation of project proposals. Next we present a synthesis of the science of fluvial geomorphology as it relates to river system habitat, beginning with watershed controls and progressing to the specifics of stream channel morphology. This synthesis provides a thorough scientific foundation for evaluating the consequences of stream projects, with emphasis on their potential impact to physical processes and associated habitat. Finally, we present a logical process for developing stream management projects, including those restoration and stabilization projects intended to improve habitat. Together, the tools and document provide an efficient, scientifically based method for evaluating proposed stream management projects with respect to their potential risks to species and habitat.

Projects proposed as restoration, stabilization, or remediation typically include elements that are site specific (e.g., 10s to 100s of meters in stream length), in large part because many habitat constraints to aquatic species are identified at this scale. Many projects are unsuccessful because they address local-scale symptoms without understanding the wider causes of habitat loss or degradation. Site-specific actions, such as meander reconstruction, the addition of weirs, installation of large wood structures, and biotechnical bank stabilization, have become the default solution to many habitat problems, yet they are often planned and implemented without consideration of all physical processes involved or the potentially negative impacts of some project elements (Roni et al. 2002, Abbe et al. 2003).

Application of engineering standards to the design process, while bringing benefits in terms of professional accountability and rigorous analysis, has often increased the degree of risk aversion associated with stream restoration schemes. The problem with risk aversion is that it leads to overdesign to ensure an engineering factor of safety. Risk aversion tends to increase as the uncertainties inherent to natural systems become apparent, such as variability in seasonal and annual flows, or lack of knowledge concerning sediment transport processes. The resulting projects impose unnecessary constraints on natural channel adjustment and long-term habitat value. To address these issues, the source document and tools facilitate identification and evaluation of the constraints, uncertainties, and risks associated with proposed stream management projects. To this end, the document and tools encourage project development and review to include:

- Understanding how engineering and management actions affect the physical stream channel processes operating at varying scales (e.g., site, reach, and watershed).
- Acceptance that uncertainty is inherent in all engineering and management actions in river systems with respect to predicting project outcomes and potential risks to physical processes and the habitats and species they sustain.
- Promotion of solutions to identified problems that address the root causes at appropriate scales, rather than treating the symptoms of the problem at the site scale.
- Acknowledgement that human influences are fundamental components of all river ecosystems, at all scales, in the western United States.

The document makes every effort to avoid jargon and discipline-specific terms or terms with specific regulatory interpretation. Where technical terms are used, a comprehensive glossary is provided. Within this document and associated tools, we define the term restoration as action taken to enable natural physical and biological processes to operate naturally and free from artificial constraints.

For the purposes of this document, terms that in some contexts have legal implications are not intended to imply any specific legal interpretation. For example, while the term mitigate may have specific implications in the context of regulatory frameworks, in this text it simply means “to lessen the seriousness or extent of” or “to make up for.” We universally apply all terms within this document outside of their possible legal context and define them as such. Further, while the thrust of this document relates primarily to listed species of salmon and trout, the document uses the term salmonid inclusively.

2. Tools for Project Review

This document is intended as a resource for reviewing stream corridor projects, primarily in the context of consultations conducted by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS). Review may occur at one or more points in the project development process and may be conducted by multiple entities working together or separately. The document and associated tools are intended primarily to assist with evaluating potential project impacts to physical processes and associated habitat, or with developing projects where habitat has been identified as a factor that limits ecological recovery.

We provide three tools for project review: a Project Screening Matrix, a Project Information Checklist, and the River Restoration and Analysis Tool (RiverRAT). These tools are online at www.restorationreview.com. The screening matrix, presented in this document, is intended to assist reviewers in making an initial assessment of the level of risk to habitat resources associated with a proposed project. The matrix enables reviewers to assess the risk posed by the project should it be permitted and, in particular, to decide whether the risk is sufficiently high to merit technical assistance from specialists in other disciplines. A separate project information checklist is used to determine whether the project proposal contains sufficient information to conduct a comprehensive review. The checklist identifies the exact information needed for review to proceed, enabling the review process to be faster and more efficient. After receiving all pertinent information, reviewers may then use the RiverRAT (available as a Web-based application) to conduct a thorough and comprehensive review of the project.

The RiverRAT sequence proceeds in the logical order in which information is considered in project development (see Section 4, Project Development). The document has a parallel information sequence to provide consistency among the checklist, the RiverRAT, and the document. The checklist content, however, is presented in a sequence similar to what is commonly required for Biological Assessment submittals.

2.1. Project Screening Matrix

In reviewing stream management project proposals, regulatory agencies must ensure that projects that pose a risk to natural resources are adequately reviewed while avoiding overscrutinizing proposals that pose very little risk to resources. The project screening matrix (Figure 1) has been developed to help reviewers identify an appropriate level of review. By identifying the project impact potential and stream response potential associated with a proposed project, this screening tool helps reviewers characterize the relative risk to natural resources and stratify review time and intensity for various project types. The principle underlying the screening matrix is that stream projects should do no lasting harm to aquatic habitat on-site, upstream, or downstream, and that short-term and long-term negative impacts will be avoided where possible, minimized to the greatest extent, and mitigated where necessary.

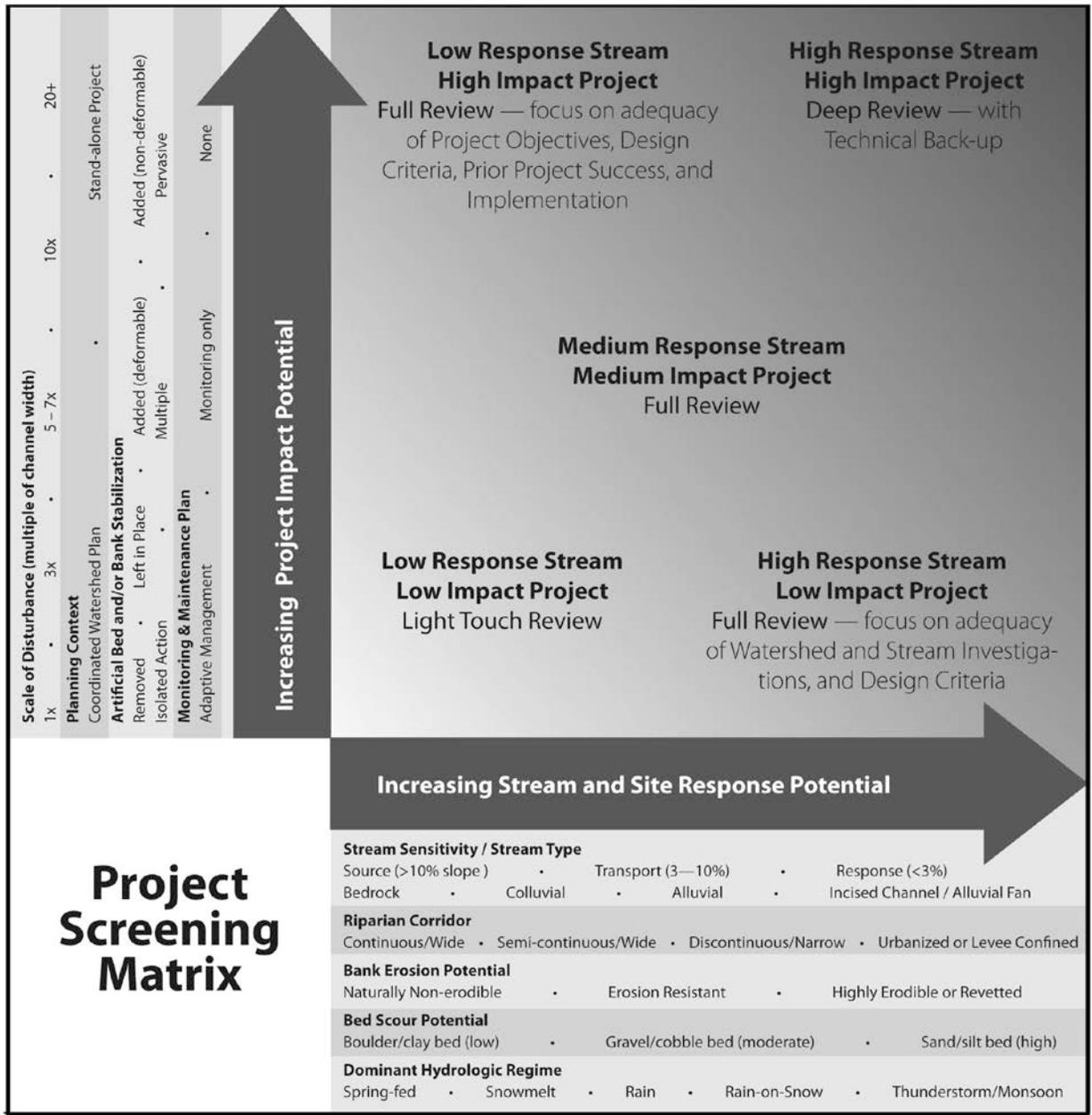


Figure 1. Project screening matrix, which indicates the continuum of appropriate levels for design and review.

2.1.1. Explanation of the Axes

The screening matrix (Figure 1) transitions from light gray in the lower left corner, indicating that a light-touch review of the project may be sufficient, to dark gray in the upper right corner, indicating that a deep review may be justified or necessary. The matrix indicates an appropriate level of design and review as a function of potential risk to natural resources; it does not mean that a project is either good or bad for habitat. For example, many restoration projects

that provide great benefit to habitat and species may also plot in the dark gray zone, due to the level of disturbance necessary to restore or connect valuable habitat.

The x-axis represents stream and site response potential—the inherent potential for the stream to express morphologic response to disturbance. Disturbances may be natural, such as those caused by a flood or drought, or anthropogenic, such as channelization or stream restoration work. The x-axis, therefore, uses attributes such as stream type, riparian vegetation, bed and bank materials, and flow regime, to assess overall response potential. Because these are inherent response characteristics of a stream system, risk to natural resources associated with stream response cannot be reduced unless the project is changed or the site is relocated. Additionally, because of the inherent stream sensitivity, long-term or persistent impacts are more likely to occur on higher response streams.

The y-axis represents project impact potential. Some disturbance is inevitable when performing management or restoration actions; therefore, this axis uses project disturbance indicators, such as project scale, watershed context, stabilization features, and monitoring and maintenance activities, to assess overall impact potential of the project if implemented. Because the level of impact potential is related to the proposed action, reducing risk to natural resources resulting from a project is often feasible through project redesign, implementation of best management practices, and adaptive management.

Explanation of stream and site response potential factors—x-axis

Stream sensitivity/stream type—Channel response to disturbance can vary by channel type, and some simple classifications can help define possible sensitivity of channels. Source reaches are dominated by local sediment inputs from hill slopes; transport reaches correspond to supply-limited channel types; and response reaches correspond to transport-limited channel types (Montgomery and Buffington 1998). Consequently, the potential for morphologic response to a stream project is lowest in source (colluvial and bedrock) reaches, intermediate in transport (step-pool, cascade) reaches, and greatest in response (plane-bed, pool-riffle, dune-riffle) reaches. Stream slope at the reach scale is often used as a surrogate for source (>10%), transport (>3% to <10%), and response (<3%).

Response potential is relevant at the reach scale and should be evaluated in the context of an entire stream reach (similar slope and confinement). Reach breaks may include, but are not limited to, natural or artificial grade control, significant changes in channel slope, confluence with a significant tributary, changes in channel confinement, or changes in bed or bank materials.

If a stream is bedrock or colluvium dominated, then the remaining response factors of riparian corridor and bank and bed characteristics are generally not applicable. Alternatively, if the channel is on an alluvial fan, the site response potential will likely remain high even if the other risk factors are all rated low.

Stream sensitivity also includes the potential for disturbance to propagate upstream or downstream. An example of upstream disturbance propagation is erosion of the channel bed, creation of a headcut, and the migration of this nickpoint; this process is commonly initiated when artificial grade controls, such as culverts, are removed. This erosion process sets off a

series of feedback mechanisms that can cause sedimentation downstream, channel widening, loss of base flows, and other related impacts. This response is highly influenced by stream type; headcuts are unlikely to migrate upstream through a high-gradient, colluvial reach, but may migrate many miles up a lower-gradient, alluvial response reach.

Riparian corridor—In steep streams, narrow riparian corridors provide important functions, but large riparian corridors are generally associated with lower-gradient, unconfined stream systems. The capacity of the stream to absorb disturbances without harm to habitat and species, often referred to as resilience, generally increases with the width of the riparian corridor; however, the probability that the stream may be adversely affected increases when the riparian corridor is narrow or discontinuous. Riparian vegetation reduces velocity and increases soil strength. The risk to resource associated with morphologic response is greatest in urban and levee-confined streams that lack the space necessary to respond to disturbances.

Bank erosion potential—Bank erosion and lateral channel migration rates are lower in channels with naturally nonerodible bank materials, such as rock or highly cohesive clay and banks that are reinforced with vegetation. Conversely, erosion and migration rates are higher in channels with banks that are highly erodible, either due to natural conditions or because of vegetation removal or management practices. Channels with artificially revetted banks (e.g., riprap) are also classed as having a high response potential because a flood event may cause failure of the revetment, leading to rapid rates of channel change. The presence of a revetment indicates an inherently erodible bank.

Bed scour potential—Channels with erodible bed material such as sand will respond to disturbance more rapidly and to a greater degree than those with less erodible material. Coarse sediment, particularly immobile material such as boulders, creates streams with much lower scour risk. Artificial grade-control structures may indicate vertical instability, though these are often unnecessarily applied. Thus streams with grade controls are classed as having high morphologic response potential. Grade-control structures can fail during large flood events, causing rapid incision and channel instability, with impacts propagating upstream and downstream.

Dominant hydrologic regime—Flow characteristics are a function of climate and watershed hydrology and determine the frequency and degree of hydrologic disturbance, which affect the relative channel stability and potential for stream response. For example, spring-fed stream systems have low flow variability and hence are highly stable and predictable. In contrast, convective thunderstorm-driven hydrology results in streams with high flow variability and more frequent high flows, thus they are often disturbed and destabilized.

Stream reaches that are transitional in their hydrologic regime should be evaluated for changes in hydrologic regime over time due to climate change. For example, if a stream reach is located 500 feet in elevation above the current snow level, it is possible that this reach will become a rain-on-snow dominated system in the future. Streams with codominant or bimodal hydrologic regimes should be evaluated at the higher response potential of the two regimes; for instance, if a basin experiences snowmelt and convective thunderstorms, then the convective thunderstorm should be considered the dominant regime in the context of the screening matrix.

Coastal California and coastal southern Oregon streams may be dominated by El Niño Southern Oscillation (ENSO) climate cycles, repeating in approximately 5-year intervals. In this hydrologic regime, it is the El Niño phase of the cycle that dominates sediment transport and drives major channel changes.

Explanation of the project impact potential factors—y-axis

Scale of disturbance (multiple of channel width)—The project impact potential factor is intended to capture potential effects to stream habitat by scaling the project extent to the channel. For instance, if the primary disturbance of a channel management action is within the channel and is 75 feet in length in a channel that is 150 feet wide, then the disturbance index would be 0.5; however, if the channel is only 15 feet wide, then the disturbance index would be 5. The potential for impacts is higher for smaller streams because more habitat units, which are also scaled to channel width, would be affected.

If the primary disturbance is in the floodplain, such as a levee setback project, then the disturbance can be indexed to floodplain width instead of channel width. If the levee is set back, creating a 100-foot wide floodplain, and the length of the project is 1,000 feet, the index would be 10. The greater the extent of floodplain disturbance associated with project implementation, the greater likelihood of impact to natural resources.

Planning context—All stream management and restoration projects should be developed within a watershed framework; this is especially important when identifying the underlying cause of the problem. This risk factor uses watershed plans as a surrogate for project prioritization and context; it is assumed that, if the project is specifically identified as part of a larger plan, some level of technical analysis has been performed to justify the need and appropriateness of the proposed project.

Artificial bed or bank stabilization—Projects that constrain stream processes, morphologic adjustment, or channel/floodplain sediment exchange are generally riskier than projects that either remove existing constraints or leave them undisturbed. Hence the potential risk to resources associated with channel stabilization measures is lower for temporary, deformable structures than for permanent, rigid ones.

Deformable structures are designed to provide short-term stability (5 to 10 years) before degrading, thus allowing for vegetative reestablishment. Construction material may include large wood, soil lifts, brush mattresses, and other forms of bioengineering using live materials. Nondeformable structures are generally designed to last longer (50+ years) and are composed of nondegradable materials such as rock and synthetic geotextiles.

As the level of artificial channel stabilization increases within a stream reach, the more significant the impacts on aquatic species and habitat. For instance, if a rigid bank stabilization project is an isolated action, it will likely have a lesser effect on habitat than a pervasive project action that cumulatively affects 50% of the stream reach. A single project may be considered as stand-alone or in the context of cumulative impacts of other associated projects, in which case it may represent a greater impact potential.

Monitoring and maintenance plan—All projects have some level of habitat impact, hence monitoring is required to determine the extent of the impacts along with the anticipated benefits. While monitoring will detect changes and help to identify problems, adaptive management will allow for correction of these problems. For higher impact potential projects, or new project types, an adaptive management plan can significantly reduce the overall risk to resources in the long term and facilitate improved future projects.

Short-term versus long-term impacts and associated monitoring

The left-hand side of the project screening matrix (Figure 1) represents low stream response potential; hence minimizing direct impacts during construction to reduce short-term impacts may be the greatest concern. Because the stream has a low response potential, focus is placed on good project design, minimization of construction impacts, and best management practices. Table 1 indicates varying emphases for project review depending on where a project plots on the matrix.

The right-hand side of the screening matrix represents high stream response potential; hence while minimization of construction impacts is important, it is the longer-term processes that may result in ongoing impacts to the stream system. Because of the high stream response potential, emphasis is placed on the adequacy of the monitoring and adaptive management plan.

2.1.2. Using the Screening Matrix to Screen Project Proposals

Once the impact and response factors have been assessed, an appropriate level of review can be determined. Screening factors can be combined and analyzed in at least three different ways:

1. Assume that all screening factors are critical to avoid resource harm. In this case, the overall risk category is defined by the highest screening factor on each of the x- and y-axes. A good example of this precautionary principle is a stream on an alluvial fan, which would always receive a high rating for stream response potential.
2. Consider none of the screening factors to be individually critical to the resource. In this case, the overall risk category is defined by the average of the screening factors on each of the x-axes and y-axes—there is a balance among factors.
3. Deem some of the screening factors to be more important than others with no single factor dominating. In this case, the overall risk category is defined by weighting the screening factors on each of the x-axes and y-axes.

There is no easy cookbook solution to deciding how to select the overall risk category, as each project and stream presents different challenges and risks. What is required is consistent critical thinking and transparent, evidence-based decision making. The level of risk to natural resources is often reduced when more data are available or when the reviewer has more familiarity with the site.

There is no correlation between project rating and habitat benefits—the screening matrix is used simply to determine the level and intensity of project design, review, and monitoring.

Table 1. Selection of treatment based on risk source and risk to resource.

Impact and response potential	Level of review	Indicated treatment
Low impact project Low response stream	Light	<ul style="list-style-type: none"> • Only light review needed • Light touch okay for RiverRAT evaluation
High impact project Low response stream	Full	<ul style="list-style-type: none"> • Full review needed • Particular attention paid to adequacy of: <ul style="list-style-type: none"> ○ Project objectives ○ Project elements that pose greatest threats ○ Design criteria ○ Evidence of prior success with similar projects ○ Implementation plan • Since stream risk is low, responses to action may be limited to project and adjacent reaches • Thus lighter touch okay for evaluating wider watershed and stream channel contexts and implications of proposed work
Medium impact project Medium response stream	Full	<ul style="list-style-type: none"> • Full review needed • Careful application of RiverRAT is recommended
Low impact project High response stream	Full	<ul style="list-style-type: none"> • Full review needed • Particular attention paid to adequacy of: <ul style="list-style-type: none"> ○ Watershed and stream investigations ○ Design criteria related to preventing project impacts on greater fluvial system ○ Plans for postproject monitoring and adaptive management to limit unforeseen impacts within project reach
High impact project High response stream	Deep	<ul style="list-style-type: none"> • Full, extensive review needed • Proposals may be complicated or groundbreaking, requiring backup from subject specialists to deal with challenging technical aspects (such as those pertaining to engineering, geomorphology, or complex social or economic issues) • Reviewers should not hesitate to seek assistance where necessary

2.2. Project Information Checklist

The project information checklist (available at www.restorationreview.com) summarizes all information that a project proposal should contain for a thorough review by services staff.¹ The advantages of the checklist are twofold. First, by providing all information suggested in the checklist, the project team can avoid delays during the review process. Second, the reviewer can be reasonably assured that a project team using the checklist has put in the effort required to develop a well-thought-out project that encompasses appropriate spatial and temporal scales, risk, and uncertainty. Ideally, use of the checklist by project developers and reviewers will promote time and resource efficiency and make the review and consultation process more transparent to both parties.

The primary purpose of the checklist is to determine whether sufficient information exists to use the RiverRAT. However, the checklist may also be used to determine whether sufficient information exists to conduct a preconsultation or preapplication review. In addition, the checklist may be employed during or after evaluation to ensure that the review process was properly completed. Finally, the checklist was also developed to use as a possible template for a biological assessment, thus providing a consistent model for the organization and content of a complete biological assessment.

2.3. River Restoration Analysis Tool—RiverRAT

RiverRAT provides a framework that guides reviewers in evaluating a project proposal. This framework encompasses the entire project development process, including problem identification, establishment of goals and objectives, project design, implementation, and postproject monitoring. RiverRAT is geared to answering the question, “What are the potential impacts and risks to resource?” It also enables a review of project and design integrity with respect to species or ecosystem recovery. In an Endangered Species Act context, RiverRAT could be used during preconsultation, in preparation of a biological assessment, or in effects analysis for a biological opinion. In a Fish and Wildlife Coordination Act context, RiverRAT could be used for preapplication discussions or evaluation of potential project impacts to the services’ trust resources. Access to RiverRAT by project sponsors, stakeholders, and specialists will give them insight regarding the review process and guide them in developing project proposal documents that are more informative and better tuned to the needs of the services staff who must review the proposal.

RiverRAT is designed to identify risk associated with projects. As reviewers become familiar with its application, differentiation between low-risk and high-risk projects should become more efficient. Those projects identified as having low risk may be eligible for a light touch review. For projects with high risk, RiverRAT provides a framework for detailed reporting of project concerns.

¹ While use of the term services staff in this document refers to NMFS and USFWS as a primary audience, the intention is not to be exclusive of state fish and wildlife agencies. Acknowledging that NMFS and USFWS employees are largely trained in biological sciences, these resources emphasize understanding of physical processes that influence stream habitat and that are affected by management actions.

3. Fluvial Geomorphology and Stream Habitat

3.1. Introduction: Geomorphic Factors that Determine Stream Habitat

Stream habitat is determined by channel morphology, flow characteristics such as velocity and temperature, substrate type, the quantity and quality of organic matter, and vegetation characteristics, which together provide food and shelter for fluvial species. In the context of this document, stream habitat is defined as the suite of physical, chemical, thermal, and nutritional resources created by processes operating at scales ranging from landscapes and watersheds to site-specific channel reaches.

Stream habitat is often characterized in terms of localized features, such as a spawning habitat, or in the context of physical forms, such as pools and riffles. A snapshot of these elements portrays them as static features, but habitat actually is a dynamic outcome of landscape drivers, watershed controls, stream processes, and channel characteristics operating at a range of scales and disturbed by a range of natural phenomena and human activities (Figure 2). Indeed, the capability of habitat to adjust and evolve is essential to ecosystem function (Naiman and Latterell 2005).

At the top of the hierarchy of factors that influence habitats are landscape drivers: climatic and geologic factors that determine the input of water and sediment to the fluvial system, primarily through precipitation and weathering. Thus on a regional scale, landscape drivers determine the variations in hydrologic and sediment inputs to the river system, which are termed the hydrologic regime and sediment regime, respectively. Next in the hierarchy are the physical features of the watershed that affect habitat. These watershed controls include terrain, soils, vegetation, and land use, all of which control the distribution of water and sediment over time and space. Stream channel processes also influence stream habitat. Sediment transport and flow resistance interact with the bed and bank materials (including riparian vegetation) to shape the channel, creating local habitat features such as pools, riffles, side channels, and log jams.

In summary, habitat is the outcome of 1) independent landscape drivers, consisting of climate and geology, 2) watershed controls, which determine the movement of water and sediment through the river system, and 3) stream channel processes that interact with channel boundary materials to create and sustain reach-scale and site-scale channel form and habitat features. Each of these levels in the fluvial system is considered in turn in the following subsections.

3.2. Independent Landscape Drivers

Landscape drivers such as climate and geology act at the regional scale, encompassing multiple watersheds over time frames of thousands of years or more. They operate

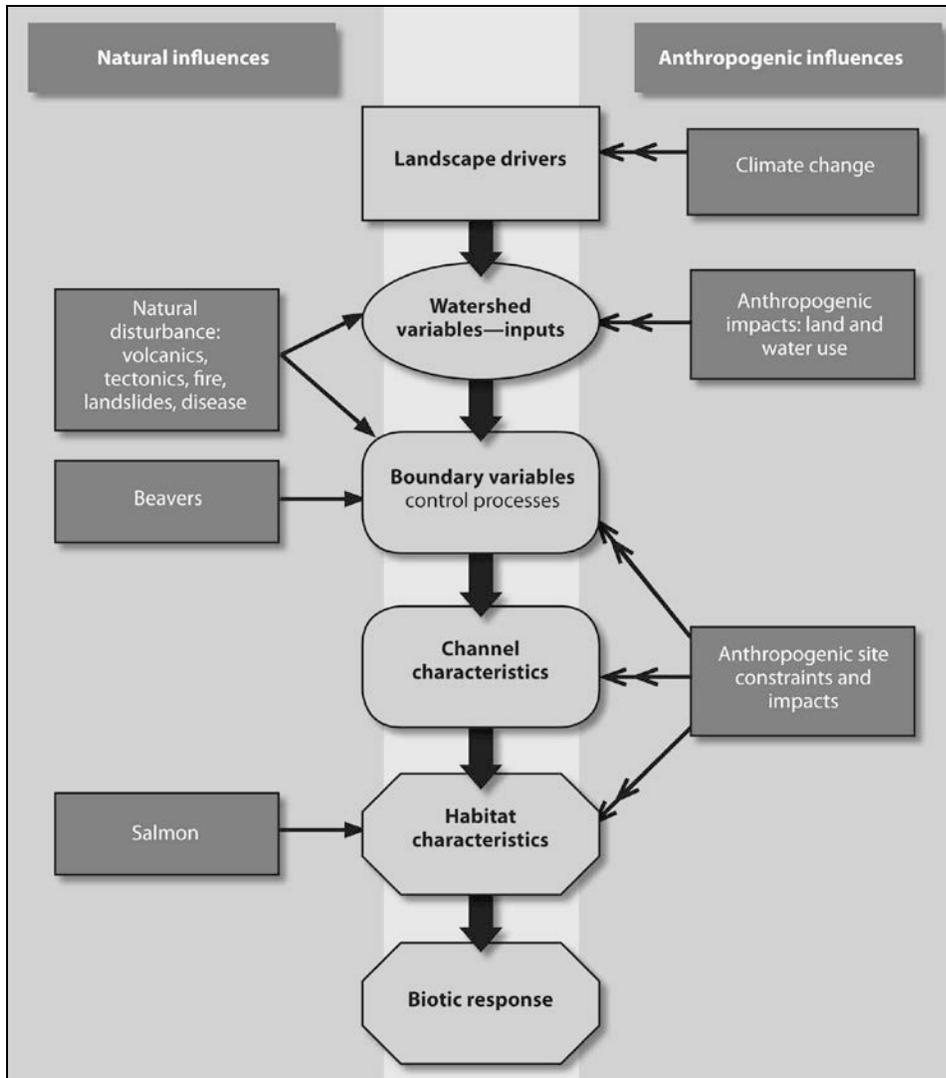


Figure 2. Hierarchy of factors influencing stream habitat and biotic response. Biotic response to environmental change is driven by a cascading spatial hierarchy of factors. Most contemporary restoration and stabilization projects focus efforts near the bottom of this hierarchy, addressing primarily symptoms or responses, rather than causes. Ecosystem health and species recovery will require greater focus on factors near the top of the hierarchy. Dark solid boxes represent external influences on elements within the hierarchy and are divided into natural influences on the left and anthropogenic influences on the right. Double arrows indicate human influences. Varying box shapes represent varying scale of influence and response, decreasing in area from landscape (rectangle) to watershed (oval) to reach (rounded rectangle) to site (octagonal).

independently of watershed controls and stream channel processes. However, climate and geology are not mutually independent. That is, geologic features influence regional and local climates (e.g., orographic rain shadows), while climate influences weathering rates that sculpt and erode such landscape features.

Interactions between climate and geology act over long time periods to determine the physical geography of a watershed. These drivers also ultimately determine land use practices

such as agriculture or forestry, which in turn affect rainfall-runoff relations and catchment sediment yield. Consequently, these landscape drivers are ultimately responsible for the inputs of water, sediment, and organic matter to the river system. The channel forms and dynamics that result determine the habitat provided by the river. For example, stream flow is derived from effective precipitation, which is the total amount of precipitation less that which returns directly to the atmosphere through evapotranspiration.

The characteristics of precipitation—its form (snow or rain), seasonality, intensity, and duration—are fundamentally determined by the interplay of climate and geology, and ultimately control how much of the precipitation is effective in generating stream flow. To become stream flow, the effective precipitation enters the river system via surface runoff (quick flow), interflow (delayed quick flow through surface particles), or groundwater seepage (base flow). The distribution of effective runoff between these pathways is controlled by watershed attributes including terrain, soils, vegetation, and land use, and has a major bearing on the flow regime, as discussed in the subsequent subsections. Watersheds dominated by surface runoff have flashy regimes that respond quickly to each precipitation event, generating spiky hydrographs with low flow between events. Conversely, rivers in regions where permeable soils and rocks allow precipitation to enter the groundwater system are slower to respond to storm events and feature perennial base flow.

The sediment supply regime is also ultimately controlled by landscape and climate drivers. The original source of all sediment in a river is weathering of in situ rock, which is driven by the interplay of climate and geology. Consequently, the sediment regime and the characteristics of sediments making up the streambed ultimately depend on these independent landscape drivers. The same is true for the mineralogy and chemistry of water and sediment in the river system at all scales (watershed, reach, and site).

While the interplay between climate and geology determines the physical geography of a watershed (e.g., elevation, relative relief, drainage area, channel network, basin shape, aspect, and base level), geology also acts semi-independently to produce physiographic features in the watershed that further influence basin hydrology, river regime, stream processes, and channel forms. Examples include geologic features that determine valley floor slope and control the local availability of potential energy, permeable rocks (aquifers) that supply base flow, and the occurrence of springs that feed streams where aquifers intersect the ground surface.

While landscape-scale geologic conditions are essentially immutable over hundreds to thousands of years (i.e., geologic time), climate is naturally variable over decadal time scales and subject to anthropogenic influences. In the western United States, climate records indicate ongoing trends of increasing temperatures, increasing winter precipitation, decreasing summer precipitation, and unpredictable changes in total annual precipitation (Miller et al. 2003, Mote et al. 2003). Climate change predictions suggest that these trends will continue (Mote et al. 2003), although predicted precipitation trends are more uncertain than predicted air temperature trends (Mote et al. 2003, Rauscher et al. 2008). Uncertainties in climate change predictions make it challenging to forecast future changes in stream processes, channel morphology, and habitat beyond the reasonable assumption that increases in ambient temperatures will result in higher stream temperatures, especially in summer. While increasing water temperatures will stress salmonids and other cold water species in some rivers, the effects of these stresses will be most

profound in river systems that are already at or near threshold temperature conditions for these species (McCullough 1999, Poole et al. 2001, Yates et al. 2008). However, increasing temperatures will begin to stress other streams not currently at thermal threshold conditions.

The trend for increased temperatures during winter and spring has the potential for far-reaching and disruptive impacts on rivers and habitats in the western United States through its likely effects on snowpack. Where precipitation falls as snow, water stored in the watershed as snowpack determines the runoff regime and is a key variable affecting water temperature in many basins. As such, snowpack is a significant determinant of habitat availability and quality. In watersheds that accumulate significant volumes of snowpack through much of the winter, the flow regime is either dominated by a snowmelt hydrograph in spring and early summer, or features a bimodal distribution with snowmelt and rain-fed hydrographs (see subsection 3.3.2, Flow Regime). Basins that are most susceptible to changes in flow regime due to increased temperatures are those with headwater elevations at or near the average annual snowline, because even small increases in temperature will result in loss of snowpack. Even if the volume of snowpack does not change, climate change may still impact habitat in snow-fed rivers by altering the timing of snowmelt runoff (Roos 1991, Mote 2003, Stewart et al. 2004, Rauscher et al. 2008).

3.3. Watershed Controls

3.3.1. Overview

Controls on stream processes and channel forms that operate at the watershed scale strongly influence habitat at the reach and site scales. Watershed controls determine the distributions of hydrologic and sediment inputs to the river system through time and space. These watershed controls include such physical features of the watershed as terrain, soils, and vegetation, all of which may be influenced by human land use practices (Figure 3). These watershed attributes control the flow and sediment regimes, which in turn are the dominant variables controlling the stream processes that create channel form. Thus the movement of water and sediment define the range of environmental conditions within the river network and influence habitat character, availability, and quality.

Under natural conditions, watershed controls are functions of the independent landscape drivers of climate and geology, but they are highly susceptible to alteration by anthropogenic activities, such as quarrying, farming, grading, aggregate mining, water resource management, and urbanization. In fact, practically all watersheds within the lower 48 states have some degree of anthropogenic alteration that affects the watershed controls, though these activities may not be obvious and their effects difficult to identify (Reid 1993). For example, urbanization clearly alters the rainfall-runoff relationship and the sediment yield (decreasing the delivery of coarse sediment while simultaneously increasing fine sediment loads). Conversely, even subtle changes in vegetation characteristics resulting from land management may have far reaching hydrologic impacts that are hard to attribute causally to anthropogenic activities. In many cases, the influence of human activities on watershed controls is impossible to eliminate or reverse. Thus unalterable impacts must be identified as constraints on the natural operation of the river system.

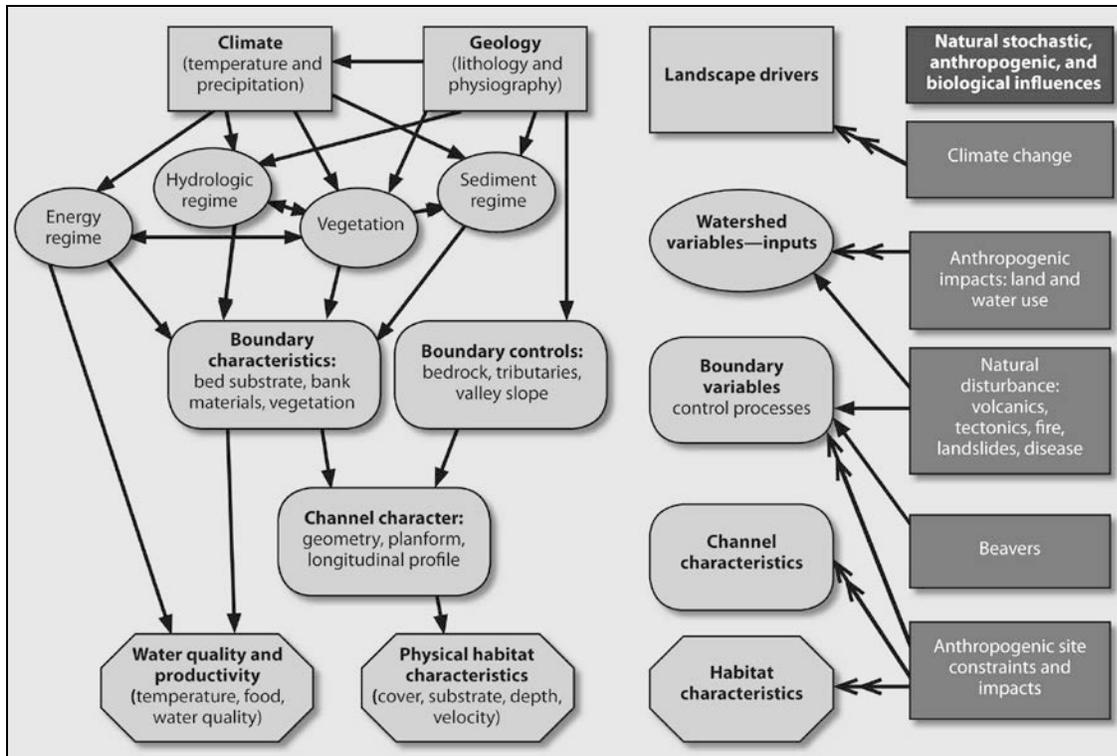


Figure 3. Drivers, inputs, controls, and habitat outcomes. River systems are governed by processes and variables acting at varying scales, generally characterized as independent landscape-scale climatic and geologic factors, watershed-scale variables of hydrologic and sediment regimes and vegetation, and reach-scale channel processes and characteristics that determine site-specific habitat values. Dark solid boxes represent external natural and anthropogenic influences on elements within the hierarchy. Double arrows indicate human influences. Varying box shapes represent varying scale of influence and response, decreasing in area from landscape (rectangle) to watershed (oval) to reach (rounded rectangle) to site (octagonal). (Adapted from Beechie et al. 2003, NWFSC, and with permission from Buffington et al. 2003, copyright University of Washington Press.)

3.3.2. Flow Regime

Flow regimes in the western United States are characterized by a wide array of discharge conditions, ranging from base flows to extreme floods, and including spring freshets driven by snowmelt, short duration flash floods caused by thunderstorms, long duration floods of intermediate magnitude resulting from frontal rain, and prolonged periods of low or zero flow during droughts (Schmidt and Potyondy 2004). The flow regime is defined by the magnitude, frequency, duration, timing, and rate of change of these discharge conditions (Poff et al. 1997). The flow regime exerts a strong influence on stream habitat and the biological communities it supports (Richter et al. 2003). It can be dramatically altered by climate change or changes in land use, water use, and river regulation, which have a ripple effect on ecological integrity and species (Figure 4).

Natural flow regimes typical of salmonid-bearing rivers in the western United States can be generally classified according to their differences in timing and volume of flow through the

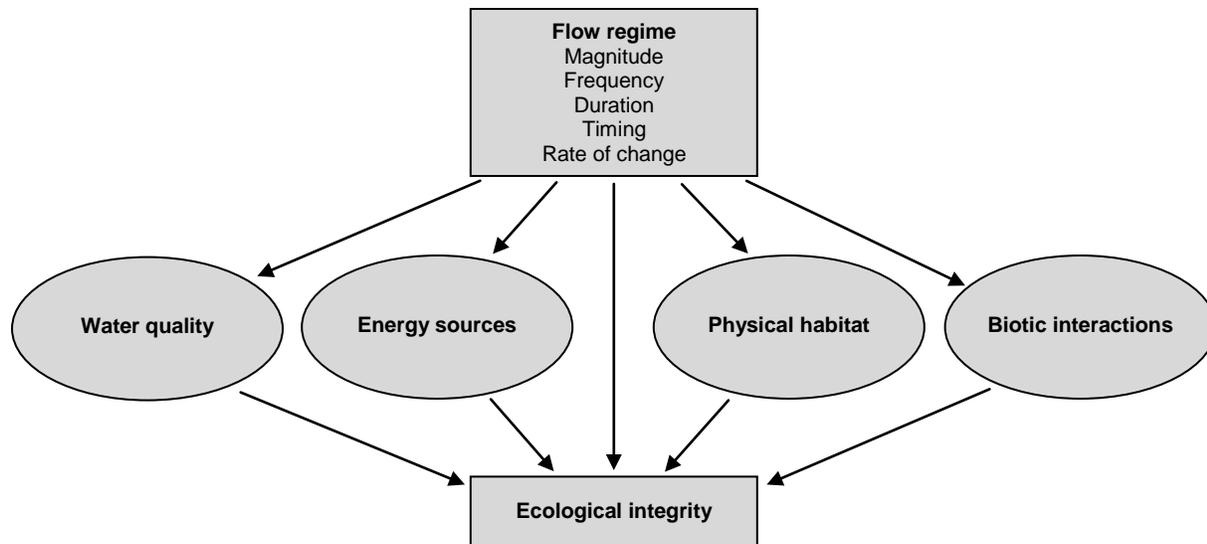


Figure 4. Flow regime influences ecological integrity. The flow regime, characterized by magnitude, frequency, duration, timing, and rate of change in flows, influences numerous parameters that affect ecological integrity of aquatic habitat. (Adapted with permission from Poff et al. 1997, copyright University of California Press.)

year (Figure 5). In mountainous regions in the continental interior, as much as 75% of annual runoff may come from snowfall (Wohl 2000). In high elevation watersheds closer to the continental margin, such as the Cascade Mountains in Washington and Oregon and the Sierra Nevada in California, 50% or more of stream flow is derived from snowmelt (Mount 1995, Beechie et al. 2006b). The annual hydrographs for coastal, mountainous regions and the interior Columbia and Snake River basins are often bimodal, reflecting a mixed regime of snowmelt and rainfall runoff. The rivers in these watersheds also feature numerous, short duration high flows during the winter season due to winter rain-on-snow events, while late spring, rain-on-snow events may result in extreme floods. Coastal watersheds of southern and central California are dominated by the ENSO climate cycle, which produces heavy winter rainfall events on roughly 5 year intervals, and relatively dry winters otherwise. Due to their basalt-dominated geologies and vast, highly porous aquifers, rivers in the interior Columbia River and Snake River basins and the Klamath Basin in northern California and southern Oregon receive generous groundwater inputs that maintain relatively high base flows during dry periods.

Flow in smaller rivers with little or no contribution from groundwater or where groundwater fluctuates seasonally may be ephemeral or intermittent. These streams are typically the most variable in terms of discharge, commonly featuring flashy hydrographs and extreme variation within and between years. While short-term variations in discharge may be large in ephemeral streams, the seasonality of flow and response to rainfall is generally predictable. In contrast, groundwater dominated rivers typically exhibit less flow variability, since the response of discharge to precipitation is generally dampened with a more pronounced lag time.

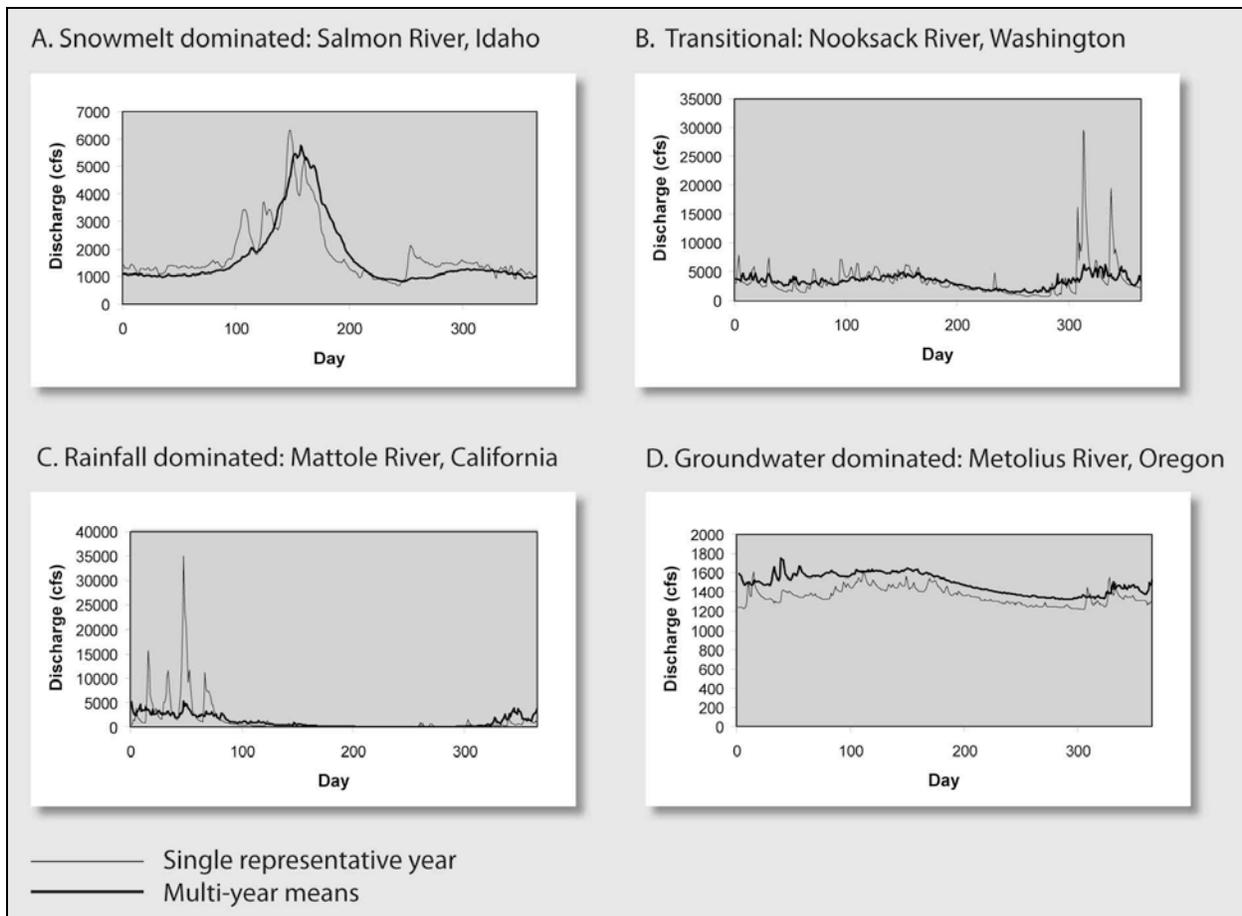


Figure 5. Flow regimes of unregulated western river systems. Flow regimes demonstrate regionally characteristic flow variation that is a function of precipitation patterns and regional geology. Panel A, the Salmon River is characterized by a spring snowmelt runoff with low summer and winter flows; panel B, the Nooksack River reveals snowmelt and winter rain-driven high flows with low summer flow; panel C, the Mattole River is a winter rain dominated regime with extreme individual flows and low summer flows; and panel D, the Metolius River is moderated year-round by a basalt geologic which absorbs rainfall in the upland to moderate storm inputs and contributes spring flow year-round. Multiyear means are derived from a 20-year period of record (1985–2004) and mute the significance of individual storm or melt events that may create flow pulses many times the discharge of the mean seasonal flow. Single year hydrographs demonstrate the variability and extremes of individual flow pulses through a year associated with rain events or pulsing snowmelt.

Return interval

The return interval of a flow event is defined as the inverse of its probability of occurrence in any one year and provides a measure of its frequency (Dunne and Leopold 1978). For example, a 5-year flood has a 20% probability of occurring in any year, while the probability of a 100-year flood is 1% in any given year. However, a 5-year flow does not necessarily occur once every 5 years. If a 5-year event happens one year, the chance of it happening again in the following year is still 20%, and if 5-year events have happened in consecutive years, the chance

of there being a 5-year flood in the third year is still 20%. Further, many flow statistics are derived from limited periods of record. One hundred-year flow values are usually not derived from 100 or more years of data, but are extrapolated from shorter periods of record. Because of climate periodicity, several years of increased flood severity may commonly be followed by periods of drought and can skew return intervals estimated from short periods of record.

Flow regime and ecology

The flow regime has been identified as the primary factor in sustaining the ecological integrity of river systems (Poff et al. 1997) and is a master variable in determining the abundance, distribution, and evolution of aquatic and riparian species (Schlosser 1985, Resh et al. 1988, Power et al. 1995, Doyle et al. 2005). For salmonids in particular, each population has evolved within the flow regime of its home river basin, typically adapting its life history to the distribution of high, intermediate, and low discharges making up the typical annual hydrograph. For example, the timing of entrance to the river from the sea, upstream migration, spawning cues, incubation and emergence from spawning beds, and downstream migration to estuaries are all genetically programmed through centuries of adaptation to the hydrologic regime of the home basin (Quinn 2005).

Clearly, understanding the flow regime is fundamental to sound stream project design. Not only does the flow regime largely determine the character of physical habitat, but it also strongly influences the behavioral relationship between fish and their habitat—when and how they feed, spawn, seek refuge, and rear. Historically, fisheries management has tended to focus on a single flow or small range of flows to quantify habitat value and estimate restoration potential. The prevalence of instream flow incremental methodology² (Bovee et al. 1998) and physical habitat simulation³ in management approaches to evaluating and managing fisheries habitat in the western United States has promulgated a single-flow perspective, according to which summer low flows are of primary concern (Postel and Richter 2003). This has erroneously implied that minimum flows are the single measure of acceptable habitat, whereas in fact, habitat and flow requirements are complex.

Decades of ecological research show that wide ranges of flows are essential to maintain stable and functioning habitat and ecological systems (Poff et al. 1997). The importance of the flow regime to channel form, habitat, and ecological function is summarized in Table 2. The spectrum of flows necessary to sustain functioning systems can be generally described using three discharge bands—low flows, channel-forming flows, and flood flows, as described below.

Low flow

Often referred to as base flow, low flow is the most frequent and persistent flow condition and consequently determines the amount of habitat available for much of the year

² This is a methodology developed to enable quantification of aquatic habitat as a function of stream flow, primarily in the context of altered or managed flow regimes (information online at www.Fort.usgs.gov/products/software/iFim).

³ This is a suite of software models developed to predict microhabitat conditions in rivers as a function of stream flow and the relative suitability of those conditions to aquatic life, primarily in the context of altered or managed flows (information online at www.Fort.usgs.gov/products/software/PHABSIM).

Table 2. Ecological significance of different river flows relative to flow duration, not flow recurrence interval. Seasonal flow variations correlate to varying ecological values and events. Flow can generally be categorized as low flow, channel-forming flow, or flood flows, each with specific ecological significance. (Adapted with permission from Postel and Richter 2003, copyright Island Press.)

Flow level	Ecological roles
Low flow (base flow)—frequent, occurring more than 90% of the time	<ul style="list-style-type: none"> • Provide year-round habitat for aquatic organisms • Maintain suitable water conditions (temperature, dissolved oxygen) • Provide water for riparian plants and animals • Enable movement through stream corridor and refuge from predators • Support hyporheic functions and organisms
Channel-forming flow —infrequent, flow duration of a few days or weeks per year	<ul style="list-style-type: none"> • Shape and maintain physical stream channel form • Create and maintain pools, spawning gravels, and refuge habitat • Redistribute and sort fine and coarse sediments • Prevent encroachment of vegetation in channel and establishment of exotic species • Maintain water quality by flushing pollutants • Maintain hyporheic connection by mobilizing bed and fines • Create in-channel bars for colonization of native riparian plants
Floods —very infrequent, flow duration of a few days per decade or century	<ul style="list-style-type: none"> • Deposition of fine sediment and nutrients on floodplain • Maintain diversity, function, and health of riparian floodplain vegetation • Create side-channel habitat, new channels, sloughs, and off-channel rearing habitat through lateral channel migration and avulsion • Recharge floodplain aquifer • Recruitment of wood and organic material into channel

(Postel and Richter 2003). Low-flow periods provide the opportunity for aquatic organisms to conserve energy (Lytle and Poff 2004). Periods of low flow are typically the most sensitive to stresses associated with water withdrawals, water temperature, pollution, and predation (Poff et al. 1997).

Channel-forming flow

Channel-forming flow is a higher discharge that is dominant in driving the stream processes (erosion, sediment transport, and deposition) that shape the channel and its physical habitat. As such, channel-forming discharge is a keystone variable in stream restoration design. The finding that intermediate flows with relatively short return periods, rather than rare, large floods, have the greatest influence on the physical form of the channel has long been one of the most influential paradigms in fluvial geomorphology (Wolman and Miller 1960, Doyle et al. 2005). The channel-forming discharge is commonly represented by one of three flows: the effective discharge (Q_{eff}), the bankfull discharge (Q_{bf}), or the 2-year flow (Q_2) (Wolman and Miller 1960, Andrews 1980, Emmett and Wolman 2001, Shields et al. 2003, Doyle et al. 2007).

The effective discharge is that flow which over a period of years transports the most sediment, and which consequently does the most work in forming the channel (Figure 6). While researchers initially suggested that the effective discharge should be represented by a single flow, recent studies suggest envisaging an effective range of discharges that consist of a range of flows of moderate frequency (typically between the 2- and 5-year events), which together transport the great majority (usually about 70%) of the sediment load (Biedenharn and Thorne 1994).

Bankfull discharge is the most commonly applied concept as a surrogate for channel-forming flow in contemporary restoration and management practices. Bankfull discharge is the flow that just fills the channel to the top of the banks without spilling out onto the floodplain. Arguments for its merits as the dominant or channel-forming flow are actually linked to the effective discharge concept. As a channel fills with progressively greater discharge, its capacity to do work on the channel boundary by entraining bed and bank materials increases with increasing depth and velocity. At the point at which flow reaches the tops of banks, additional flow increases are largely distributed across a floodplain, and thus do not significantly add to the stream's in-channel capacity to entrain and transport sediment, or do work. Thus bankfull discharge may approximate effective discharge.⁴ However, flows a little greater or less than bankfull discharge may have nearly equal sediment transport capacities and longer flow durations, making them more effective at transporting sediment than the bankfull flow over the long term. This observation supports the idea that there is an effective range of discharges, rather than a single flow, that determines the form of an alluvial channel.

Research in fluvial geomorphology and hydrology has shown a statistical correlation between this bankfull discharge and flows with 1- to 2-year recurrence intervals in stable alluvial

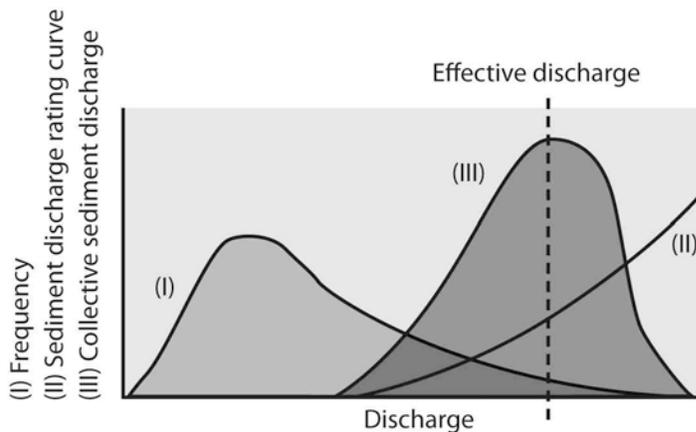


Figure 6. Hypothetical effective discharge curve illustrates that maximum volume of sediment transport over time, represented by the effectiveness curve, is a product of the flow frequency curve and sediment load rating curve. (Adapted from Biedenharn et al. 2000, U.S. Army Corps of Engineers.)

⁴ Bankfull discharge approximates effective discharge only in stable streams that are in equilibrium. Bankfull discharge measured in an incised or incising, modified or constructed, aggraded or aggrading, or widening channel will not approximate the channel-forming flow.

ivers, where the dimensions of the channel are fully adjusted to the flow and sediment regimes (Wolman and Miller 1960, Andrews and Nankervis 1995, Castro and Jackson 2001, Lawrence 2003). Based on this, Q_2 is often taken to represent Q_{bf} in stream project design, yet this is not a safe assumption because a stream where intervention is proposed is likely not in equilibrium or adjusted to its flow and sediment regimes. The return period for bankfull discharge may vary significantly from the 2-year flow in natural streams 1) where climate is dominated by ENSO storm cycles or other highly variable precipitation events; 2) where the channel is unstable or not fully adjusted to the current flow regime; 3) in channels that have been urbanized, channelized, or incised; or 4) in channels that have been altered for flood control, navigation, or land drainage. Unfortunately, bankfull flow interpreted as the Q_2 flow is commonly specified for design flow by practitioners who believe that constructing a bankfull channel geometry achieves balance with geomorphic processes and therefore is in equilibrium, is stable, and provides optimal ecological function.

The precise definition of bankfull may vary as used by a particular practitioner or researcher. The work of Williams (1986) is often quoted as indicating that a wide range of return periods may exist for bankfull discharge and Williams' reference was to the top of bank. The definition given by Dunne and Leopold (1978), which bases bankfull flow on physical evidence such as scour lines, elevation of depositional bars, transition to perennial vegetation, and other field indicators, is more commonly used (Castro and Jackson 2001, Lawrence 2003). Therefore, the definitions of terms must be identified before comparing results from different researchers. Practitioners who use bankfull discharge should clearly articulate its definition and those who measure or estimate bankfull discharge should clearly identify the methods used.

In addition to being dominant in forming the channel, discharges of about the magnitude of bankfull flow also drive stream processes that redistribute sediment for spawning habitat, scour fine sediment from the streambed and spawning gravels, erode banks to supply coarse sediment and recruit large wood from the riparian zone, and play important roles in riparian plant propagation (Shafroth et al. 2002, Lytle and Poff 2004). Hence the occurrence of channel-forming flows is vital to ecosystems, because without them, habitat would neither be created nor renewed.

It is important to note that the relationships between bankfull, effective, and two-year discharges referred to herein were derived primarily from alluvial streams in humid regions and perennial streams in semiarid environments (Biedenharn et al. 2000, Soar and Thorne 2001). Streams with ephemeral flow regimes, with channels dominated by large wood, or in valleys confined by bedrock will not necessarily exhibit the expected relationships between moderate-discharge, moderate-frequency flows, and channel form. Nonalluvial, nonequilibrium streams are discussed in further detail in subsequent subsections of this document.

Flood flow

Floods can be defined as flows that overtop the channel banks and inundate part or all of the floodplain (Bates and Jackson 1984). Practitioners often assume that floods are the dominant force in shaping river systems, and to some extent this is true. During floods the river interacts directly with its floodplain and valley, depositing sediment, nutrients, seeds, and plant propagules in lower energy areas, scouring the land surface where velocities are higher,

recruiting large wood from floodplain forests, and recharging the shallow aquifer beneath the floodplain surface.

Floods affect the channel, often dramatically. For example, a flood may excessively erode or deposit large amounts of silt in the channel where flood water is prevented from spilling onto the floodplain by natural or artificial constraints such as high bluffs or flood embankments. Floods may trigger channel avulsion, where one course of the river is abandoned in favor of another; this is particularly likely where there are remnant or side channels. Channel avulsion is especially important in reinvigorating and renewing riparian and floodplain habitat and ecosystems.

While floods may produce dramatic immediate effects along streams, these effects tend to be localized and may not be as geomorphically significant as the features produced by smaller but more frequent events, when considered at the reach scale. Flood flows in reaches that are hydraulically connected to their floodplain spill out of the channel, transferring stream energy (momentum) out of the channel, where it is dissipated by the much higher relative roughness and shallow flow depth. Conversely, stream energy for channel-forming flows is dissipated with the channel, which is why the channel-forming flow often corresponds to about the bankfull discharge. Thus intermediate flows with return periods of between about 1 and 5 years are dominant in forming alluvial stream channels, rather than much larger, less frequent flood flows. A wealth of theoretical, empirical, and experimental evidence accumulated over decades supports this as a general rule for natural alluvial streams that are unconstrained and in equilibrium.

Groundwater and the hyporheic zone

The importance of surface stream flow to creating and sustaining river forms, processes, habitats, ecosystems, and species is fully recognized. However, the importance of subsurface water is not as widely appreciated. In fact, the quantity, quality, and dynamics of water stored in the subsurface hydrological system can be crucial to the river environment and the life the river supports (Hynes 1983). Many subsurface hydrological systems are vulnerable to adverse impacts from poorly planned or executed works in the channel or on the floodplain.

Floodplains absorb and then release water from flood flows, attenuating downstream flood peaks and subsequently providing an important source of base flow that nourishes the stream between precipitation events and during prolonged dry seasons. Water stored in the saturated zone below the water table is referred to as groundwater, while storage in the partially saturated zone above the water table is termed soil moisture. That part of the subsurface system that is closely coupled to the stream is termed the hyporheic zone, defined as the area beneath the stream channel and adjacent floodplain where groundwater and surface water are exchanged freely (Boulton et al. 1998). Water in the hyporheic zone moves down and laterally across a valley by seeping through the interstitial spaces in floodplain soils and streambed sediments; this water is also intimately connected to stream and surface water bodies such as ponds and lakes. The area making up the hyporheic zone may be large: for example, on the Flathead River, Montana, the hyporheic zone extends as much as 2 km away from the channel and is a greater source of nutrients to the stream than are the surface waters (Stanford and Ward 1988). In

contrast, sand bed streams may exhibit less hyporheic storage and exchange and associated biogeochemical processing than steeper or coarser bed streams (Stofleth 2008).

The subsurface hydrology of the floodplain increases in complexity when more than one water table exists. In this case, in addition to the water table separating deep groundwater from the partially saturated soils above, one or more perched water tables are present. Perched water tables are associated with different combinations of seasonal and event-related wetting of the soil by rainfall and high stages in the channel. In fact, it is not unusual for the deep groundwater system to operate semi-independently or entirely independently of discharges in the stream system, while a separate, shallow water table is closely coupled with the movement of water in the stream and across the floodplain surface.

Connected floodplains are ecologically vital to stream geomorphology and river ecosystem health because between rainfall and flood events—and especially during long dry spells—subsurface water maintains a base flow in the stream. This base flow results from floodplain storage into the channel via seepage through the bed and banks or spring-fed tributaries. In unmodified floodplains, the quality of this hyporheic water is typically high and its temperature is low; both of these attributes deliver important benefits to stream ecology in general and the rearing habitats of salmonids in particular. In temperate climates, in-flowing groundwater can substantially reduce the water temperature in pools during high summer ambient temperatures (Nielson et al. 1994, Baxter and Hauer 2000). Because of the importance of hyporheic flow to water quality and fish survival, interactions between a stream's surface and subsurface flows should be considered when planning, designing, and constructing stream works (Harvey and Wagner 2000). The biological role and importance of hyporheic zones is further discussed in subsection 3.7.2, Stream Energy: Factors that Influence Primary Productivity.

Anthropogenic impacts on flow regime

In the great majority of watersheds within the western United States, human settlement has affected land and water resources, and consequently altered river flow regimes (Table 3). Restoration or stabilization projects are often proposed to address the adverse impacts on channel morphology and habitat that result from anthropogenic changes to the flow regime.

Direct impacts on flow regime—These include river regulation through impoundments, such as dams and reservoirs, or water diversions. Impoundments are constructed to store and release water, with the aim of regulating river flow for a variety of purposes, including moderating floods, generating hydropower, improving navigation, and providing water for dry-season irrigation or urban needs.

Direct anthropogenic impacts on the flow regime from dams, impoundments, diversions, or hydropower operations include:

- reduction of the magnitude and frequency of high flows, including channel-forming and flood flows;
- increased duration of moderate flows;

- increased volume and duration of base flows, especially downstream of flood control reservoirs;
- increased number of spates, or rapid changes in discharge, especially downstream of hydropower dams; and
- changes in the seasonal timing and duration of high and low flows.

All of these impacts affect geomorphic processes and associated ecological functions. For example, accelerated rates of change in discharges due to releases from hydropower dams can affect riparian plant vitality and also cause geotechnical instability in banks due to rapid drawdown that generates excess pore water pressures in poorly drained soils (Thorne 1982). Widespread bank failures supply excessive amounts of fine sediment to rivers, with adverse impacts on instream and benthic habitats. Similarly, water diversions take water primarily during dry periods when irrigation demand is greatest, thus adversely impacting habitat availability, stream temperature, cool water refuge, passage, hyporheic function, and riparian community health (Postel and Richter 2003). Impoundments also trap sediment, especially in the coarser size fractions, breaking continuity in the sediment transport system, which results in bed degradation and armoring.

Table 3. Physical responses to flow alteration with various anthropogenic impacts. (Adapted with permission from Poff et al. 1997, copyright University of California Press.)

Source of alteration	Hydrologic change	Geomorphic response
Dam	Capture sediment moving downstream	Downstream channel erosion and tributary headcutting Bed armoring, coarsening
Dam, diversion	Reduce magnitude and frequency of high flows	Deposition of fines in gravel Channel stabilization and narrowing Reduced formation of point bars, secondary channels, oxbows, and changes in planform
Urbanization, drainage	Increase magnitude and frequency of high flows Reduced infiltration into soil	Bank erosion and channel widening Incision and floodplain disconnection Reduced baseflows
Levees and channelization	Reduce overbank flows	Channel restriction causing downcutting Floodplain deposition and erosion prevented Reduced channel migration and formation of secondary channels
Groundwater pumping	Lowered water tables	Stream bank erosion and channel downcutting after loss of vegetation stability

While most flow diversions in the western United States employ diversion structures in the channel, pumping of groundwater from alluvial aquifers can similarly affect low flows by drawing water from the stream into the aquifer, and fundamentally changing the dynamics of energy and nutrient exchange between stream channels and their hyporheic zone (Boulton et al. 1998).

Indirect impacts on flow regime—Those resulting from land use are far more pervasive than the direct impacts of flow regulation. For example, conversion of a naturally vegetated watershed to agricultural, industrial, or urban land uses can have multiple impacts that dramatically affect the flow regime (Richter et al. 1998, Leopold 1968). In this context, agricultural land use changes the watershed controls that determine rates of interception, infiltration, and evapotranspiration. When combined with associated changes in surface roughness, these alterations have multiple impacts on the rainfall-runoff relationship. Further, agriculture often involves irrigation withdrawals, which reduce low flows, as well as land drainage and flood defense works that alter the flow regime and stream processes. Additionally, irrigation return flows tend to increase instream water temperatures and decrease water quality, and may even artificially increase low flows with abnormally high water temperatures and nutrient loads (Richter et al. 1998). Similarly, forestry operations can result in immediate and significant changes in the discharge, duration, and timing of flow events (Burton 1997), especially if a dense road network accompanies the operations. Clearly, the multiple and cumulative effects of agriculture and forestry can radically reduce habitat availability and quality throughout a river system.

Urbanization converts significant areas of watershed land surfaces to an impermeable condition, reducing infiltration capacity and fundamentally changing the character of the runoff hydrograph from storm events. Urbanization also involves the construction of gutters and drains that convey precipitation rapidly from its point of origin to the nearest watercourse. The outcomes of urbanization for the flow regime typically include dramatically reduced base flows and flashier storm flows, with shorter times to peak, higher peaks, and shorter recession curves. The severity of these impacts varies regionally with development density and watershed size (Booth and Jackson 1997). Urbanization may also drive indirect impacts on habitat by disturbing the balance between sediment supply and sediment transport capacity in the river system. This happens because the frequency of channel-forming flows usually increases within and downstream of urbanized watersheds, while the duration of runoff events is often substantially reduced. While construction activities may temporarily elevate sediment supply, sediment supply in established urban areas is typically lower than that under predisturbance conditions. This may initiate a feedback loop such that 1) an initial pulse of sediment is introduced to the river system, 2) a flashier flow regime is established that is starved of sediment, 3) the sediment balance becomes rapidly destabilized, and 4) the resulting channel instability feeds back to further alter the flow regime (Booth 1990, Konrad 2000, Trimble 1997).

The direct and indirect impacts of land use change affect all of the ecologically significant characteristics of the flow regime, including the magnitude, frequency, timing, duration, and rate of change of discharge conditions. These impacts have particular implications for aquatic and riparian organisms (Postel and Richter 2003). Ecological responses to these impacts are many and varied (Table 4).

Table 4. Ecological responses to alterations of varying flow components. (Adapted with permission from Poff et al. 1997, copyright University of California Press.)

Flow component	Specific alteration	Ecological response
Magnitude and frequency	Increased variation	Washout or stranding or both Loss of sensitive species Washout of organic matter Life cycle disruption Altered energy flow
	Flow stabilization	Invasion or establishment of exotic species leading to local extinction and altered communities Reduced water and nutrients to floodplain plants Encroachment of vegetation into channels
Timing	Loss of seasonal flow peaks	Disrupt cues for fish spawning, egg hatching, and migration Loss of fish access to off-channel habitat and refuge Modification of food web structure Reduction of riparian plant recruitment Invasion of exotic riparian species Reduced plant growth rates
Duration	Prolonged low flows	Concentration of aquatic organisms Reduction or elimination of plant cover Diminished plant species diversity Desertification of riparian community Physiological stress leading to reduced plant growth, morphological change, or mortality
	Altered inundation duration Prolonged inundation	Altered plant cover types Change in vegetation functional type Tree mortality Loss of riffle habitat for aquatic species
Rate of change	Rapid changes in river stage	Washout and stranding of aquatic species Increased stream bank failure
	Accelerated flow recession	Failure of seedling establishment

Finally, changes in climate triggered by human activity have far ranging effects on the flow regimes of even pristine and relatively undisturbed watersheds. While the details of observed changes in temperature and precipitation in the western United States continue to prove challenging for climate change scientists to decipher, the unquestionable trend of global warming has led to changes in the seasonal timing of snowmelt dominated hydrologic regimes, typically toward earlier spring peak flows and reduced summer base flows (Cayan et al. 2001, Mote 2003).

The stresses on habitat and species caused by human impacts on flow regimes are likely to grow in watersheds throughout the western United States. The high uncertainties associated with climate and land use change predictions currently inhibit our ability to predict, plan, or manage for specific outcomes. However, we can be proactive by planning and designing river

restoration and management projects to be resilient and sustainable,⁵ and to include postproject monitoring and adaptive management that may help account for future changes.

3.3.3. Sediment Regime

The sediment regime describes the supply, transport, exchange, and deposition of sediment within the fluvial system. Sediment dynamics interact with the flowing water to drive channel evolution (see subsection on channel evolution models) and create and renew in-channel and floodplain habitats (Dunne and Leopold 1978) (Figure 7).

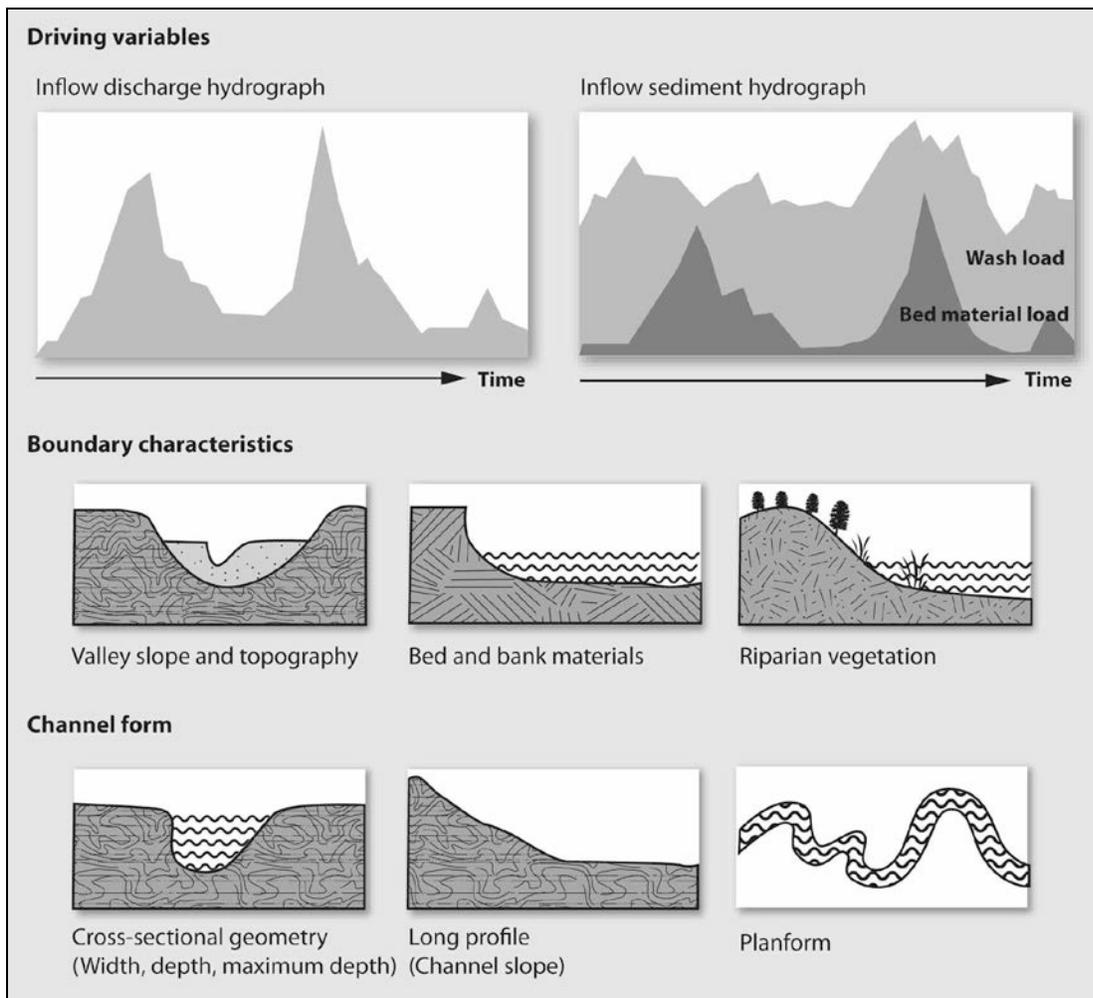


Figure 7. Sediment role in channel form and habitat. Sediment regimes interact with the boundary conditions to drive the stream processes that generate channel form and habitat. (Adapted from an original sketch by David Biedenbarn, U.S. Army Corps of Engineers.)

⁵ Concepts of resiliency and sustainability are paramount to planning and design concepts discussed in Section 4, Project Development. Projects that change or manage river systems to be resilient and sustainable will allow for project evolution as climate changes.

Schumm (1977) characterized three primary stream process domains in fluvial systems: the sediment supply zone, sediment transfer zone, and sediment storage or deposition zone (Figure 8). While such a characterization is simplified and schematic, it serves as a template within which to examine the significance of the sediment regime to river projects and management.

While median particle size (D_{50}) is the property most commonly used to describe stream sediments (Table 5), attributes such as shape and density are also relevant (Figure 9). For example, particle shape affects how tightly grains pack together in the channel bed and how quickly they fall back to the bed after being lifted into the flow.

Overall, particle characteristics such as size, shape, and density help determine the sediment-related characteristics of channels, bars, and floodplains, which include sorting, layering, packing, porosity, permeability, and imbrication. All of these parameters (rather than just grain size) affect sediment transport and storage in stream channels, and thus are important in understanding the sediment regime.

Especially along rivers with gravel and cobble beds that provide essential habitat for fish, understanding the sediment dynamics of natural and degraded streams is important. If a project seeks to restore degraded bed habitat through, for example, gravel augmentation, a thorough understanding of the distributions of particle size and shape for existing conditions and for any material that is added to the stream is needed in order for restoration to be most effective.

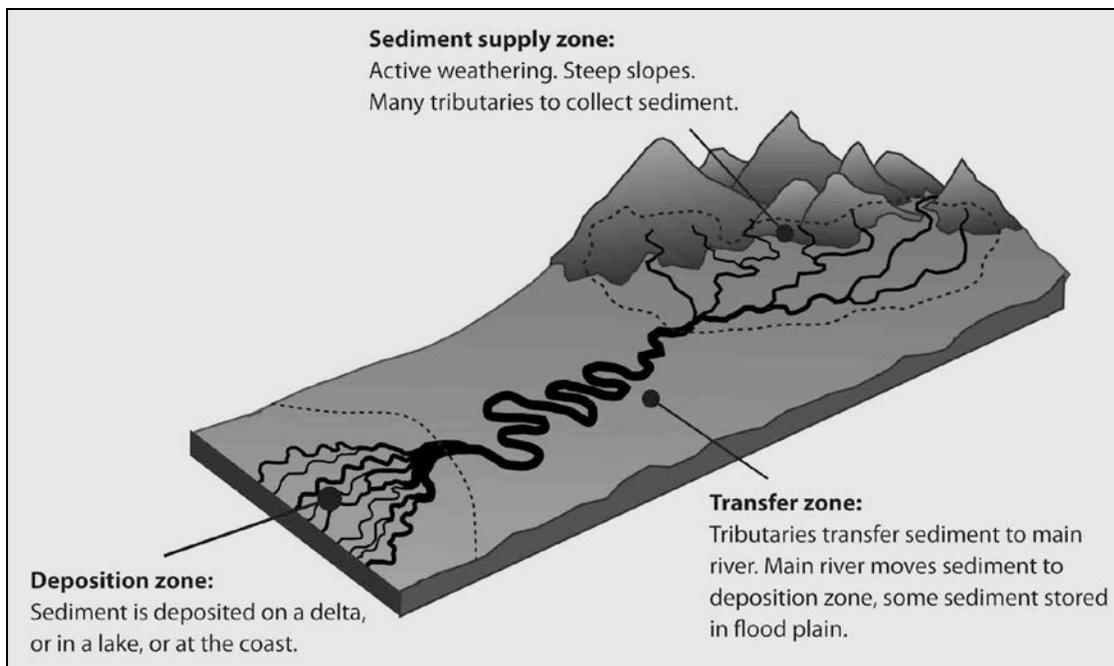


Figure 8. Process domains in the fluvial system. Process domains refer to segments within a fluvial system that are governed by the same general fluvial and geomorphic processes. Domains in a river basin can be generally characterized as governed by sediment inputs, transfer of sediment down stream, or deposition of sediments. (Adapted with permission from Schumm 1977, copyright Wiley.)

Table 5. Wentworth scale for sediment particle size. Logarithmic scale of sediment particle size related to common name of sediment size.

Millimeters	phi	Name
256	-8	Boulders
128	-7	Cobbles
64	-6	Cobbles
32	-5	Cobbles
16	-4	Pebbles
8	-3	Pebbles
4	-2	Granules
2	-1	Very coarse sand
1	0	Coarse sand
0.5	1	Medium sand
0.25	2	Fine sand
0.125	3	Very fine sand
0.063	4	Coarse silt
0.031	5	Medium silt
0.0158	6	Fine silt
0.0078	7	Very fine silt
0.0039	8	Clay

The probability of a successful restoration project on a stream that carries a significant sediment load is greatly enhanced if its design is based on a sound understanding of the sediment regime. Furthermore, knowledge of the reach-scale balance between sediment supply and transport capacity is a prerequisite for any sustainable project success.

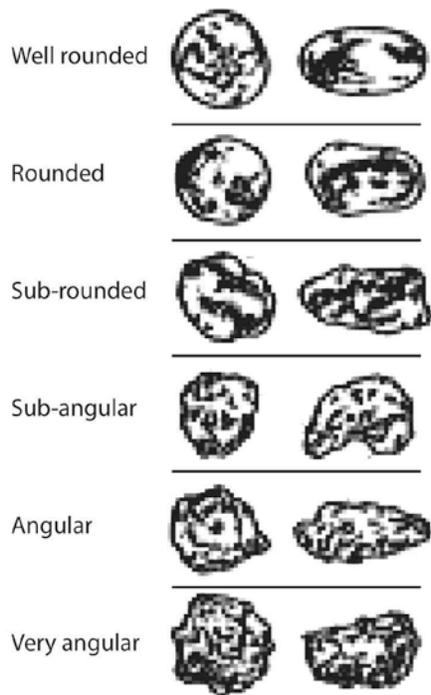
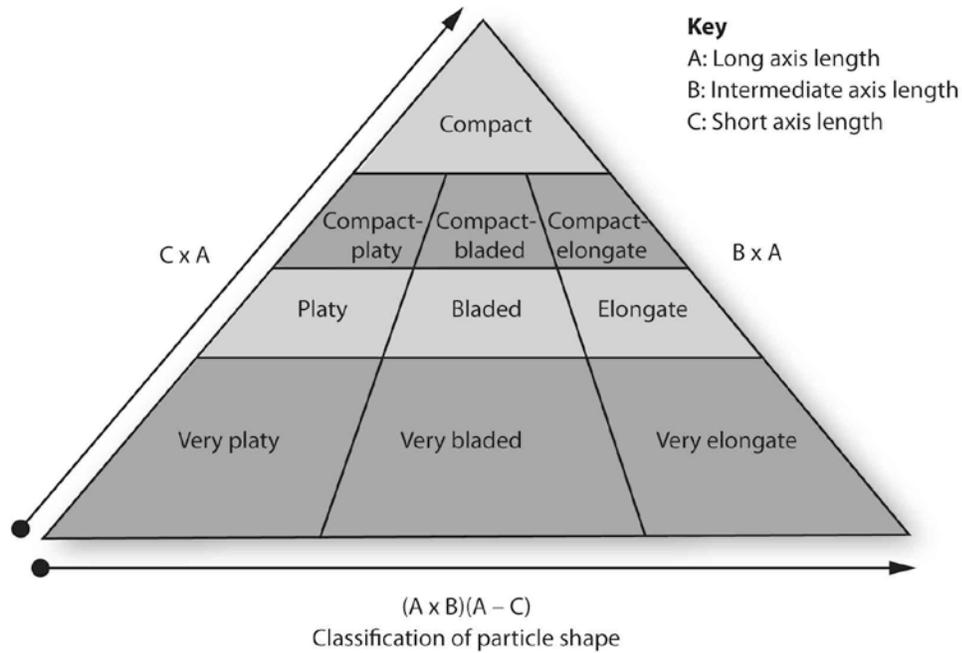
Five elements are key to understanding the sediment regime:

1. The geographical distribution of sediment sources and pathways to the stream.
2. Characterization of the sediment load.
3. Sediment transfer and storage in relation to channel morphology.
4. Anthropogenic influences on sediment dynamics.
5. The sediment balance, relating sediment transport capacity to the sediment supply.

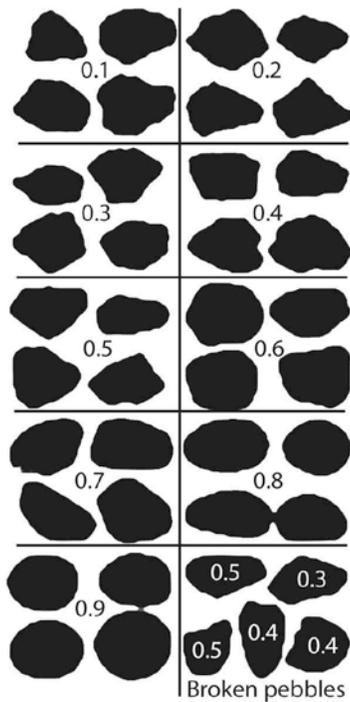
Each of these elements is discussed in the following five-step guide to investigating and understanding the sediment regime of river systems and the reach-scale sediment balance of stream channels.

Step 1: Geographical distribution of sediment sources and pathways

Establishing the geographical distribution of sediment sources and the processes and pathways by which sediment enters the channel system constitutes the first step in understanding the sediment regime of the river system (Reid and Dunne 1996). Sediment sources in the watershed include loose material stored in and at the foot of hill slopes (colluvium) and sediment stored in floodplains, channel banks, or the channel bed (alluvium). Figure 10 provides a



Images for the visual assessment of sand grain roundness



Images for the visual assessment of pebble roundness

Figure 9. Properties of sediment particle shape. Particle shape descriptors include angularity, elongation, and roundness. They influence how quickly particles settle to the bed after being mobilized and how closely particles pack together.

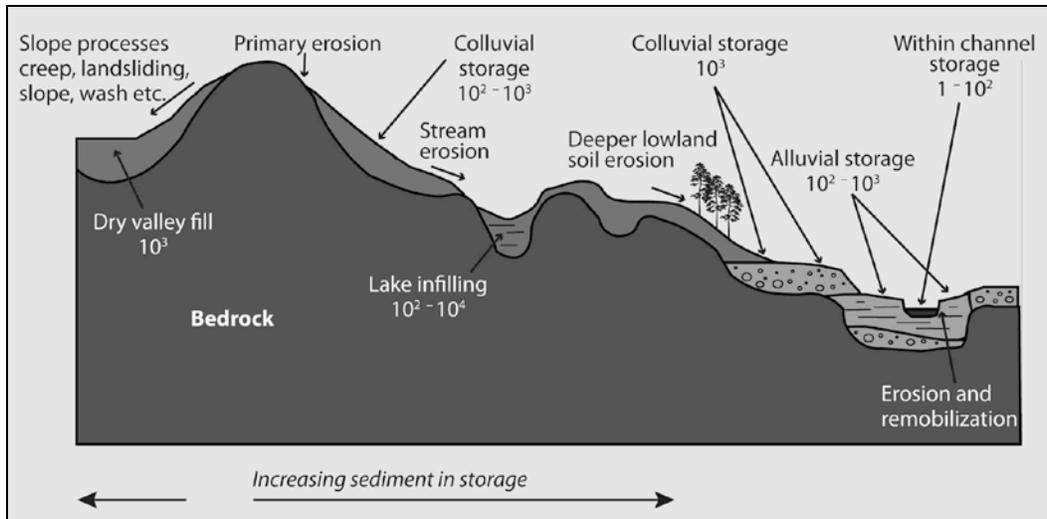


Figure 10. Sediment sources and typical storage times (years) in the watershed and river channel. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

schematic representation of sediment sources and pathways. The processes delivering sediment to the channel include:

- hill slope processes, such as rock fall, landslide, creep, and solifluction;
- debris flows;
- slope wash erosion of slope and colluvial deposits;
- sheet erosion by surface runoff (especially in arable fields); and
- rilling and gullying.

The pathways and processes by which sediment enters a stream system are strongly affected by the physical proximity of the source to the channel (Figure 11). When hill slopes and channels are closely coupled, sediment may travel directly from its source to the stream channel in one event only (A in Figure 11). More commonly, sediment is stored at intermediate locations in the landscape for long periods, from which it is subsequently eroded (B and C in Figure 11). Sediment may remain in storage in the watershed for long periods (centuries or millennia) awaiting suitable events to erode and carry it to the stream (Madej and Ozaki 1996). However, once sediment reaches the stream, its residence time within the channel is usually much shorter (years or decades) (Figure 10). In this respect, the fluvial system may be regarded as a jerky conveyor belt because sediment moving through a watershed spends long periods in storage between transport events.

Not all parts of the sediment transfer system are equally jerky; the events that actually move sediment to the stream from the watershed may be episodic (high in magnitude, but infrequent in occurrence) or semicontinuous (low in magnitude, but frequent in occurrence). For example, a landslide may occur only once in 100 years, but it can supply a very large volume of sediment to the channel (Sutherland et al. 2002). Conversely, soil erosion may occur in an arable field during every rainstorm, but the volume of sediment supplied to the stream during each

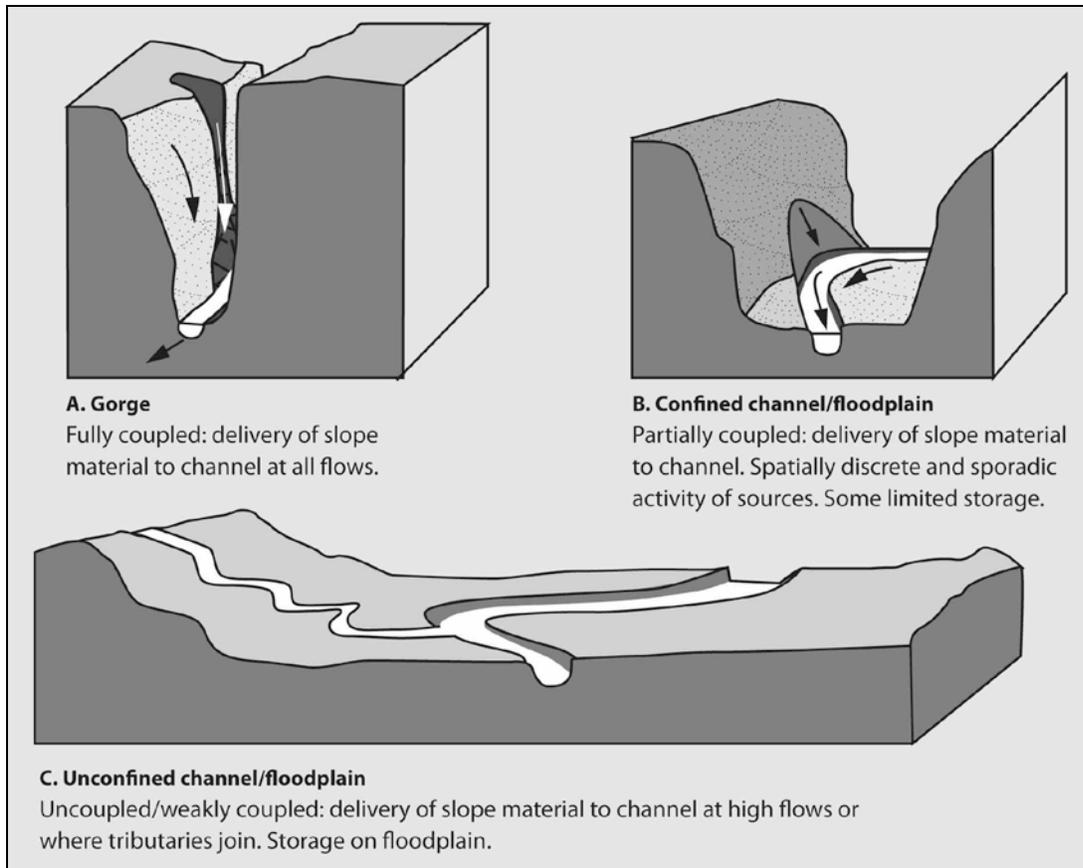


Figure 11. The degree of coupling, or proximity and connection, between sediment sources in the catchment and channel influences the nature of events that supply sediment to the fluvial system. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

event is relatively small. Sediment is natural in all watersheds, but resource industries (farming, forestry, quarrying, etc.) and watershed development (roads, urbanization, etc.) often add anthropogenic sediment sources that tend to significantly elevate rates of supply (Figure 12).

Sediment is also entrained from within the channel by flows that are strong enough to erode the boundary materials, as described later in this section. Entrainment may occur as a result of channel bed scour, erosion of banks, or remobilization of channel bars (Figure 13). Once sediment is supplied to the channel or entrained from its boundaries, it becomes part of the sediment load.

Step 2: Characterization of the sediment load

Characterization of the sediment load and understanding how the load moves through the channel is the second key step in understanding the sediment regime. Two definitions exist for characterizing the various components of total sediment load:

- mode of transport (suspended or bed load) and
- method of measurement (measured or unmeasured).

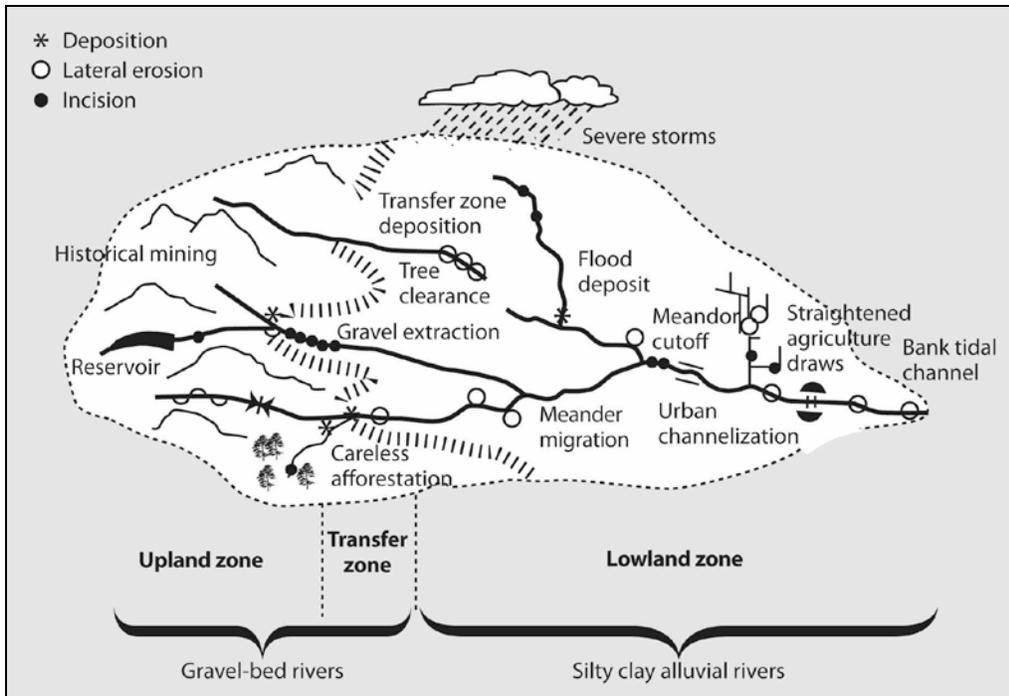


Figure 12. Natural and anthropogenic processes affecting sediment sources. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

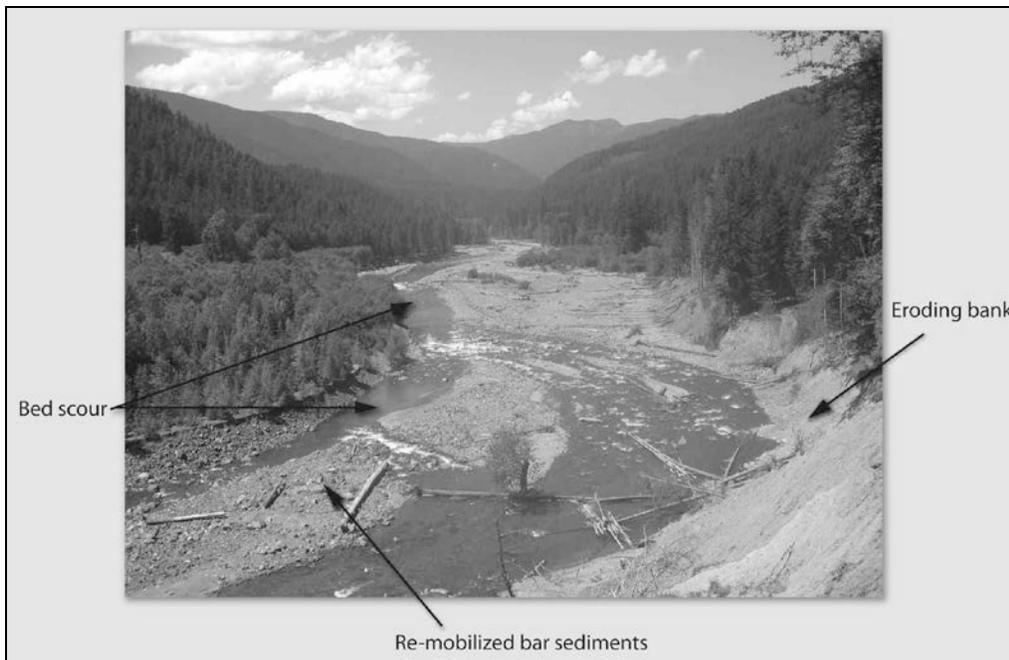


Figure 13. Primary sediment sources within the channel. Within a channel, sediment may be scoured from the channel bed, eroded from the channel banks, or remobilized from channel bars. (Photo of Elwha River, Washington, by Tim Beechie.)

Mode of transport—Describing the sediment load is often related to the mechanics of sediment transport. Bed load is that part of the total load that travels in constant or frequent contact with the bed. This includes relatively coarse grains that roll, slide, or bounce (saltate) along the bed. The suspended load, that portion of the total sediment load that is suspended in the water column, is made up of finer particles that are carried within the water column above the bed and only come into contact with the bed infrequently. The distinction between bed load and suspended load is based on how the weight of the grains is supported. The submerged weight of bed load is supported by solid-to-solid contact with the bed, while the submerged weight of suspended grains is supported by turbulence in the flowing water (Bagnold 1966). In most streams, the great majority of the sediment load moves in suspension, with bed load accounting for only 10–15% of the total load and as little as 5% in U.S. West Coast rivers (Collins and Dunne 1990). However, the percentage varies depending on discharge. For example, during moderate flows, sand may be part of the bed load, thus increasing the bed load percentage, while at high flows sand becomes part of the suspended load and the bed load percentage declines.

Even though it may comprise a small proportion of the total load, bed load is the material making up bedforms. In sand-bed streams, bedforms characteristically evolve from ripples to dunes, plane beds, standing waves, and anti-dunes as the available stream power and intensity of bed load motion increase (Figure 14). In gravel and cobble bed streams, bedforms include small-scale patches of coarser particles, termed pebble clusters, and large-scale bar features, termed riffles, interspersed with pools (Figure 15, panel A). In steep, very coarse bedded streams, boulder steps occur with intervening pools between them (Figure 15, panel B). Bedforms are a key determinant of habitat in streams of all types. The bed load interacts with and influences channel form directly, while the suspended load is less important in forming channel features. However, suspended load plays an important role in:

- accretion on the floodplain,
- accretion in lateral vegetated margins,
- strongly depositional reaches, and
- water quality.

Method of measurement—The other way that the total sediment load may be classified is according to the method used for measurement. Historically, the sediment load in American rivers has been measured using a DH-48 depth-integrating sampler developed by the U.S. Geological Survey (Figure 16, left) (IARBC 1961). This device takes a sample of the suspended load from the water surface down to about three inches above the bed. The DH-48 therefore misses the bed load and that portion of the suspended load that is carried close to the bed. Consequently, the sediment load in the stream that is computed based on sampling using a DH-48 should be described as the measured load, while that which is missed constitutes the unmeasured load. In the 1970s, a device designed to sample the missing sediment transported in the lowest 3 inches of the water column was devised by Ed Helley and Wink Smith of the USGS. The Helley-Smith sampler (Figure 16, right) is strictly speaking an unmeasured load sampler. However, it is often referred to as a bed load sampler, which is not necessarily correct as (depending on the mesh size in the catch bag) the Helley-Smith may also retain the near-bed portion of the suspended load (Helley and Smith 1971).

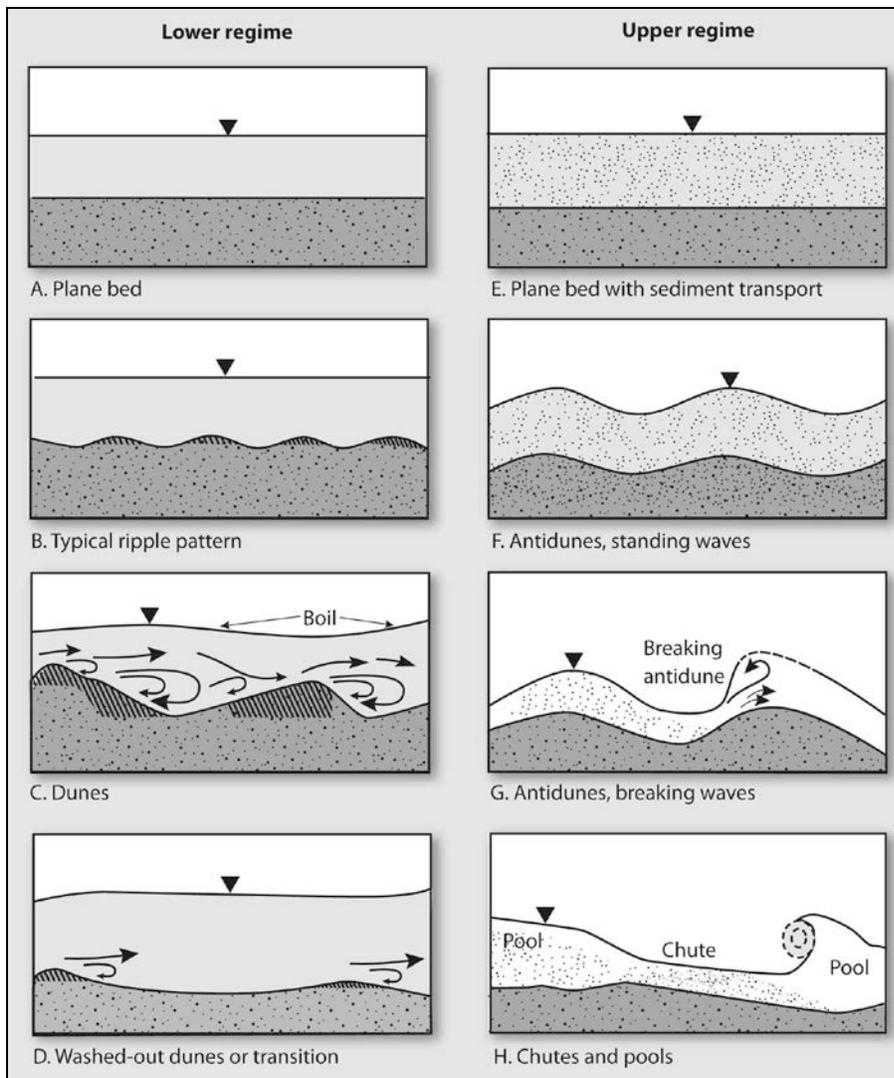


Figure 14. Bedforms in sand bed streams evolve with increasing stream power (increasing continuously from A to H) and vary depending on the amount of bed load. (Adapted from Simons and Richardson 1966, U.S. Geological Survey.)

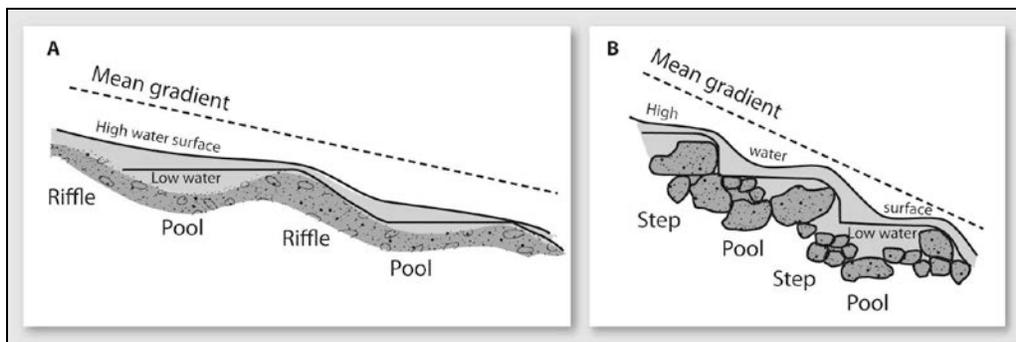


Figure 15. Bedforms in gravel and cobble bed streams include small-scale riffles interspersed with pools (panel A). Boulder bed stream bedforms (panel B) feature boulder step and pool sequences. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

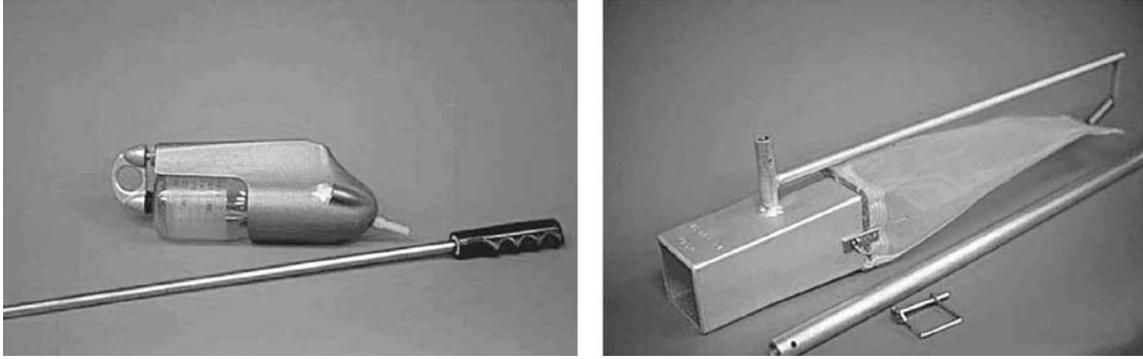


Figure 16. DH-48 suspended load sampler (left) and Helley-Smith bedload sampler (right). (Reprinted from Davis 2005, U.S. Geological Survey.)

Typically the suspended sediment loads and concentrations reported by USGS are extrapolations of field measurements of suspended sediment to cross-sectional averages, using empirical relationships. Classifying the load by measurement technique is important when applying sediment transport equations to predict the rates of transport. When calibrating a sediment transport equation using field data, the load measured in the field must be clearly related to the load predicted by the chosen equation. This is the case because some equations predict the bed load, others the suspended load, and yet others the total load. Clearly the load measured using a DH-48 cannot be used to calibrate a bed load equation. Hence comparability between measured and calculated loads is essential in order to produce a sound calibration and reliably model sediment movement.

Step 3: Transfer and storage of sediment in the river system

Conceptually describing sediment transfer and storage processes and how they have evolved over the geomorphic history of the watershed is the third key step in understanding the sediment regime. Understanding the relationship between water flow and sediment transport demands detailed measurements of channel form, flow hydraulics, and sediment load characteristics that are expensive and time consuming. To be reliable, data must be collected over the entire range of flows and for prolonged periods; this happens only at long-term monitoring stations scattered thinly across the United States. Field data on sediment transport is rarely available for even one site along a study river and often no data exist at all. Since difficulties arise when trying to understand the mechanics of sediment transport using just one or even a few points in the system, a more useful focus is on understanding how sediment is transferred through the fluvial system at the watershed scale. Sediment transfer is intimately linked to sediment storage; knowledge of both is essential for understanding sediment dynamics in a river system, as well as for the selection of appropriate management or restoration actions.

The domino effect associated with sediment transfer was first characterized by Newson in the 1980s, and is illustrated in Figure 17 (Sear et al. 2003). This effect encompasses the entire watershed and shows the importance of continuity and connectivity in the sediment transfer system. For example, a landslide in the upland supply zone triggers the domino effect throughout the river system as sediment travels through, exchanges with, and is stored in each of the different zones.

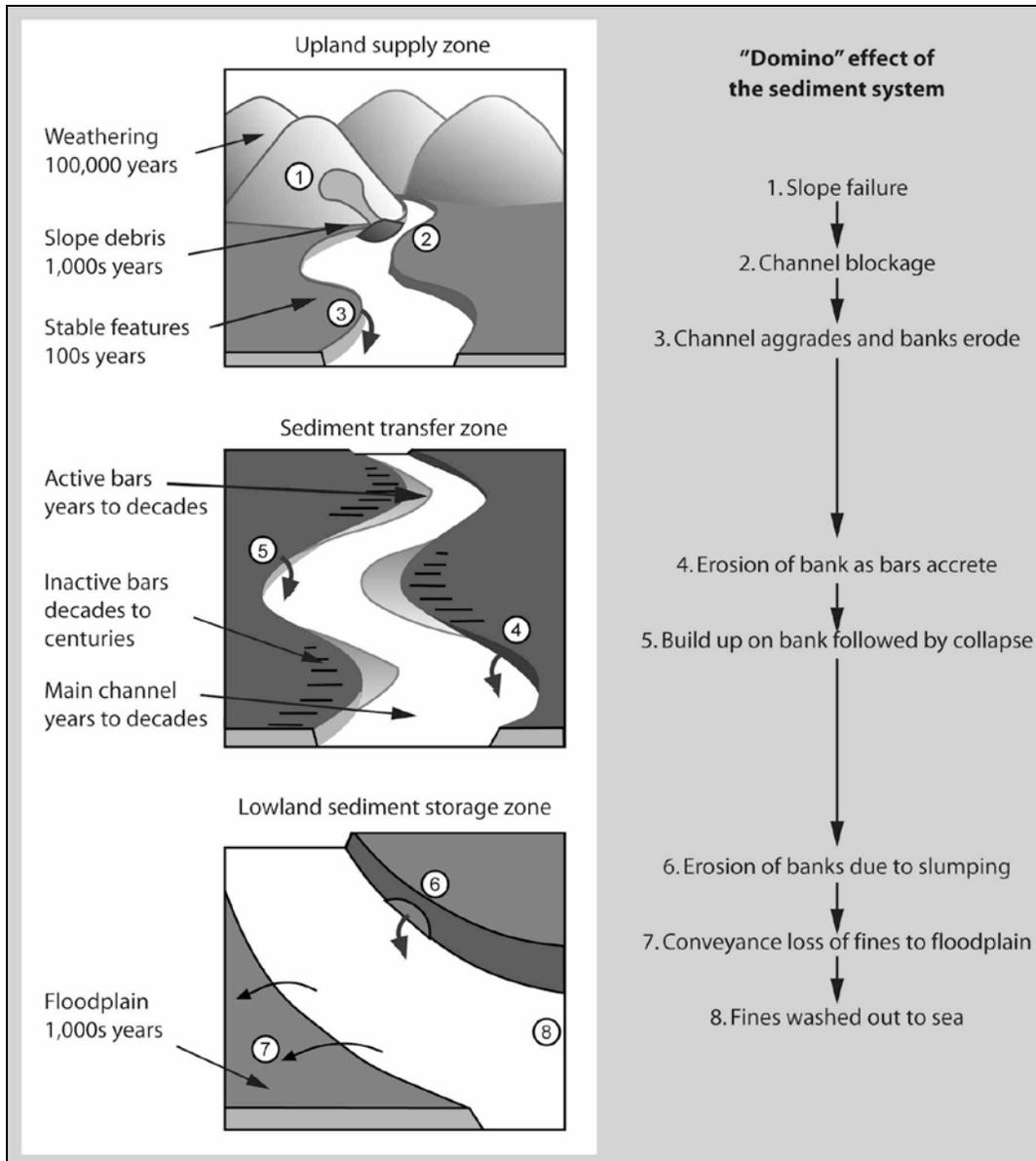


Figure 17. Sediment connectivity in the river system. The domino effect of sediment transfer depicts the transfer of sediment from an upland supply zone to a midwatershed sediment transfer zone, where sediment storage residence time is on the order of years to decades, and from there to a lower watershed lowland sediment storage zone, where sediment storage time may be on the order of thousands of years. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

While numerically modeling the sediment transfer system for an entire watershed is seldom possible, conceptualizing and qualitatively describing sediment transfer is a reasonable goal. This is vital in order to identify sediment sources and the transfer pathways that link them to natural sediment sinks, such as the floodplain, fans, deltas, and estuaries.

Finally, characterizing the feedback loops that operate between sediment dynamics and morphological channel adjustments is also vital in understanding the sediment regime of a river

system. As illustrated in Figure 18, the sediment and flow regimes of a river system interact to drive channel morphology; channel adjustments then initiate feedback loops occurring over different spatial and temporal scales.

Step 4: Anthropogenic influences on sediment dynamics and channel morphology

Identifying and characterizing anthropogenic activities that influence sediment dynamics and channel morphology is the fourth key step in understanding the sediment regime of a river system. In the western United States, sediment regimes have been altered by development, land use, river regulation, and in-channel engineering interventions. Construction of dams, diversions, undersized culverts, and road embankments has created artificial sediment sinks. Overwidening and dredging of stream reaches for on-line flood control and construction of artificial flood basins or detention structures for off-line flood control have also increased sediment storage. These human alterations introduce additional, unnatural storage capacity in the sediment transfer system and may completely or partially break the connection between sediment sources upstream and natural storage features downstream. Such disruptions in sediment transport processes may trigger unintended and adverse responses in stream morphology (its channel and floodplain) and associated stream habitat.

In addition, unnatural sediment exports from the river system, for example, aggregate mining or the transfer of landslide material that has intersected a road and is hauled to an upland

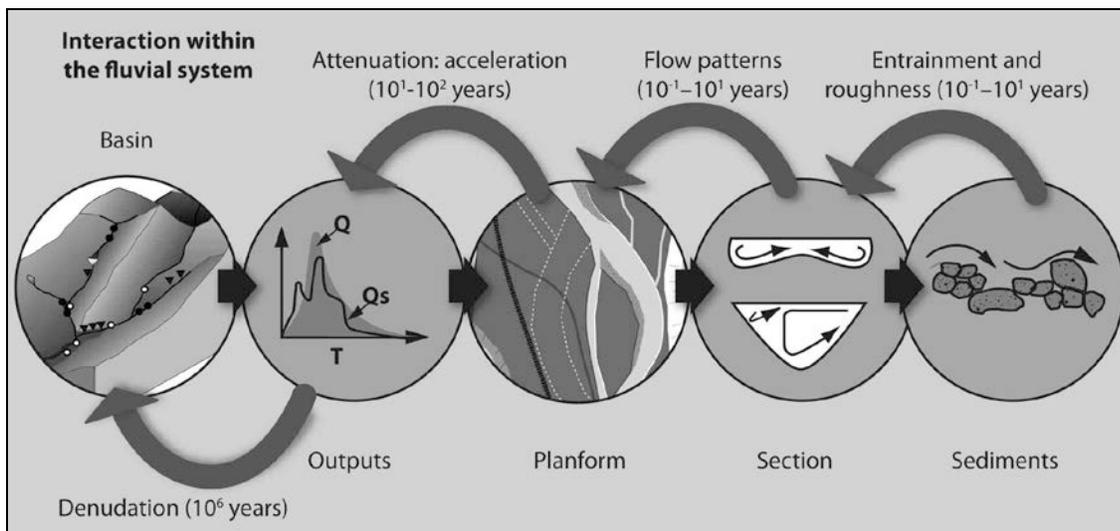


Figure 18. Drivers and feedback loops operating in the sediment transfer system illustrate the importance of the sediment regime. The stout horizontal arrows indicate the movement of sediment downstream through the river system and how this controls the planform, section, and sediment characteristics at the reach and site scales. The curved arrows illustrate how morphological adjustments that occur in response to the sediment driver in turn alter the sediment, section, and planform attributes of the channel and how, over longer time periods, these morphological responses feed back to affect the flow and sediment regimes. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

site, have the potential to disturb the river's sediment regime. Therefore, when studying the sediment regime, all activities involving sediment removal must be identified and analyzed. Since perturbations to the sediment regime may have long lasting effects in river systems, the history of land use and other human activity in a watershed must also be accounted for. Further discussion of anthropogenic impacts and associated channel response is provided in subsection 3.5.2, Anthropogenic Disturbance.

Step 5: The sediment balance

The final step in understanding the sediment regime is to determine the sediment balance for the project site or reach. In a dynamically stable alluvial reach, the local capacity of the flow to transport bed material load is delicately adjusted to match the supply of bed material load from upstream. While short-term and event-related imbalances are expected (and are beneficial in disturbing and renewing habitat), on average the sediment output balances the sediment input and the form of the channel, including its sediment features, does not change markedly through time. When implementing a restoration project in a dynamically stable reach, the risk is of creating an imbalance that leads to morphological succession away from the previously stable condition through channel changes that are either erosion led (if the postproject transport capacity exceeds the supply of bed material load) or deposition led (if the postproject transport capacity is insufficient to carry the supply of bed material load from upstream).

When designing management and restoration schemes for stable reaches, the desirability of matching the sediment transport capacity to the sediment supply is increasingly recognized and forms the basis for some contemporary design methodologies (Soar and Thorne 2001). The stability and sustainability of the channel and habitat in the project reach as well as that of the entire watershed must be considered in project design. The destabilizing effects of a restoration scheme that disturbs the sediment balance translate downstream (through either sediment starvation or an excessive sediment supply to the next reach) and upstream (through headward migration of scour or nickpoints). Given the considerable uncertainty inherent in assessment of current and future channel stability, restoration projects should 1) include features that insure stability of key aspects of the project (often unsuitable because such stability is detrimental to ecological processes), 2) be resilient in the face of future instability, or 3) be implemented with all parties fully aware of the risks of failure of project objectives. (Appendix B, Design of Stream Channels and Streambanks, and Appendix C, Management Alternatives, provide further discussion of design and management strategies and alternatives.)

However, achieving a zero sediment balance is not a legitimate design goal for all management schemes. For example, in streams that cross an alluvial fan, the natural sediment balance is non-zero, as the fan is a depositional feature built and maintained by the net accumulation of the relatively coarse fraction of the sediment load supplied from upstream. Thus seeking a zero sediment balance is inappropriate in the geomorphic setting of an alluvial fan. (The Alluvial Fan subsection below describes the challenges posed by the morphologies and dynamics of streams on alluvial fans.) Instead, stream corridors on a fan must be designed to provide the space necessary for net sediment storage and associated aggradation and, if possible, periodic avulsion of the alluvial channel. This means that any levees must be set back as far as is practical and channel boundary constraints should be avoided wherever possible. Again, the importance of such measures extends beyond the project reach. For example, if the

capability of the stream on a fan to transport coarse sediment is enhanced, the natural trend for that material to be stored in the fan will be lost and the coarse material will instead be transferred further downstream to trigger aggradation and channel instability in a previously stable reach.

In conclusion, sediment transfer and the morphological features it drives are of great significance to habitat. Therefore, understanding the sediment regime and reinstating its natural functions of sediment transfer and storage are crucial to restoring sustainable habitats in environmentally degraded river systems.

3.3.4. The Influence of Upland Vegetation

At the watershed scale, vegetation affects the basin hydrology and the flow regime by influencing interception, infiltration, and evapotranspiration of rain and snow, and the sediment regime by binding the soil and reducing surface erosion.⁶ The difference between the amount of water that falls in a watershed and that runs off into streams or percolates into the water table is explained primarily by evapotranspiration, which dominates the water balance of most watersheds. In the conterminous United States, more than two-thirds of precipitation is returned to the atmosphere through evapotranspiration (Dunne and Leopold 1978), though regional variations may be pronounced (Wolock and McCabe 1999). Vegetation also affects hill slope erosion and mass wasting (and resultant sediment inputs to the river system), drainage density (affecting the flow regime), and water chemistry (affecting nutrients). Because of its strong influence on the flow and sediment regimes—the two dominant controls of reach-scale channel form and geomorphic processes—vegetation is often presented as a major determinant of stream condition and habitat (Gurnell et al. 1995). In fact, in some conceptual models of watershed controls, vegetation is considered to have the same level of influence as geology and climate (Beechie et al. 2003).

Land use practices invariably alter the vegetative character of a watershed. Historic forestry practices not only removed forests, thereby affecting the hydrologic regime by altering interception, infiltration, and evapotranspiration rates, but also created efficient vectors via road networks for fine sediment transfer from readily available and erodible soils no longer protected by the forest canopy (Meehan 1991). Further, following timber harvest, conversion of some forested watersheds to agricultural or other land uses typically results in permanent changes to vegetation as well as to roads and drainage patterns.

In more arid regions, grazing is the dominant impact on vegetation, thus acting as a watershed control on runoff and soil erosion, and has a remarkably similar effect to forest logging in increasing channel-forming discharges and sediment loads in rivers (Platts 1991). In regions historically dominated by shrub steppe and grasslands, grazing of natural vegetation has impacted watershed flow and sediment regimes for nearly two centuries (Mount 1995). For example, research shows that grazing of streambanks causes sedimentation of spawning gravels, reductions in stream shading, significant changes to channel form (such as overwidening), increased stream temperatures, and channel incision (NPPC 1986, Elmore and Beschta 1987, Belsky et al. 1999).

⁶ Vegetation also plays a major role at channel margins and within the channel. These influences are discussed separately in the Riparian Vegetation subsection below.

Urbanization produces one of the most dramatic impacts on watershed vegetation: replacing natural vegetation, forest plantations, or crops with impermeable surfaces, which reduce infiltration capacity and fundamentally change the character of the flow regime. Outcomes of urbanization typically include dramatically reduced base flows and flashier flood flows (shorter times to peak, higher peaks, shorter recession curves), although the severity of the impacts varies regionally and with the size of the watershed (Booth and Jackson 1997).

In summary, changes in vegetation have direct and indirect impacts on the ecologically significant characteristics of the flow and sediment regimes. These impacts have serious implications for aquatic, riparian, and floodplain habitats and ecosystems (Postel and Richter 2003).

3.4. Stream Processes and the Channel Boundary

The physical form of a stream is a channel that conveys water, sediment, and organic matter from its contributing watershed to a larger downstream river system,⁷ a closed basin, or the sea. An alluvial stream channel is self-formed, that is, the boundary materials making up its bed and banks are composed of the same materials that it routinely transports, and the stream is free to adjust its form, dimensions, and position in the floodplain through the action of processes driven by the flow and sediment regimes.

We have discussed processes operating at the scale of landscapes and watersheds that determine channel form and its associated habitat. In this subsection we examine stream processes and channel boundary characteristics and controls that affect habitat at a reach scale. First, we focus on factors of force and resistance that determine basic channel capacity, including sediment transport processes and flow resistance. Next, we discuss equilibrium and stream channel adjustment, the processes that adjust the channel to accommodate changes in watershed inputs. Finally, we examine the role of channel boundary characteristics (bed substrate, bank materials, and riparian vegetation) and boundary controls (such as bedrock, large wood, and beaver [*Castor canadensis*] dams) as they influence channel form and associated habitat.

3.4.1. Force and Resistance in Stream Channels

Since habitat is intimately linked to stream morphology, the factors that influence channel form also determine habitat. Both force and resistance are at play in shaping stream channels: force is primarily determined by the river flow and usually increases with increasing discharge, while resistance is dependent primarily on the roughness associated with channel bed and banks.

Forces driving sediment transport

The forces associated with flow in the channel move sediment particles along the bed (bed load) or within the body of the flowing water (suspended load), which in turn shapes the channel bed. For sediment transport to occur, the flow must be sufficient to entrain the available sediment or, in a similar sense, some of the available bed material must be of a size that can be

⁷ While it is tempting to differentiate the terms stream and river based on scale, there is no size threshold at which a stream becomes a river, other than the convention that rivers are considered larger than streams.

entrained by the flow. Scientists have developed numerous equations to measure and predict the ability of the flow to move sediment, using stream parameters such as velocity, boundary shear stress, and stream power to predict the transport rate for a given particle size or specified particle size distribution (Simons and Senturk 1992, Julien 1995, Knighton 1998).

Velocity distribution refers to the variability of flow velocity within the channel. The velocity distribution is represented by a velocity profile or the range of velocities across the channel, a key variable in determining the boundary shear stress acting on the bed and banks.

Boundary shear stress refers to the fluid force per unit area acting tangentially on the bed and banks of the channel. The equation for boundary shear stress is

$$\tau = \gamma RS \quad (1)$$

where τ is the shear stress exerted by the flow, γ is the specific weight of water, R is the hydraulic radius, and S is the energy slope. The cross-sectional averaged boundary shear stress is proportional to the depth of flow multiplied by the channel slope. Boundary shear stress is a key parameter in determining the sediment transport competence of the channel. Competence reflects the ability of a stream to move a particular size of sediment.

Stream power as developed by Bagnold (1966) is a measure of the energy available to move sediment in a stream channel and is a function primarily of discharge and slope. Unit stream power represents the power exerted on a unit segment of the channel cross section, and is equal to the boundary shear stress times velocity, or

$$\omega = \gamma DSV \quad (2)$$

where ω is unit stream power, γ is the specific weight of water, D is depth, S is slope, and V is mean velocity. Unit stream power determines the sediment transport capacity of the stream channel. Capacity is a measure of the rate at which a stream can transport volumes of sediment.

These equations attempt to assess the flow's ability to move sediment, or the force required for the flow to shape the channel. However, significant uncertainty exists concerning the applicability and accuracy of available sediment transport equations, especially when they are used to predict the sediment load without calibration against reliable field data from the stream in question. Predictions of the sediment load based on uncalibrated application of sediment transport equations are, at best, indicative and may be off by as much as one or two orders of magnitude. Appendix A, Investigative Analyses, describes this in greater detail.

Flow resistance

Elements that add hydraulic roughness to a stream channel affect flow velocity and depth, thus affecting measures of force such as shear stress and stream power. Flow resistance is a function of a number of factors: the depth of flow; the size, shape, and packing arrangement of bed material; the size and shape of bedforms (riffles, pebble clusters, dunes, ripples); the cross-sectional shape of the channel; the abruptness of bends; the presence of constrictions; and the height, density, and stiffness of aquatic and bank vegetation (e.g., woody vegetation on banks creates more flow resistance than herbaceous vegetation). In larger channels, bedforms become

the dominant variable influencing channel roughness, as the roughness of bed grains and bank vegetation becomes smaller relative to channel dimensions and contained flow (Barnes 1969).

Flow resistance equations describe the relationship between channel roughness and the mean velocity of the flow. The most widely used flow resistance equation is the empirically derived Manning equation (in SI units⁸) for uniform flow in an open channel (Chow 1959),

$$V = (\phi/n) R^{2/3} S^{1/2} \quad (3)$$

where V is mean velocity; ϕ is 1 in SI units (1.49 in English units); n is Manning's roughness coefficient, an empirically derived measure of the resistance to flow in the channel; R is the hydraulic radius, which is the ratio of the cross-sectional area of the channel to the wetted perimeter; and S is the water surface slope. Manning's roughness coefficient is derived empirically when all other variables can be measured. Alternatively, tables (Chow 1959) or photographs (Barnes 1967) are customarily used to estimate Manning's n for situations where the other variables are unknown.

The Manning equation is the basic relation at the heart of many analytical design methods, particularly those describing hydraulic forces and flow characteristics. Manning's roughness coefficient, in particular, is important because it can greatly affect the output of models or equations. Where channel dimensions and flow are known, the roughness coefficient can be calculated. However, for most channel design, dimensions are modeled, and so the roughness coefficient must be estimated (see the Hydraulic Analyses subsection of Appendix A).

Large wood or log jams may best be viewed and modeled as obstructions to flow or reductions of cross-sectional area rather than simply increased roughness. Intentional removal of snags and large wood from natural channels has reduced flow resistance or increased cross-sectional area, thereby disturbing relationships between stream processes, channel form, and habitat.

3.4.2. Equilibrium and Channel Adjustment

Through time, the channel of an alluvial stream evolves to form characteristic patterns and dimensions that are adjusted to the inputs of water, sediment, and organic material as they interact with channel boundary materials. Given sufficient time, and if the watershed controls and boundary characteristics remain unchanged, the resulting cross-sectional shape and planform of the channel reflect a balance between the inputs of water and sediment, the action of stream processes, and the erosion resistance of the boundary materials and vegetation (Figure 3). Under these conditions, the alluvial stream conveys the water and sediment delivered from its contributing watershed without appreciable aggradation, degradation, or change in width. The stream is then said to have achieved a graded condition and be in a state of dynamic equilibrium. As a result, the channel dimensions are stable and its form is that of a regime channel. The

⁸ SI units refers to the International System of Units (meters, grams, etc.), as opposed to English units (feet, pounds, etc.) commonly employed by engineers in the United States. Much of the original research in this area and many common engineering practices have been expressed in English units. However, as we are part of a global scientific community, SI units are preferable.

concept of equilibrium in stream channels is discussed further in subsection 3.6.3, Channel Incision and Evolution.

However, in nature the form and dimensions of a regime channel are rarely static; more often, they adjust continually to changes in the flow regime, sediment regime, or boundary conditions. Lane (1955) expressed the relationship between the discharge of water, Q , the sediment discharge, Q_s , the median bed particle size, D_{50} , and the channel slope, S , in the form of a balance (Figure 19) represented by the expression

$$Q_s D_{50} \sim QS \tag{4}$$

According to Lane’s relation, the stability or trend of adjustment displayed by an alluvial stream depends on the balance between the size and quantity of sediment supplied from upstream, $Q_s D_{50}$, and the power available to transport that sediment downstream, QS . In a stream that is fully adjusted to its flow and sediment regimes, the scales are balanced, the power available is just sufficient to transport the sediment supplied from upstream, and the channel is dynamically stable.

The balance also provides a useful tool for predicting the stream’s response to disturbance or changes in any of the variables. For example, if a landslide increases the amount

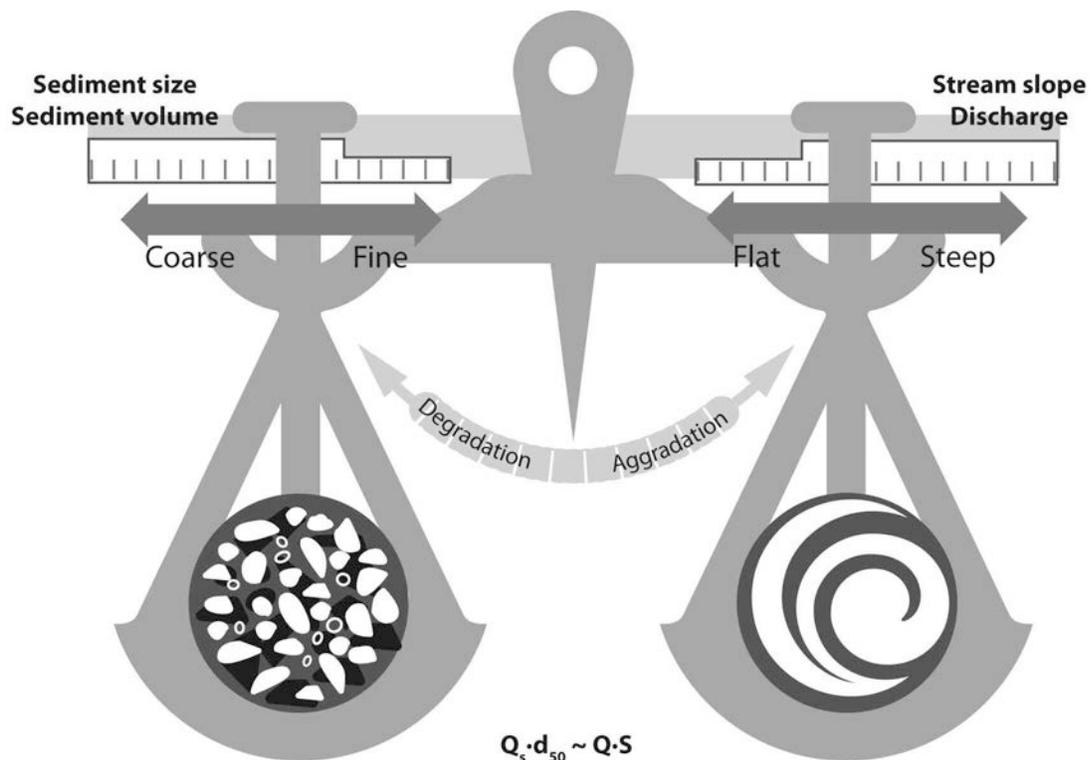


Figure 19. Lane’s balance. Lane (1955) characterized alluvial channel dynamics as a balance between the size and volume of sediment supplied and the power available for transport, a function of stream discharge and channel slope. The balance provides a useful conceptual framework for considering probable channel response to changes in any of the variables.

of sediment supplied from upstream, Q_s , the scale will tilt to the sediment side and the pointer indicates channel adjustment through aggradation. If the water discharge and sediment size remain constant, Lane's balance suggests that aggradation will act to steepen the channel slope, S , thereby increasing the power available to transport sediment, thus restoring the balance and centering the pointer.

Another type of adjustment occurs when a meandering stream channel is straightened, which increases the slope, S , by shortening the length of channel between fixed elevations upstream and downstream. Assuming that discharge, Q , sediment supply, Q_s , and sediment caliber, D_{50} , are unchanged, an increase in slope, S , will tilt the balance to the energy side, moving the pointer to degradation that lowers the channel bed relative to the floodplain and generating channel incision. Lane's balance suggests that degradation will act to reduce the channel slope, S , decreasing the power available to transport sediment, thereby restoring the balance and centering the pointer, though not restoring the previous morphology of the channel and its habitat.

Lane's balance is a simplified representation of stream channel dynamics that considers only some of the variables involved in driving channel adjustments. In reality, there are many more variables at play, which can generally be categorized as independent or dependent. Independent variables include the flow regime, sediment regime, or boundary characteristics. Dependent variables adjust in response to changes in the flow or sediment regime and include the cross-sectional dimensions, planform, and slope of the channel. Additional independent variables include the valley terrain and characteristics of the bank materials.

Adding to the variables represented in Lane's balance, Figure 20 provides a more sophisticated picture of stream dynamics and reveals that, in nature, interactions and feedback loops link the dependent variables. On the outside of the interactive loop are the flow and sediment regimes, which act as independent variables. Within the loop, the dependent variables are depicted with arrows indicating the direction of influence between them. Variables not previously defined are described briefly below:

- Bed material load transport refers to that fraction of the sediment load that is derived from scour of the bed. Its transport affects and is affected by the character of the bed material, as illustrated by the internal feedback loop of selective transport and sediment availability. Changes in the rate of bed load transport relative to supply from upstream generate erosion and deposition that adjusts channel form.
- Character of the bed material is defined by its size distribution, shape, and arrangement into bedforms, which determine mobility. Bed material character also affects flow resistance and is thus a key determinant of the velocity distribution in the channel.
- Channel form refers to the shape of the channel cross section, and is described by its hydraulic geometry. At-a-station hydraulic geometry describes how the cross-sectional channel dimensions vary as a function of discharge. Downstream hydraulic geometry describes how the channel geometry changes longitudinally along the channel at channel-forming discharge (usually taken as bankfull).

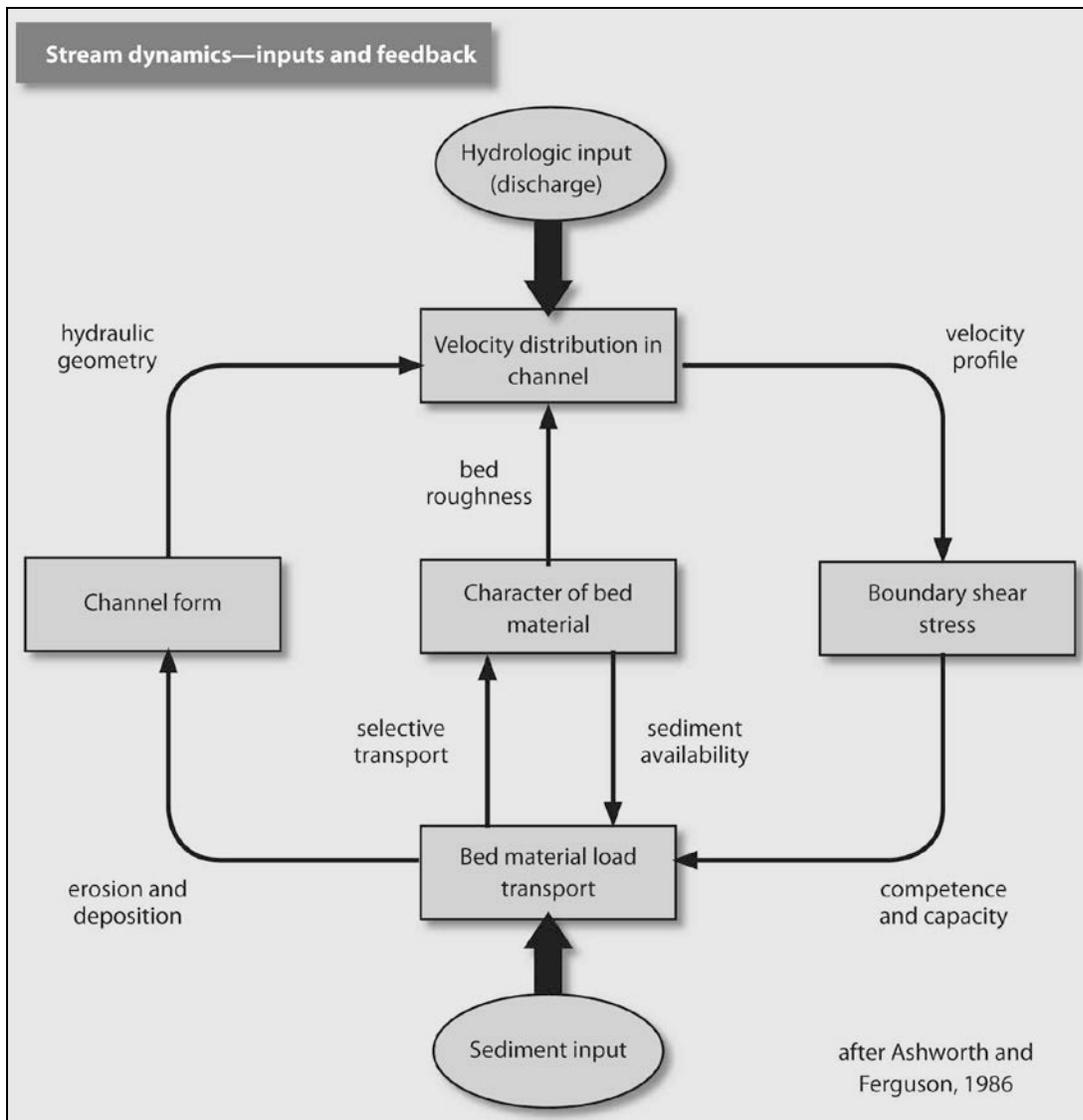


Figure 20. Stream dynamics inputs and feedback. Independent variables include hydrologic and sediment inputs and are not affected by stream processes. Dependent variables adjust to changes in independent or other dependent variables, often forming feedback loops of iterative adjustments among dependent variables. Oval boxes represent watershed inputs; square boxes represent processes and responses. (Adapted with permission from Ashworth and Ferguson 1986, copyright Wiley-Blackwell.)

3.4.3. Channel Boundary Characteristics

Processes of force and resistance in stream channels interact with the materials making up the channel boundaries (comprised of the bed and banks) to initiate, maintain, and adjust the form of the channel. The important boundary characteristics of alluvial stream channels are the size, sorting, and imbrication of the bed material, the physical and chemical properties of the bank materials, and the presence, type, and density of riparian vegetation. These characteristics determine the susceptibility of the bed and banks to erosion, and thus greatly influence channel

form and habitat (Newson 2002, Wiens 2002). Even in fully alluvial streams, natural variability in the properties of alluvium mean that boundary characteristics are nonuniform, generating local variability in channel dimensions and complicating what would otherwise be simple and predictable associations between stream processes and resulting channel forms (Newson 2002).

We discussed the characteristics of bed sediments as they affect boundary characteristics in subsection 3.3.3, Sediment Regime. The following discussion examines bank stability and riparian vegetation characteristics as they affect the channel boundary.

Bank stability

The banks of a dynamically stable alluvial stream that is in regime are adjusted so that they largely withstand the erosive forces applied to them. Under this condition, bank erosion is slow and progressive, matching deposition as the stream meanders. Rapid bank erosion occurs when a channel becomes unstable, taking it out of the regime condition. Rapidly eroding banks produce bank retreat that leads to channel widening. However, by definition, the banks of an alluvial stream channel cannot be fixed in position and must be formed predominantly of erodible sediment. Thus the fluid shear forces applied to the bank face in an alluvial channel will periodically exceed the resisting forces of friction and cohesion and reinforcement between the particles making up the bank material.

The stability of streambanks is influenced by bank height, slope angle, materials, stratigraphy, drainage conditions, pore water pressure and matric suction, and vegetation. In addition to externally applied fluid shear stress, streambanks are also subject to internal loadings and pressures that reduce their stability with respect to gravity and can produce bank retreat through mass failure. This occurs when fluvial processes erode the bank to the point that the internal loadings and pressures make it unstable, so the bank collapses by a geotechnical failure. In this context, soil moisture and groundwater processes are often crucial, thus bank hydrology (particularly the state of soil drainage) and soil stratigraphy play significant roles in determining bank stability.

Bank stability analysis is performed through considering the balance of internal forces of weight, soil strength, and pore water pressure. Geomorphologists are making increasingly important contributions to understanding and predicting the behavior of natural streambanks (Simon et al. 2000). These contributions are especially significant for vegetated streambanks, where plants interact with the geomorphic, geotechnical, and hydrological attributes of the bank to influence its stability and rate of retreat (Simon et al. 2006). A more complete discussion of bank stability and slope stability analyses are provided in the Geotechnical Analyses subsection of Appendix A.

In practice, bank retreat that is accelerated, severe, or sustained is usually associated with a combination of fluvial erosion and geotechnical instability (Thorne 1982). Consequently, where measures must be introduced to control or prevent bank retreat, it is necessary for the design to deal effectively with the fluvial (bank erosion resistance versus fluid shear stress) and geotechnical (soil strength versus gravity) elements of the problem, while also recognizing the potential for vegetation to protect and stabilize the bank.

Riparian vegetation

Riparian vegetation influences boundary characteristics by increasing bank stability, increasing flow resistance and sediment deposition, and providing a source of woody debris. In a general sense, riparian vegetation influences basic fluvial forms and processes, such as channel depth, bank height, and channel stability. In a more specific sense, it influences site and reach-scale channel form and its associated habitat. The presence of riparian vegetation:

- generates near bank turbulence, which increases flow resistance, reducing boundary shear stress and thus inhibiting the ability of the flow to entrain and transport sediment;
- generates large eddies during overbank flows that export momentum (energy) from the channel to the floodplain, which reduces shear stresses on the channel bed and banks;
- promotes the deposition of sediment and growth of in-channel berms and natural levees;
- reinforces the soil comprising the channel banks to increase bank stability;
- increases evapotranspiration to reduce soil moisture levels and the frequency of bank saturation, both of which increase bank stability (Hoitsma and Payson 1998, Pollen 2007); and
- acts as a source of large wood entering the stream to form obstructions including log jams.

These influences, which are particularly important to the form of alluvial channels with erodible boundaries, are limited by the type and extent of vegetation cover. For example, root reinforcement of streambanks is limited to the rooting depth of the species of plants growing on the bank and in the riparian corridor, so in incised streams, riparian vegetation provides less of a stabilizing effect because plant roots do not extend through the full height of the bank. Thus the characteristics of the vegetation—the species, density, age, size, and health—are important factors to assess when evaluating impacts to the channel and its associated habitat (Beechie 2006a).

Empirical and statistical research has demonstrated that at the reach scale, riparian vegetation exerts significant influence on stable channel form (Gilbert 1914, Hey and Thorne 1986). Research has also shown that riparian vegetation is important to channel and overbank hydraulics as the dominant roughness element responsible for dispersing high and potentially erosive stresses during high flow events (Arcement and Schneider 1989, Fetherston et al. 1995). Beechie et al. (2006a) demonstrated that for alluvial streams in forested areas, riparian vegetation often controls the regime channel pattern in streams less than 15 to 20 m wide through its stabilizing effects on the banks; in bigger channels with correspondingly greater channel depth, plant rooting depths are exceeded by channel depth and riparian vegetation is less significant. Even where riparian vegetation is not a dominant control of channel dimensions, it may increase sediment deposition on bars and floodplains, promoting the evolution of channel and floodplain habitats. It has other roles as well, such as providing large wood for structural habitat, influencing stream temperature through shading of near-bank habitat, and providing a base for food web production through the input of nutrients, organic litter, and macroinvertebrates to the stream.

Riparian ecosystems are adapted to the flow and sediment regimes of the river. Indeed many riparian plant species are fully dependent on the natural cycle of flood disturbance, inundation, and variation in stream flow for natural regeneration and propagation. Some riparian species, such as cottonwood (*Populus* sp.) and willows (*Salix* sp.), are well adapted to colonize fluvial deposits, such as bare sand and gravel bars, but require specific rates and spatial patterns of stream flow recession following floods to establish successfully (Rood and Mahoney 1990). Consequently, anthropogenic alterations to the natural flow and sediment regimes that, for example, change the duration of floodplain inundation or alter sediment redistribution can limit regeneration of natural riparian vegetation and associated communities, leading to loss of the benefits they provide for instream habitat (Stromberg 1993).

3.4.4. Channel Boundary Controls

The boundaries of an alluvial stream are free to adjust to the imposed flow and sediment regimes such that the channel has the dimensions and slope necessary to convey the water and sediment supplied from upstream without incising or aggrading significantly (Thorne 1997). However, in nature few streams are truly alluvial, most featuring controls on channel form at the site and sometimes at the reach scales.

Natural boundary controls may be permanent or temporary. Piegay and Schumm (2003) identify permanent controls on reach morphology as: bedrock sills and outcrops in the bed or banks, terraces, alluvial fans, coarse sediment inputs at tributary junctions, and tectonic features such as fault lines and hinge zones. These forms of control may act locally to produce features that would not be found in alluvial streams, such as deep scour holes, extensive depositional areas, or impediments to the lateral shifting of the channel (hard points). Where they are more extensive, natural boundary controls may control the base level for a reach, the location of the channel within its valley, channel planform development, and channel shifting through time and space. Log jams and beaver dams are examples of temporary boundary controls. As the influence of boundary controls in a reach increases, a point is reached where the channel can no longer be considered alluvial and the rules and classification systems for alluvial channels can no longer be applied. In addition, each of these types and scales of boundary control has implications for habitat.

These natural controls have many anthropogenic analogs that also act to constrain the channel at the site or reach scale. Weirs, grade control structures, culverts, bridge sills and abutments, and bank protection structures may constrain the width and reduce the opportunity for the kinds of lateral or vertical channel adjustments that are essential to maintaining dynamic equilibrium. Dams act as boundary controls by changing the longitudinal profile of the river. A dam determines the base level for the reach upstream in a manner similar to a geological valley obstruction such as a glacial moraine or fault scarp. Dams also create reservoirs upstream and alter the flow and sediment regimes downstream, thus influencing the river system for long distances in both directions from the control point.

Bedrock as a boundary control

Bank features, such as bedrock outcrops or landslide deposits, act as constraints over decade or longer times scales, thereby creating spatial and temporal controls on channel

adjustment and migration. For instance, exposed bedrock in a streambank locally constrains lateral migration and forms a deep pool because the bank cannot erode, and channel adjustment is focused in the vertical dimension. Riprap placed on a streambank similarly constrains lateral channel adjustment, thereby exaggerating adjustment in the vertical dimension. Additionally, riprap often has a lower roughness coefficient than a naturally vegetated streambank and, consequently, near bank velocities may be higher, resulting in increased boundary shear stress that drives deep scouring of the bed next to the riprap revetment. Hence efforts to protect property by introducing unnatural constraints may result in exaggerated vertical adjustments and unanticipated morphological impacts. This is also true for habitat restoration projects where introduction of unnatural constraints (e.g., boulders, rock weirs, and root wads) may generate unanticipated morphological responses.

Large wood as a boundary control

Only in recent decades have scientists recognized the importance of large wood in acting as a boundary control on stream processes and a catalyst in the formation of habitat. Large wood is naturally recruited by stream processes from streambank, floodplain, and headwater forests. Historically, wood has played a major role in channel and habitat formation in river systems with forested watersheds and riparian corridors throughout the world. Large wood forms jams that act as local boundary controls (often in association with other types of natural controls), prompting the formation and affecting the physical and chemical attributes of pools, riffles, bars, and boulder steps; promoting sediment storage; and reducing rates of channel evolution in unstable channels. The channel features generated from log jams differ from those found in alluvial streams and are termed forced morphologies (Montgomery and Buffington 1998). These features increase morphological diversity and thus play a key role in determining channel type, increasing the range of habitat and diversifying the associated aquatic and riparian communities (Montgomery and Buffington 1998).

Large wood, particularly when it accumulates in jams, influences not only channel form but also stream processes through its effects on the storage and transport of sediment (Smith et al. 1993, Wallerstein and Thorne 2004). While it usually acts to increase in-channel sediment storage at the reach scale, wood jams can also trigger local scour and lateral channel migration by forming obstructions that concentrate or deflect the flow, depending on the length of key elements compared to the width of the channel (Abbe and Montgomery 1996). The life span of log jams is relatively short in process terms, and so an ongoing supply of large wood is essential to maintaining the role of wood as a boundary control at the reach scale. For this reason, the continued action of large wood as a boundary control is vulnerable to clearing of streambank, floodplain, and headwater forests that may greatly reduce recruitment of large wood or change the age and species of wood recruited (Murphy and Koski 1989). In wood-dominated rivers, removal of large wood from the channel or riparian corridor can destabilize the fluvial system, leading to a fundamental shift in stream type with adverse impacts on habitat qualities (Smith et al. 1993, Montgomery et al. 1995, Montgomery et al. 1996).

Biogenic boundary controls

Aquatic animals also play a fundamental role in creating temporary boundary controls that affect the creation, maintenance, and diversity of stream habitat (Jones et al. 1997). For

example, in river systems of the western United States, beaver dams were historically an important factor in creating and maintaining channel habitat, especially for rearing salmon and some species of trout. In essence, beavers maintain environmental heterogeneity. Their dams store water, sediment, and nutrients and improve water quality. The life histories of many riparian and aquatic plant species require changes in water table depths that beaver dams and ponds create (Naiman et al. 1992a). Beavers were of particular importance in semiarid regions, where their ponds contributed to groundwater recharge, elevated water tables, boosted summer base flows, increased the area of aquatic and riparian habitat, and attenuated flashy storm flows (Wohl 2004). While the physical and chemical influence of beavers was greatest in smaller, low-gradient streams in unconfined valleys (Pollock et al. 2003), they played important roles in riparian wetlands and side channel habitats on larger rivers as well (Naiman et al. 1988).

The historic distribution of beaver in North America included all of the Pacific Northwest, northern and central California, and isolated populations in southern California (Pollock et al. 2003). The systematic trapping of beavers reduced populations to near extinction at the turn of the nineteenth century. In fact, current populations are a small fraction of their historic numbers (Naiman et al. 1988). The decline of the beaver population was one of the earliest major impacts on salmonid populations throughout the western United States (NRC 1996). The loss of beavers, and subsequent degradation and failure of their dams and associated wetlands, has dramatically affected the hydrology and sediment regimes of many western streams. Impacts associated with beaver decline are particularly pronounced in semiarid regions and likely contributed to impacts associated with grazing, resulting in accelerated channel incision and associated lowering of groundwater levels and loss of summer base flows (Pollock et al. 2007). A recent comprehensive literature review of the effects of beaver impoundments on fish (Pollock et al. 2003) illustrates that loss of beavers in all probability was directly related to significant population declines of virtually all native fish species cohabiting with beaver.

Salmonids also play a role in the maintenance of their own habitat through disturbance of the streambed gravels through their spawning activities. While salmonid spawning does not necessarily influence geomorphic processes at the reach scale in the way beavers did, salmonid spawning has significant effects at the patch scale and influences not only the physical attributes of the channel bed, but also benthic community organization, fine sediment storage and transport, and the distribution of sediments through the channel (Moore et al. 2004). Salmonid spawning thus affects channel boundary characteristics, in addition to being critical for maintaining population levels. Research shows that the streambed disturbance associated with mass spawning populations plays an important role in establishing positive feedback between the level of spawning activity and quality of spawning habitat (Faustini 2005). This bed disturbance also plays a significant role in benthic invertebrate dynamics (Moore and Schindler 2008).

3.5. Disturbance, Impact, and Response

Disturbance can be defined as any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (White and Pickett 1985). In natural channels, disturbance is fundamental to the functioning of the fluvial system and the ecosystem. In their natural state, dynamically stable channels and the ecological communities for which they provide habitat are not only resilient to disturbances, but may be inherently dependent on them. Natural

disturbances trigger channel adjustments that renew existing habitat and create new habitat to produce the diversity and complexity that is necessary to provide for all life stages of all stream organisms. Disturbances foster the process of natural selection and thereby increase population fitness (Minckley and Meffe 1987, Reeves et al. 1995, Lytle 2001).

3.5.1. Natural Disturbance

In rivers of the western United States, natural disturbance occurs in association with events such as floods, droughts, landslides, fires, and volcanic eruptions. These natural disturbances are inherent to river systems, and have been part of long-term salmonid evolution for millennia. Disturbance events impact stream processes by significantly altering watershed hydrology, flow and sediment regimes, boundary conditions, or vegetation. These alterations trigger morphological responses that shift channel form out of adjustment to long-term average conditions for years or decades. The ecosystem outcome is a significant disruption, redistribution, rejuvenation, or creation of new habitat.

Details of the channel, habitat, and ecosystem responses to disturbance depend on the magnitude and rate of the disturbance, as well as the resilience of the stream channel to adjustment; that is, its response potential. Bedrock or other supply limited channels are unlikely to exhibit marked responses except locally, and over reach scales may respond only to severe disturbance. Low gradient, alluvial channels (e.g., transport-limited channel types such as pool-riffle gravel-bed streams and dune-ripple sand-bed streams) may be resilient to minor disturbance, but more sensitive to extreme disturbances.

In natural systems, disturbances are relatively discrete events, ranging from major events such as volcanic eruptions, megafloods, landslides, and forest fires, down to local disturbances such as the failure of beaver dams. A disturbance may cause a permanent change in the flow or sediment regime, referred to as a step change, or may occur as a short-term, temporary change, referred to as an impulse change (Figure 21 and Figure 22).

A step change results in postdisturbance conditions that differ from predisturbance conditions, while an impulse change results in a return to predisturbance conditions (Knighton 1998). The frequency, magnitude, and spatial distribution of recurring impulse disturbances are termed a disturbance regime. Studies from a number of disturbed rivers in different parts of the United States indicates that fluvial systems are highly nonlinear, complex systems that, once disturbed, display complex responses (Schumm 1977, Simon and Thorne 1996). Natural and anthropogenic disturbances, particularly as they relate to habitat and the survival and evolution of salmonids, occur over a broad range of spatial and temporal scales (Table 6 and Table 7).

3.5.2. Anthropogenic Disturbance

Human impacts to watershed controls and stream channel processes create disturbances in the river system. These impacts often have natural disturbance analogs and may cause similar responses in the channel. For example, the impacts associated with forestry practices may be similar to those of a wildfire with respect to changes in the flow regime and sediment yield. However, anthropogenic disturbances typically differ from natural disturbances in that they often:

- reoccur over wider spatial scales and more systemically,
- reoccur at a higher frequency or magnitude,
- reoccur more persistently and over longer temporal scales,
- cause permanent changes to watershed controls,
- result in chronic or more rapid channel responses, and
- artificially constrain natural stream processes and morphological responses.

Disturbances related to anthropogenic actions tend to impact channel form, habitat, and ecosystems because of their cumulative impacts, which are a consequence of their high

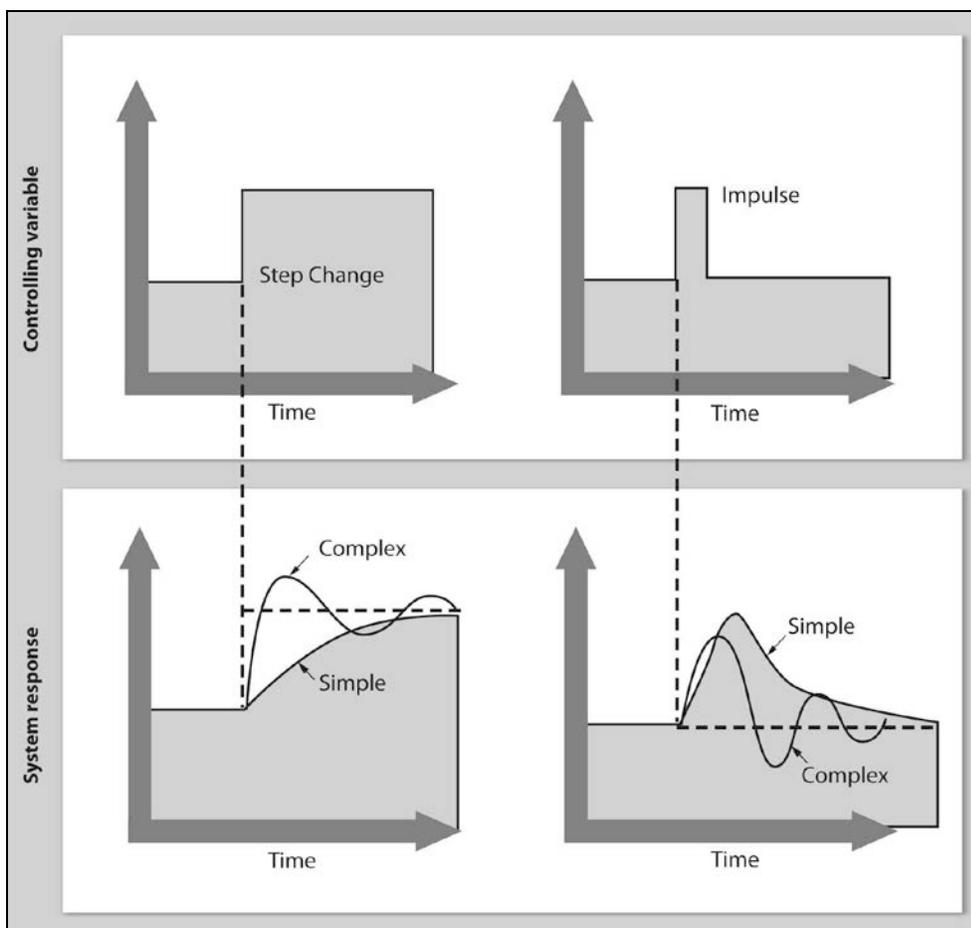


Figure 21. Conceptual diagram depicts step change and impulse change coupled with system response to these changes, which may be simple or complex. A simple system responds to an impulse change by gradually and uniformly recovering its predisturbance equilibrium condition. In contrast, a complex system responds by overcompensating for the impact of the impulse change by making a series of oscillatory adjustments until equilibrium is restored. With a step change, the postdisturbance equilibrium conditions will differ from the predisturbance condition, resulting in a new channel form that is achieved through either simple or complex response. (Adapted with permission from Summerfield 1991, copyright Wiley.)

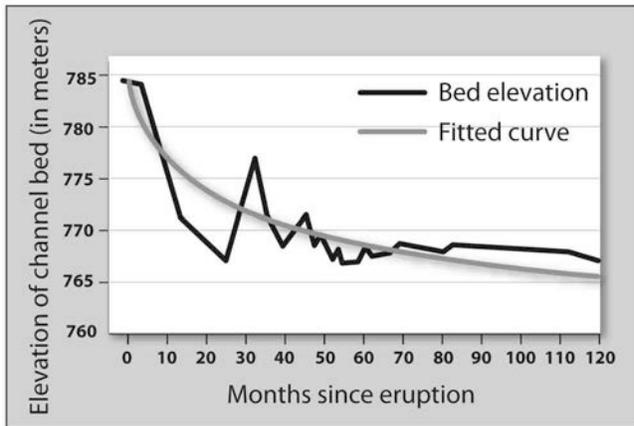


Figure 22. Example of the Toutle River channel response to the impulse of a massive material deposition as a result of the volcanic eruption of Mount St. Helens, November 1980. Graph shows only response following impulse, not the predisturbance bed elevation. (After Simon 1992, U.S. Geological Survey.)

frequency or wide extent (Table 8). For example, a natural disturbance might involve a single landslide that contributes an elevated supply of wood and sediment, including spawning gravels, to downstream environments. The morphological response would increase the diversity and complexity of habitat in downstream reaches. An anthropogenic disturbance, such as construction of a single splash dam, might produce similar results, but the systematic implementation of repeated splash damming in channels throughout a basin creates a widespread, cumulative impact that may perpetuate instability in the fluvial system for decades (NRC 1996, Massong and Montgomery 2000).

While many anthropogenic actions that lead to disturbance of the fluvial system are now regulated, a legacy of historic impacts persists and is largely unaddressed in conventional management and restoration. In particular, the impacts of historic riparian forest clearing, channelization, floodplain draining, base level blasting, splash damming, beaver eradication, placer mining, metals mining, gravel mining, and grazing have caused fundamental changes in watershed controls, flow and sediment regimes, and stream processes, leading to responses that put channel morphologies out of adjustment.

Many of these impacts occurred long before surveys or aerial photos were available. The result is that our best available record of pristine channel conditions often represents the legacy of historic anthropogenic impacts, rather than only naturally disturbed conditions. Indeed our contemporary view of natural states has very few remaining pristine analogs from which to model or develop objectives and targets for restoration (Wohl 2004, Turner 2005, Wohl 2005, Walter and Merritts 2008). For example, the Queets River in western Washington is recognized as one of the most pristine and undisturbed river basins in the western United States, as its headwaters and mainstem channel have been protected within Olympic National Park since 1916. Yet even the Queets lower mainstem channel has impacts from forestry within the watershed of the Clearwater River, a major tributary to the Queets (Skidmore 2006). This perspective on the limited availability of natural analogs for pristine conditions is significant in a

Table 6. Characteristics of natural disturbances affecting habitat. A range of natural habitat disturbances in Puget Sound and the Columbia River basin have affected salmonid evolution and adaptation. (Adapted with permission from Waples et al. 2008, copyright Blackwell Publishing Ltd.)

Type	Recurrence interval	Magnitude	Duration	Spatial extent of effect	Location	Time period
Continental glaciation	10^4 – 10^5 years	Several km ice depth	10^4 years in center of ice sheet; 10^2 – 10^3 years near margins	$>10^6$ km ²	British Columbia, Puget Sound, Okanogan Basin, upper Columbia River	400,000–12,000 years BP
Alpine glaciation	10^5 years	>100 m ice depth	10^2 – 10^3 years	$\approx 10^5$ km ²	Cascades, Strawberry Range, Elkhorns, NE Oregon, Klamath Mts.	400,000–12,000 years BP
Lake Missoula floods	30 to 70 years	$>10^7$ m ³ /s; >100 m deep	ca 2 weeks/flood; ca 100 floods during ca 2,000 years	$\approx 10^5$ km ²	Columbia plateau and gorge	13,500–15,700 years BP
Earth dam floods	Single events	10^4 – 10^6 m ³ /s	Days; effects last decades to centuries	$<10^3$ km ²	Upper Snake R. canyon, lower Owyhee R. and lower Snake R.	\approx 13,000 years BP
Volcanic eruption	1,000s of years	Multiple valley, aggradation up to 10s of meters	Mudflows can last several days; habitat effects last decades to centuries	Single volcano with multiple watersheds	Cascade Range	16,000 years BP
Bonneville landslide	Single event	Blocked mainstem Columbia, creating large lake	Days to decades	20 km of river	\approx RKM 65	1670–1760
Contemporary landslides	10s to 100s of years	Centimeters to meters of bed scour and aggradation	Hours; sediment load present for years to decades	Local stream and downstream area	Cascade Range	Ongoing
Floods	Years to decades	Centimeters to meters of bed scour and aggradation	Hours to days	Stream reach to watershed	Entire Pacific Northwest	Ongoing
Droughts	10 – 10^3 years	Extreme low flow conditions	Months	Specific watersheds to regional	Entire Pacific Northwest	Ongoing
Earthquakes	10 – 10^3 years	Trigger landslides and changes to stream habitat	Minutes (but concomitant landslide effects last years to decades)	Specific watersheds to regional	Entire Pacific Northwest	Ongoing

Table 7. Characteristics of anthropogenic disturbances affecting habitat. A range of anthropogenic habitat disturbances in Puget Sound and the Columbia River basin have affected salmonid evolution and adaptation. (Adapted with permission from Waples et al. 2008, copyright Blackwell Publishing Ltd.)

Type	Recurrence interval	Magnitude	Duration	Spatial extent of effect	Location	Time period
Anthropogenic barriers	Continual	10–10 ³ km of habitat blocked	Years to centuries	Stream to watershed	Entire Pacific Northwest	Ongoing
Channel simplification	Continual	10–10 ³ km of habitat simplified	Years to centuries	Stream to watershed	Entire Pacific Northwest	Ongoing
Contemporary landslides	10s to 100s of years	Centimeters to meters of bed aggradation	Hours; sediment load present for years to decades	Local stream and downstream area	Cascade Range	Ongoing
Alteration in flood flows	Years to decades	Peak flow increases of more than 10%	Hours to days	Stream reach to watershed	Entire Pacific Northwest	Ongoing
Alteration in low flows	Years to decades	Moderate reductions to complete loss of summer flow	Days to months	Stream reach to watershed	Entire Pacific Northwest	Ingoing

Table 8. System response to natural and anthropogenic disturbance. Natural and anthropogenic disturbances, including projects intended to restore or stabilize channels, may impact the ratio of transport capacity to sediment supply, watershed inputs (sediment or flow regime), and boundary characteristics and controls. The spatial scale of response to disturbances may be channel pattern (Beechie et al. 2006a), channel type (Montgomery and Buffington 1997), or site/reach-scale for more localized disturbances.

Disturbance event/action	Impact to Q_c/Q_s		Variable affected: inputs or boundary		Spatial scale affected
	Increase	Decrease	Input: discharge (Q) or sediment (S)	Characteristic: bed (B), bank (K), veg (V), controls (C)	Pattern (P), type (T), site/reach (R)
	▲	▼			
Natural disturbance					
Landslide		▼	S	—	P, T, R
Forest fire		▼	Q, S	V, C	R
Major flood	▲		Q	B, K, C	R
Volcanic eruption		▼	S	B, V, C	P, T, R
Anthropogenic impact					
Land use—conversion to ag	▲	▼	S, Q	K, V, C	P, T
Land use—urbanization	▲		S, Q	B, K, V, C	P, T
Land use—forest clearing	▲	▼	S, Q	V, C	P, T
Channelization	▲		—	B, K, V, C	T, R
Diversion		▼	Q	C	R
Dam	▲	▼	S, Q	K, V, C	P, T, R
Groundwater extraction	—	—	Q	—	R
Irrigation return	—	—	Q	—	R
Beaver removal	▲		—	B, K, V, C	T, R
Snag removal	▲		—	B, C	T, R
Project impact					
Restoration	▲	▼	—	B, K, V, C	T, R
Stabilization	▲		—	B, K, V, C	R

management context, as it raises the questions of what condition to use as a baseline for restoration or stabilization.

In the context of evaluating stream corridor management and restoration actions, the impacts of anthropogenic disturbance may be characterized as either direct impacts that modify stream processes or channel form, or indirect impacts that affect watershed controls and hence the flow or sediment regimes (Wohl 2004). When considering indirect, watershed-scale impacts, such as urbanization, logging and agriculture, one can ask whether these impacts magnify or constrain watershed controls, and whether the impacts can be characterized as relatively permanent with potential for mitigation or as dynamic and thus potentially reversible. Logging, for example, can significantly alter the rainfall-runoff relationship, flow, and sediment regimes at a watershed scale (Reid and Lewis 2007). These impacts may persist for decades, but diminish naturally or through active mitigation (reforestation, road removal). Dams similarly alter flow and sediment regimes, as do natural disturbance regimes, and may be relatively permanent features that block fish passage (Ligon et al. 1995). While the impacts of dams on the flow

regime can be mitigated by managing the magnitude and timing of releases from the impoundment, sediment trapping is inevitable without specifically engineered systems to address sediment accumulation, and efforts to provide passage around dams often produce marginal results relative to free-flowing conditions.

Indirect actions in or outside the channel also have the potential to damage or diminish the shallow groundwater system and adversely affect hyporheic exchanges with water in the channel. For example, groundwater extraction through pumping or the diversion of water from surface water bodies (ponds, lakes, etc.) associated with agriculture or sediment excavation can lower groundwater tables. Where a depressed groundwater table falls beneath the elevation of a nearby stream channel or wetland, water may infiltrate and percolate away from the stream so that flow is reduced, riparian plants are water stressed, and wetlands shrink. Evidence shows that locally depressed water tables can reduce stream flows for great distances downstream (Gordon 2004). Also, where discharges in the stream are not diminished seriously, loss of the cooling effect of influent seepage may result in stream water temperatures exceeding critical levels or reductions in trophic food quantity/quality, and may threaten populations of listed species including salmonids. There is also the potential that base flow in a formerly perennial channel might go to zero, especially during low flow seasons or prolonged droughts. This can cause direct mortality to affected fish and the aquatic food base of the stream ecosystem, even if dewatered for only a few minutes where instantaneous water demand is high.

Many anthropogenic impacts are direct and localized, influencing primarily reach-scale or site-scale stream processes by introducing artificial constraints. Direct impacts include such actions as flow regulation, channelization, levee construction, wood removal, and beaver eradication. For example, the construction of levees results in isolation of all or part of the floodplain from the stream channel, resulting in loss of freshwater wetlands that historically provided important salmon rearing and refuge habitat (Beechie et al. 1994, Collins and Montgomery 2001), as well as loss of hyporheic functions. Even more localized are stream crossings—bridges or culverts—which essentially lock a stream in place, thereby constraining natural processes and morphological adjustments.

Direct anthropogenic impacts not only affect habitat availability, diversity, and value, they may also exacerbate the sensitivity of the channel to natural disturbances. Levees, for example, constrain flood flows to the channel rather than allowing water to flow over the banks, thereby concentrating energy in the channel and exaggerating erosive and depositional responses that lead to channel adjustments. Similarly, a restoration or stabilization project that incorporates hard structural features, such as rock weirs or root wads for bank protection, may exacerbate channel erosion by altering the natural alluvial channel environment.

3.6. Channel Classification, Incision, and Evolution

Stream habitat is often characterized in relation to specific, local channel features, such as pools, riffles, gravel patches, and large wood jams. Stream processes that form the channel operate almost continuously to drive changes in channel forms and features that create habitat for a range of species and life history requirements. An understanding of the genesis and succession of channel form is, therefore, fundamental to understanding the distribution and variability of habitat. As explained in the previous subsection, disturbance may take place at the site, reach, or

system scale in the river network or in the surrounding watershed. Thus understanding channel evolution and response to disturbance is necessary to effectively plan and design projects and management strategies capable of meeting their stated goals and objectives now and into the future.

3.6.1. Temporal and Spatial Scales of Channel Development

Schumm and Lichty (1965) illustrated the importance of temporal scales in assessing causal relationships among variables in fluvial systems. For the purpose of stream management actions, the influence of various watershed controls and stream processes on channel form depends on the temporal scale considered, as summarized in Figure 23.

At the time scale of thousands of years or more, geology and climate drive the development of physiographic features at the regional scale. Hence watershed controls, stream processes, and channel forms are all determined by geology and climate. For example, over geologic time an individual valley (a physiographic feature) is formed by long-term erosion (denudation) of elevated topography by rivers, glaciers, and mass wasting.

At intermediate periods of decades to centuries, the watershed-scale controls of basin physiography, soils, and vegetation drive changes in flow and sediment regimes of rivers draining the basin. Hence for river restoration and management purposes, we can consider basin physiology, soils, and vegetation as relatively constant and permanent watershed attributes that determine variations in flow and sediment regimes. Geomorphic elements that are effectively fixed at this time scale include the valley floor width (which determines the degree of confinement, except in areas of flood control works), valley slope, and the composition of the valley bed.

However, at this time scale anthropogenic impacts may also be significant. For example, land use changes may act on stream processes and channel forms either directly by altering the flow and sediment regimes or indirectly through their impacts on watershed controls. This time scale of decades to centuries is therefore an appropriate time frame for considering the possible

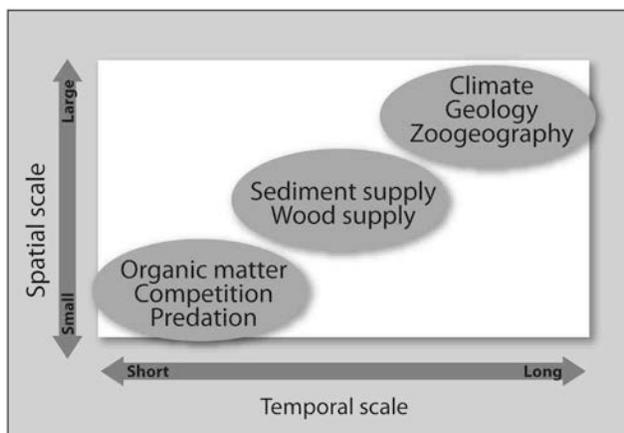


Figure 23. Spatial and temporal scale factors controlling habitat conditions. (Adapted with permission from Naiman et al. 1992b, copyright Wiley.)

effects of anthropogenic changes in planning restoration projects and making management decisions. This is important in terms of managing expectations: for example, if channel form takes a century to respond to past land use change, at least another century may be needed for the channel to recover its predisturbance form. In many cases, anthropogenic changes are irreversible and returning to a predisturbance configuration is not possible. Further, if land use has changed radically, then restoring channel form to a predisturbance configuration without restoring the watershed controls will put the channel out of adjustment with the current flow and sediment regimes, thus limiting the sustainability of a channel restoration project to no more than a few years.

Channel restoration and management actions are potentially most effective within the shorter time scale of years to decades. This time scale is too short for landscape drivers and watershed controls to change significantly, so that channel form varies and adjusts only in response to the prevailing stream processes. Close coupling of form and process at the subdecadal time scale and the reach space scale is the basis for hydraulic geometry analyses that link characteristic channel dimensions and planform to stream hydraulics and sediment transport. Further, the strong relationships between process and form allow experienced geomorphologists to work back through the linkages and infer process from form. This is the foundation for the classification of channels on the basis of their form—the assumption being that streams with similar channel forms have developed under the action of similar stream processes.

3.6.2. Channel Classification

Differences in channel form within a valley are best described along a continuum, since no thresholds exist that separate statistically defensible classes of channel form. Nonetheless, classifications of channel pattern and reach-scale form have been developed for varying reasons, not least of which is simply a human compulsion to categorize (Goodwin 1999). This compulsion, supported by a sincere desire to describe and convey an understanding of similarity and variability in channel form, has led to many efforts to classify channel forms and patterns (Leopold and Wolman 1957, Schumm 1977, Frissell 1986, Rosgen 1994, Thorne 1997, Montgomery and Buffington 1997). Classifications are, by definition, intended to codify the complex variability displayed by natural rivers. As such, they inherently aggregate subtle distinctions or arbitrarily segregate into distinct classes characteristics that can only accurately be described along a continuum and relative to multiple attributes. Furthermore, most classifications do not convey information about temporal changes in forms and patterns, and can therefore underrepresent or misrepresent important temporal distinctions (Kondolf 1995).

The most useful classifications of channel types for management applications are those that:

- relate observed forms to the processes that create them,
- account for the potential response of different channel types to disturbance by natural events or anthropogenic actions, and
- are representative of time and space scales that are of practical significance to restoration or management actions.

Most classification schemes are form based, meaning that the basis for distinguishing between different channel types is a suite of static channel form metrics, such as width/depth ratio, sinuosity, bed material, bar forms, and slope. For example, Rosgen's classification (1994), which has gained considerable popularity in the United States (Kondolf et al. 2006, Roper et al. 2008), stratifies major channel types primarily on the basis of a range of dimensionless parameters defining various attributes of channel form developed from field measurements: the entrenchment ratio (ratio between bankfull width and the width at twice the bankfull depth), the bankfull width/depth ratio, and sinuosity. Classification is further refined by estimates of stream slope and bed material size (Rosgen 1994, Montgomery and Buffington 1997, Naiman 1998). However, the extent to which form-based classifications can fully represent stream processes is inherently limited (Juracek and Fitzpatrick 2003, Simon et al. 2007, Roper et al. 2008). Furthermore, stream size can be a critical determinant of form distinctions and classes, so dimensionless parameters may fail to highlight important scale effects.

While form-based classifications are useful communication tools in describing and defining observed conditions, they have limited utility in developing management strategies because the dynamic balance between stream processes and channel form is underrepresented in most classification schemes, particularly those derived from simple analyses of channel metrics (FISRWG 1998, Simon et al. 2007). Therefore, classification schemes that link observed forms to their governing stream processes and response potential have greater utility when developing management strategies or planning restoration projects. Only with this strong link to stream processes will a classification system lead to relevant and appropriate restoration strategies and designs.

Consideration of classification scale is relevant to river restoration and management; as the scale applied in classification gets finer, approaching that of the reach and site, the number of classes or types increases, with a corresponding increase in the number of variables at play. With this increase in number of variables comes an increase in correlation and feedback between variables, and a diminishing confidence in the strength of any particular set of variables. Further, it becomes increasingly difficult to assign a particular reach of stream unambiguously to any single class or type (Roper et al. 2008). In contrast, classifications that address a broader scale are more likely to prove robust in correlation to deterministic variables (Montgomery and Buffington 1998, Beechie et al. 2006a).

Channel pattern classification

Channel pattern refers to the character of the stream channel when viewed from above. Several researchers have proposed planform categorizations (Leopold and Wolman 1957, Kellerhals et al. 1976, Schumm 1977). These systems are consistent in that they classify channels according to the degree of channel sinuosity and whether flow follows a single thread or is divided between two or more subchannels; however, the specific criteria differentiating classes varies. Beechie et al. (2006a) define four planform patterns—straight, meandering, braided, and island-braided (Figure 24). This classification encompasses the range of patterns described in the literature and also reflects the relative stability of different planform types as measured by the propensity for channel movement. Straight and meandering channels are

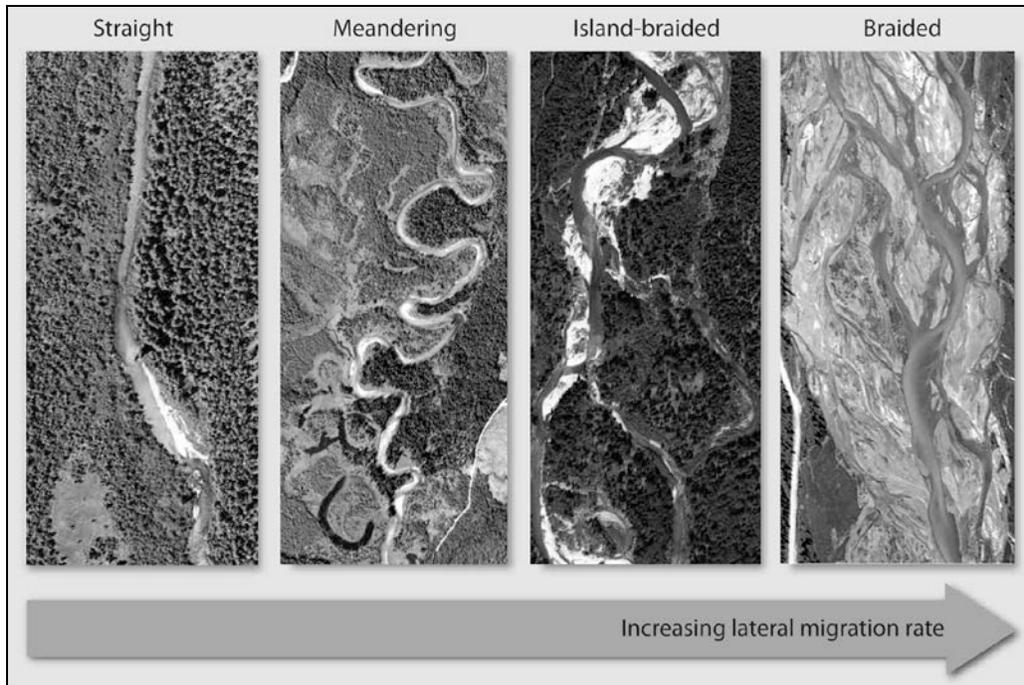


Figure 24. Four channel patterns from within the Columbia River basin, illustrating varying rates of lateral channel migration that erodes and deposits floodplain alluvium. (Images from Google Earth, copyright 2011 Google.)

primarily single thread and differentiated by the degree of meandering.⁹ Island-braided channels exhibit multiple channels separated by islands and are comparable in definition to anastomosing, anabranching, and wandering patterns variously described by others (Nanson and Knighton 1996, Huang and Nanson 2007). Islands may be vegetated or nonvegetated and the significance of this distinction varies among classifications. Braided channels consist of multiple channels mainly separated by unvegetated gravel or sandbars.

In undisturbed river systems in the western United States, these patterns often occur in a particular downstream progression, from straight or braided channels in the upper basin, to island-braided channels in the middle course, to meandering channels in the lower course of the river. This sequence, consistent with idealized longitudinal pattern sequences described in the literature (Nanson and Croke 1992, Church 2002), is a function of diminishing stream power and bed load supply downstream.

Straight channels, while common in upper watersheds, can occur anywhere in the network and result primarily from geologic control or valley confinement and the presence of nonerodible materials in the streambanks that render the stream nonalluvial. Braided channels occur in response to a heavy supply of sediment moving as bed load (Deslorges and Church 1989, Church 2002) and are typically found downstream of glaciated or alpine terrain (Beechie et al. 2006a). The transition from braided to island-braided reflects decreases in bed load and

⁹ Various researchers have established different thresholds for differentiating straight from meandering. As these forms exist along a continuum, any specific sinuosity threshold may be considered as relatively arbitrary.

valley slope, as well as the increasing importance of bank vegetation (Knighton and Nanson 1993, Harwood and Brown 1993) and debris jams that act as anchors for island deposition (Fetherston et al. 1995, Abbe and Montgomery 1996). In nonforested systems, island-braided patterns may be less likely due to the lack of large wood and associated debris jams that promote island development (Beechie et al. 2006a). Further downstream, meandering patterns are prevalent due to a continuing decline in valley slope and the lower proportion of sediment moving as bed load.

The Beechie et al. (2006a) investigation of the distribution and genesis of channel pattern in forested alluvial rivers supports the conclusions of earlier studies (Schumm 1977) that emphasized the links between alluvial stream patterns (straight, meandering, braided, and anastomosed), modes of sediment transport (bed load, suspended load), channel stability, and the downriver trend from erosional to transport to deposition reaches. The complexity of interactions within the suite of variables recognized in these classification schemes makes design of channel projects in braided and meandering rivers a challenge.

In conclusion, categorization of channel pattern is useful because it explains channel planform in terms of interactions between the flow and sediment regimes, stream processes, and boundary conditions. Further, it provides a means for evaluating the dynamic stability of the channel, which is of great relevance to restoration design, stream management, and stabilization projects.

Channel reach classification

Another approach to classification is based on how a channel reach will respond to variations in sediment supply. This approach is based on the relationship between the sediment transport capacity of a stream and the supply of sediment available for transport. The ratio (q_r) of transport capacity (Q_c) to sediment supply (Q_s),

$$q_r = Q_c/Q_s \quad (5)$$

determines whether a channel will be supply limited (capable of transporting all sediment delivered to the channel), transport-limited (not capable of transporting all sediment delivered), or in an intermediate state. This in turn determines the response of the channel reach to sediment supply changes. A classification proposed by Montgomery and Buffington (1997) portrays channel types along the continuum from transport limited to supply limited (Figure 25).

The absence of alluvial fill in bedrock channels indicates a supply limited condition, where additional inputs of sediment will have little or no effect on channel form. The channel is therefore capable of transporting a greater sediment load than the normal supply. Colluvial channels, at the other end of the spectrum, exhibit a transport-limited condition, as the channel flows on colluvial deposits but is unable to transport the coarse material. Additional inputs of sediment, as through landslides or debris flows, will not be transported. Intermediate in this continuum are alluvial channels, which may be either supply limited or transport limited, but are more likely to adjust their channel characteristics to accommodate changes in supply. Within alluvial channels, bedform character as a function of sediment transport processes is emphasized as the dominant classification variable.

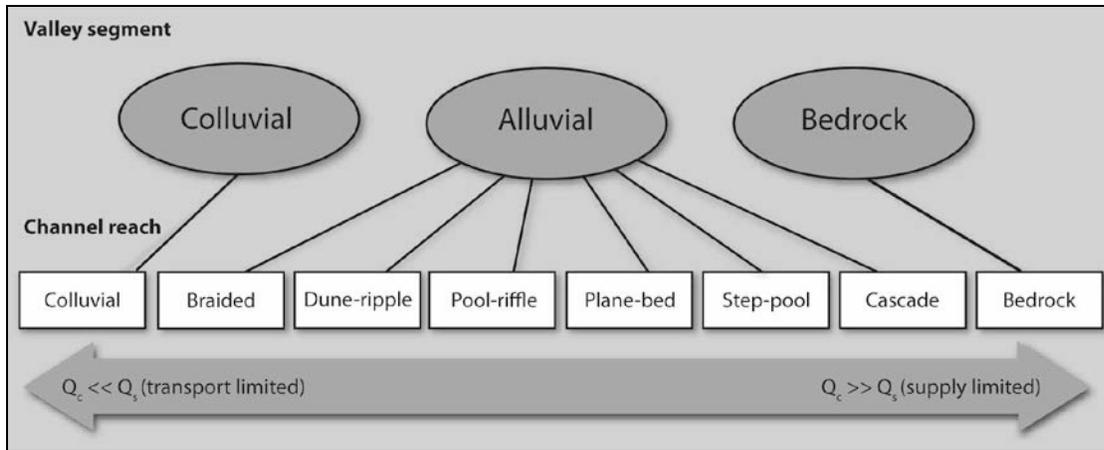


Figure 25. Classification of channel types at two scales, valley segment and channel reach, are based on the relationship between the channel's transport capacity and its sediment supply. Channel types are classified along a continuum from transport limited to supply limited, where channel type is largely a function of transport and supply conditions. (Adapted with permission from Montgomery and Buffington 1997, copyright Geological Society of America.)

Reaches classified as supply limited, or transport reaches (i.e., straight channels and bedrock, cascade, and step-pool channel types) are most morphologically resilient to changes in sediment supply or discharge (Table 9). Conversely, channel patterns and types categorized as transport limited (meandering and braided channel patterns, and pool-riffle and dune-ripple channel types) will be more responsive, displaying significant morphological adjustments to disturbance (Montgomery and Buffington 1998). Transport-limited channels will therefore present greater challenges for stream restoration and management (Beechie et al. 2006a). Restoration designs and management strategies that acknowledge these challenges and minimize elements or actions that attempt to constrain processes in the most dynamic channel types (i.e., those that are transport limited) will prove more effective and less costly over time, making them more sustainable.

In conclusion, the classifications of river pattern, process, and form offer a way of characterizing the current geomorphic state of a reach, gauging its potential to respond to disturbance (Montgomery and Buffington 1998, Beechie et al. 2006a). When applied to undisturbed alluvial reaches where the form of the channel is fully adjusted to the flow and sediment regimes, these classification systems work well because the process-form linkages on which they are based are relatively well understood. However, they apply only to alluvial streams, where channel boundaries and sediment transport processes are relatively unconstrained (Newson 2002). In practice, the rich and varied geology and management histories of rivers in the western United States mean that truly alluvial reaches are interspersed with naturally or artificially constrained reaches, so that the simple associations between process domains (zones of sediment supply, transport, and deposition) and channel patterns (braided, meandering, straight) that underpin most morphological classifications cannot always be assumed to hold true. Furthermore, disturbed systems may temporarily transition among channel pattern types at a reach scale due to pulses of sediment and feedback loops.

Table 9. Channel response potential. Channel response to moderate changes in sediment supply and discharge varies by channel type. Response channels correspond to transport-limited channel types. Transport channels correspond to supply-limited channel types. Source channels are dominated by hill slope process inputs (adapted from Montgomery and Buffington 1998). Plus (+) is likely to change, P is possible change, and minus (–) is unlikely to change.

Channel type	Reach level morphology	Width	Depth	Roughness	Scour depth	Grain size	Slope	Sediment storage
Response	Dune-ripple	+	+	+	+	–	+	+
	Pool-riffle	+	+	+	+	+	+	+
	Plane-bed	P	+	P	+	–	+	P
Transport	Step-pool	–	P	P	P	P	P	P
	Cascade	–	–	P	–	P	–	–
	Bedrock	–	–	–	–	P	–	–
Source	Colluvial	P	P	–	P	P	–	+

The alluvial fan

An alluvial fan is a cone or fan-shaped deposit formed where a stream leaves a considerable portion of its sediment load as it exits a valley or gorge to enter a plain, or where it forms a tributary junction with a larger river (Figure 26). Stream processes and morphological adjustments are particularly active where a stream crosses an alluvial fan, producing some of the most dynamic channels encountered in the fluvial system. This is significant to restoration projects because alluvial fans are common features throughout the western United States.

Fans are most pronounced where sediment is supplied at very high concentrations, such as from hyperconcentrated flows, or debris flows. The loss of stream power for sediment transport due to the reduction in slope or increase in channel width is often exacerbated by a parallel loss of discharge to percolation into highly permeable fan deposits (Schumm 1985).

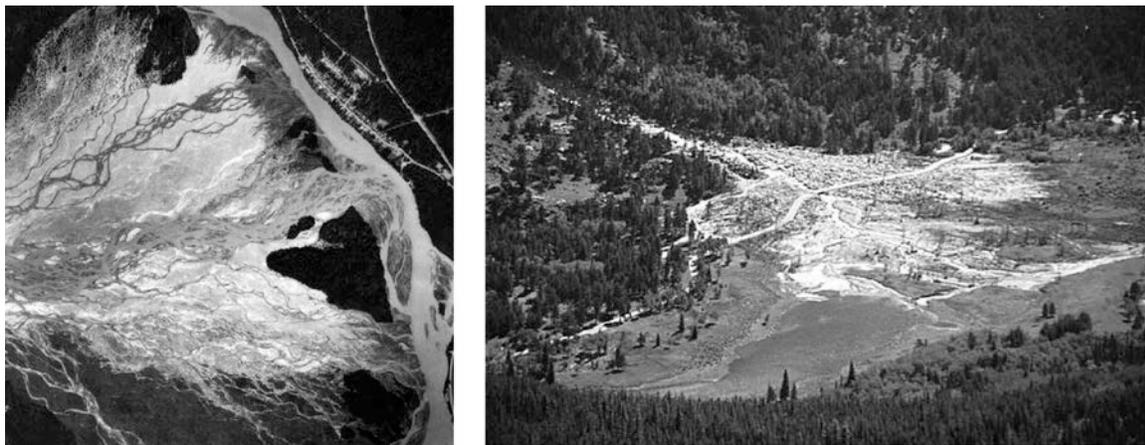


Figure 26. The Tsirku Fan, Alaska (left), dramatically reveals the dynamic and braided channel pattern common on alluvial fans. The periodicity of channel evolution and shifting on alluvial fans can vary from almost continuous, as in the example shown, to years or decades between significant channel shifts, as evidenced at Horseshoe Park, Colorado (right).

Aggradation is the dominant morphological response in the stream as it crosses the fan, leading to episodic avulsions when the channel fills with sediment and the stream finds a new route across the fan (Figure 27). Channel avulsions may occur dramatically during a single event, such as a debris flow, but are often the result of a channel systematically aggrading in response to cumulative sediment deposition over a long period (Schumm 1985). While aggradation is the prevalent morphological trend, incision may also occur as part of complex process-response feedback loops in the fluvial system (Field and Lichvar 2007). Local head cutting and incision will also occur on the fan associated with avulsion, leading to a wide variety of potential channel states and configurations that may occur simultaneously on an alluvial fan (Figure 28).

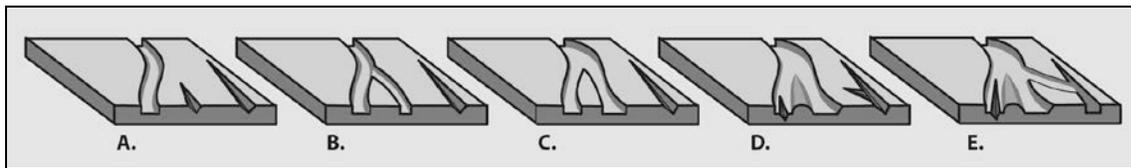


Figure 27. Alluvial fan channel evolution illustrates episodic channel avulsions. As dominant channels aggrade, avulsions occur, adopting headcuts on the fan. As new channels incise into the fan, abandoned channels fill with sediment. Alluvial fans exhibit any and all stages of channel evolution across the fan and along the channel, often simultaneously. (Adapted from Field and Lichvar 2007, U.S. Army Corps of Engineers.)

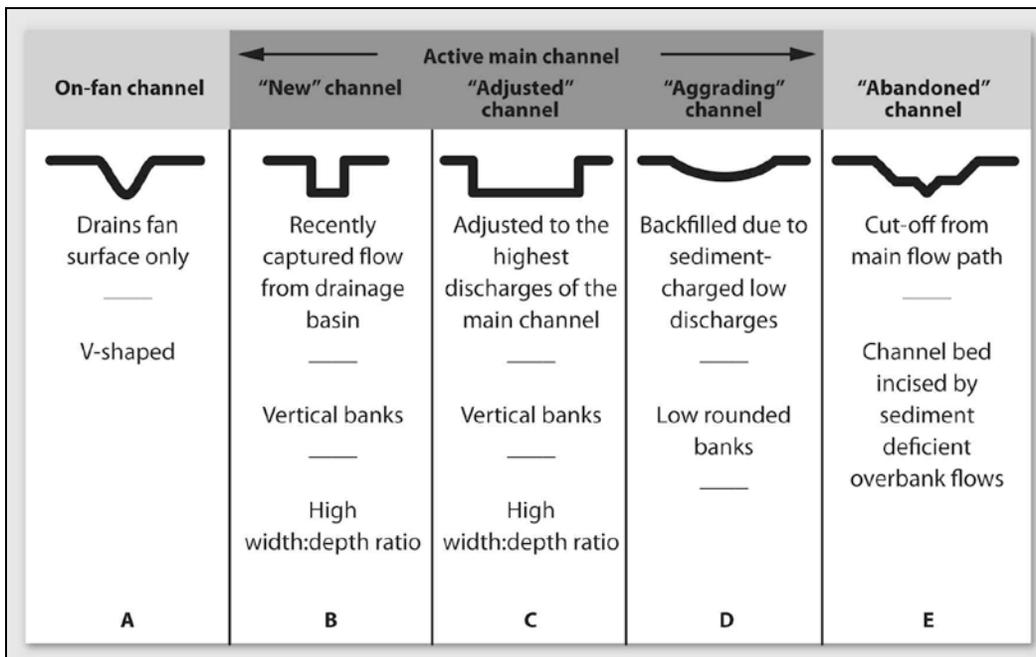


Figure 28. Channel processes on alluvial fans span the spectrum of aggradation and incision as existing channels fill with sediment and new channels cut into the fan. The full suite of channel states may occur longitudinally and repeatedly along a channel within an alluvial fan environment. (Adapted from Field and Lichvar 2007, U.S. Army Corps of Engineers.)

Channels crossing alluvial fans are in a state of perpetual and natural disequilibrium as a result of the wide discrepancy between the supply of sediment from the valley or gorge upstream and the transport capacity of the flow crossing the fan (Tooth and Nanson 2000). This results in transient channel forms that are difficult to predict or manage. However, rates of morphological change can vary from years to decades or even centuries, depending on the supply of sediment from upstream and the occurrence of trigger events for significant adjustment or avulsion. Where processes are gradual, particularly in some of the less disturbed, forested valleys of the western United States, fans may be difficult to recognize except through detailed field investigation or from careful inspection of aerial images. Similarly, where episodic change is infrequent, an apparent stability may give false indication of inactivity. However, an alluvial fan will become inactive only if a fundamental change has occurred either in base level or in the hydrology or sediment supply of its contributing watershed. Neither of these changes is likely to occur except over geologic time scales (millennia).

Development and infrastructure on alluvial fans presents frequent management challenges because of the inherent instability and unpredictability of channels crossing these landforms. As discussed above, channel evolution within fans may periodically progress to a point of apparent equilibrium, only to be disrupted by an extreme sediment transport event or by periods of accelerated sediment inputs. In either case, infrastructure developed in proximity to what appeared to be a relatively stable channel generally requires channel maintenance as the channel aggrades or avulses over time. Expensive long-term engineering solutions are commonly implemented to manage sediment and maintain the channel location, establishing a pattern of frequent channel dredging, infrastructure maintenance and repair, and impact to the river system habitat. Similarly, restoration or stabilization efforts within alluvial fan domains must recognize that unstable reaches are inherent to channel evolution on the fan, even assuming that a sustainable channel configuration can be identified.

The missing element in consideration of management strategies within fans is commonly related to failure to acknowledge the dominant controls and periodicity of destabilizing events on fans, which may be years, decades, or centuries. Apparent fan inactivity should probably be considered a respite from activity rather than evidence of stability, where periods of inactivity are governed primarily by climate cycles or random flood events rather than permanent shifts. In this light, any management actions within a fan environment will be subject to significant uncertainty in their outcomes and the risks associated with dynamic fan processes.

In conclusion, the relations between stream processes and resulting channel forms on alluvial fans do not fit neatly into the existing classification schemes. The inherently dynamic and unstable nature of the channel presents special challenges to schemes for stabilization, restoration, or hazard management. Problems are particularly acute on developed alluvial fans. For example, encroachment by urban areas or agriculture means that the river corridor is narrow or nonexistent, amplifying channel instability and precluding channel avulsions. Similarly, maintaining the safety and security of transportation crossings on an alluvial fan poses serious problems, and in such situations there may be no long-term solutions. Planning restoration projects for streams crossing fans requires recognition that one of the paradigms of restoration design—the aim of matching the sediment transport capacity of the restored reach to the supply from upstream—is inapplicable and must be replaced by the aim of allowing sediment to accumulate and periodically evacuate in ways that support habitat without introducing additional

risks to people and property on the fan. This can be accommodated by setting back levees and removing constraints on the channel boundaries to allow sufficient space for cycles of channel aggradation and degradation coupled with lateral shifting and, where possible, even channel avulsion.

3.6.3. Channel Incision and Evolution

Alluvial channels are considered stable when the dependent variables defining channel form (cross-sectional geometry, mean velocity, slope, and planform) are fully adjusted to the independent watershed controls (flow and sediment regimes), meaning no net degradation, aggradation, widening, or narrowing occurs. However, a stable alluvial channel is not static or unchanging. The concept of dynamic equilibrium recognizes that local adjustments take place almost continuously in alluvial streams, in response to natural variability in the processes (hydraulics, sediment transport, and debris movement) responsible for generating and maintaining channel forms and features. Hence in a dynamically stable stream channel, the spatially averaged parameters of channel form vary slightly through time in response to seasonal, annual, or event-driven variations in the flow and sediment regimes. However, when the independent variables change, either naturally or due to human influences, the dependent variables adjust nonlinearly until dynamic equilibrium is recovered. If the change is relatively minor or short-lived, the channel will return to its previous condition over a period termed the recovery time. If, however, the change is large or permanent, then the channel will adjust toward a new equilibrium condition over a period termed the relaxation time.

Some river systems are geomorphically sensitive and respond rapidly to changes in the independent variables, while others are more resilient. If system recovery or relaxation takes longer than the period between changes in independent variables, then the channel can never achieve dynamic stability. This holds for systems that are natural and relatively undisturbed, as well as those that are disturbed. Natural systems characterized by relatively frequent dramatic disturbances, such as channels crossing alluvial fans and systems dominated by landslides or storm events, may never achieve a dynamically stable condition.

Channel evolution models

Channel evolution models (CEMs), which describe sequences of morphological change that have been observed in a variety of alluvial channels, can be helpful when planning, designing, or evaluating river restoration and stabilization strategies and projects. Understanding where a reach is in terms of the expected sequence of evolutionary adjustments triggered in response to disturbance is essential to developing appropriate restoration and stabilization strategies in disturbed river systems. Two CEMs are in common use (Schumm et al. 1984, Simon 1989) and, while they differ in detail (Thorne 1999), they predict broadly similar progression of channel adjustments during channel incision due to anthropogenic disturbance. While both models were developed for landscapes dominated by streams with cohesive banks, the same evolutionary sequences occur in streams with noncohesive banks, though the stages of evolution may be less well-defined and more difficult to observe (FISRWG 1998). Channel incision in the western United States often results from channelization, removal or alteration of watershed vegetation, removal of large wood and beaver complexes, and increases in drainage networks due to roads.

Simon's (1989) CEM presents six stages of channel succession, beginning with channelization that reduces flow resistance, steepens the channel, and increases transport capacity (stage 1) (Figure 29). Excess transport capacity leads to degradation of the channel bed, or incision (stage 2). While Simon's model refers specifically to channelization as the initial disturbance, incision may be initiated in response to any action that leads to increased transport capacity, reduced sediment supply, or steepening of the channel. Incision enlarges the stream channel by increasing its depth (stage 3), thereby retaining increasingly larger flows in-bank and concentrating more stream power on the channel bed and banks to promote further incision. Incision also steepens the channel locally, creating a nickpoint in the channel profile that migrates upstream, although visually identifiable nickpoints do not always exist in degrading channels. Incision continues until the channel either encounters a restrictive layer, such as bedrock or large wood, or the channel banks become too steep and too high to remain geotechnically stable (stage 4). In the absence of a resistant layer that stops incision, sediment inputs from bank failures and an increased channel cross section eventually limit further incision, so that the bed stabilizes, and the local channel slope begins to flatten. Eventually, as the channel widens, flow depth decreases, relative roughness increases (dissipating some or all of the excess stream power within the channel), and the bed begins to aggrade and scour at the bank margins, allowing the banks to stabilize so that the width stabilizes (stage 5). In the final phase, a new regime channel and floodplain develop within the enlarged channel, with sediment transport capacity and supply again balanced (stage 6). The resultant equilibrium channel and floodplain are now inset at a lower elevation relative to the predisturbance condition, and the historic floodplain functions as a terrace.

However, this channel evolution sequence is altered where a resistant bedrock layer limits incision and bank failures do not contribute to halting incision but may inhibit widening (e.g., Beechie et al. 2008a). This is especially true of small channels that are deeply incised to bedrock. In such cases, bank failure sediments accumulate within the narrow, incised channel and buttress the banks, inhibiting further widening. The widening phase is therefore truncated, the inset floodplain is never significantly developed, and aggradation begins when sediment retention mechanisms recover (e.g., near stream vegetation or beaver dams, Pollock et al. 2007). In well vegetated reaches, channels may incise and remain relatively stable for decades until the riparian reinforcement dies as a result of successional processes or drought (Kondolf and Curry 1986).

In a later modification to Simon's CEM, Thorne (1999) proposed a seventh stage of succession during which 1) the straight channel adjusts by developing sinuosity, in response to oscillations in the sediment supply associated with complex response in the system upstream, and 2) floodplain roughness increases as vegetation colonizes the proto-floodplain developed in the stage 6 channel, decreasing stream power and so further stabilizing the system.

Management strategies for incising channels

CEMs are useful tools for considering management strategies for unstable alluvial river systems that are incising or which may be prone to incision because they lack natural or artificial base-level controls such as bedrock outcrops or grade control structures. By identifying the stage of evolution within a reach, scenarios can be developed that describe probable near-term channel changes locally, upstream, and downstream and provide the basis for a management strategy.

h_c = Critical bank height  = Direction of bank or bed movement

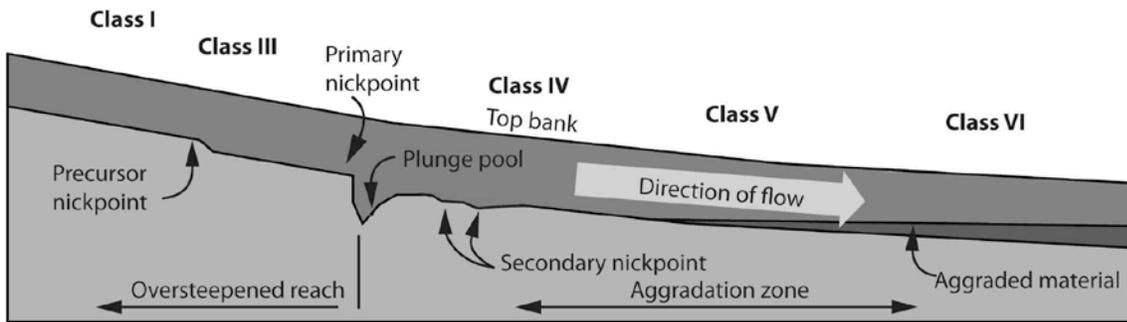
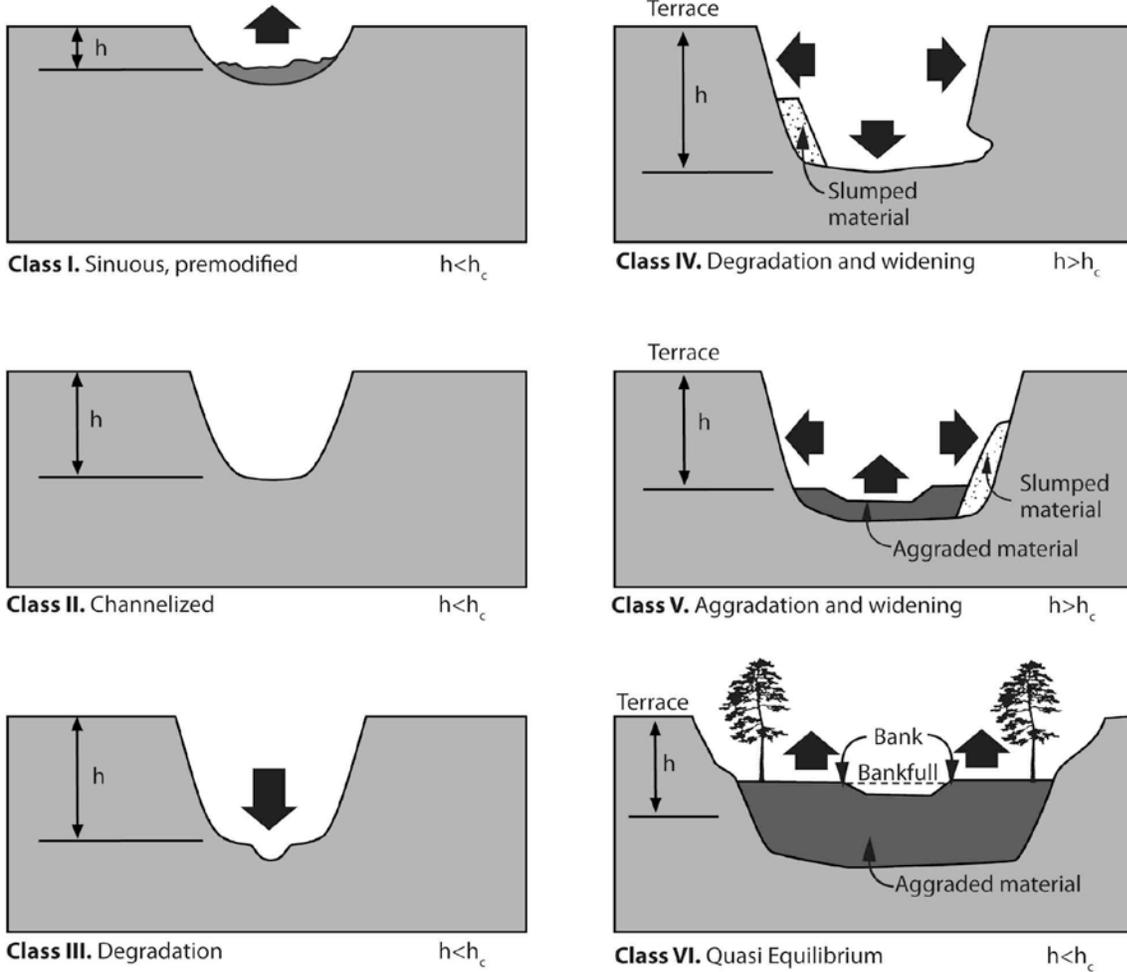


Figure 29. The channel evolution model (CEM) depicts a succession of degradation involving incision and widening, aggradation and widening, and a new equilibrium. The succession of channel condition may vary in time and space along a channel, typically progressing upstream. (Adapted from FISRWG 1998, U.S. Dept. Commerce, and Simon 1989, U.S. Geological Survey.)

Channel reaches in very early stages of unstable evolution may be higher priorities for stabilization if the underlying causes of instability can be addressed as well as the symptoms. However, management of early phases of actively incising streams is challenging.

For example, the introduction of grade control structures to artificially prevent nickpoints and associated incision from migrating upstream may present itself as an apparent strategy to stop further evolution. However, if the underlying cause of the incision is not addressed, grade controls may themselves trigger further incision downstream and may actually delay adjustment and recovery by acting as constraints that artificially lock the channel into an unstable form, only to unravel at a later date when the control eventually fails. Similarly, attempts to stabilize banks that are retreating rapidly due to incision and scouring at the bank toe in stage 3 ignores the evolutionary trend—until the bed elevation stabilizes later in the sequence of channel adjustments, attempts to stabilize the banks are likely to prove futile. Conversely, stabilizing the banks for a stage 4 channel is likely to be successful but unnecessary, as the banks would have stabilized naturally during the transition from stage 4 to stage 5.

Channel reaches in late stages of evolution may require little or no stabilization, as they are at or approaching a new equilibrium condition. An incised channel is incapable of providing the range and richness of habitat or hyporheic functions of its formerly equilibrated self. Therefore, restoration strategies for incised channels should carefully consider aggradation or re-meandering a new stable channel onto the alluvial valley surface. Management strategies for incised channels are summarized by Shields et al. (1999), and further discussed in the Incised Channels subsection of Appendix B.

Indicators of channel incision and aggradation

Identifying the signs of incision or aggradation and differentiating these from normal morphological adjustments within dynamically stable channels is challenging. There may be obvious signs of instability, such as an actively migrating nickpoint in the channel bed, extensive retreat of both banks along substantial reaches, or reach-scale infilling of the channel. But more often, the only means for establishing that a dynamic channel is in fact evolving is to evaluate trends and rates of change over a period of time and in multiple reaches. This is best accomplished using historical and current aerial photos and field surveys, coupled with site investigations intended to infer channel instability from careful observation and interpretation of channel forms and features. These interpretations must also account for varying indicators depending on channel type. For example, in cohesive sediments, an apparent nickpoint (vertical drop) may exist in the streambed, while in noncohesive sediments the nickpoint may be dispersed down the channel profile and thus only identifiable through surveying the longitudinal profile.

A comprehensive list of indicators of channel instability (incision or aggradation) that may be observed in the field are listed in the Geomorphic Analyses subsection of Appendix A. Care must be taken to avoid interpreting natural channel adjustments to the flow and sediment regimes as signs of instability. Analyses that base conclusions on a time-limited data set should be carefully evaluated. For example, in the western United States, significant variation in flow and sediment regimes may occur in association with natural cycles of wet and dry weather (e.g., La Niña and El Niño cycles). Hence hydrologic, hydraulic, and morphological changes and

trends should be placed within the context of natural drought cycles and in the context of dynamic stability assessed over at least steady time (decades rather than years). However, most alluvial channels in the west have been channelized or leveed, and are therefore incised.

3.7. Stream Ecology: Habitat, Energy, and Ecosystem Management

3.7.1. Physical Habitat Needs of Salmonids

Physical stream habitat can be schematized as providing a spatial resource for fish to spawn, eat, or hide. Salmonid spawners generally select clean gravel, often at pool tailouts where upwelling brings dissolved oxygen through the bed substrate. However, even the ideal pool tailout may be left unspawned if adequate nearby cover or refuge from persistent predators does not exist. Runs and glides along vegetated banks or pool heads at the base of a riffle provide feeding opportunities. Feeding habitats also need adequate cover and ideally lower velocities for energy conservation. While adult fish may avert predation by darting to nearby cover, young and rearing fish seek refuge from larger fishes and other predators among slack waters, in shallow waters, within large pore spaces in the bed substrate, and within tangles of roots and debris. The locations within the channel where fish find specific microhabitats that fit their needs and preferences varies with stage (flow depth associated with specific discharge), season, fish life stage, specific microclimatic conditions that determine availability of invertebrate food sources, and seasonal migrations of predatory birds (and anglers) (Quinn 2005).

Spawning salmonids generally require mobile gravels within a relatively narrow range of sizes and with adequate interstitial flow to provide oxygen to eggs (Quinn 2005). Similarly, many macroinvertebrates require clean and oxygenated gravels and cobbles that may only be maintained through regular bed mobility (Brooks et al. 2005). Sediment mobility, determined by specific hydraulic conditions, is a function of particle size, shape, and sorting; water depth; and velocity (see subsection 3.3.3, Sediment Regime). As sediment is transported and deposited along a stream channel and in bars and floodplains, the varying hydraulic conditions sort bed load into varying size classes. Hydraulic conditions vary with roughness elements, such as channel planform, bed substrate characteristics and bedforms, bank material characteristics, and obstructions such as large wood and log jams. Greater variability in roughness elements and obstructions will create greater variability in sorted deposits, thus increasing the probability that fish will find specific conditions appropriate for spawning.

The hyporheic zone beneath the channel bed exists because the downstream movement of water does not cease at the interface between the channel and its substrate. Water moves through pore spaces in the streambed, however, subsurface flow is highly nonuniform, particularly where the bed is uneven. This is the case in small (Kasahara and Wondzell 2003) and large rivers (Konrad 2006). In channels with bed features such as bars, shoals, riffles, and pools, spatially organized zones of inflow to and outflow from the bed (downwelling and upwelling) are well developed. In general, downwelling flow occurs at the heads of riffles and bars, where the bed topography is sloped slightly upstream (Thibodeaux and Boyle 1987). Upwelling occurs at the bar tail and on the downstream slopes of riffles, where cooler subsurface water lowers the ambient temperature in pools. Downwelling and upwelling in the hyporheic zone become more strongly developed as the complexity of channel planform and bed topography increase (Brunke

and Gonser 1997). Hyporheic flow for channels with sand and finer beds is much less significant than for coarser beds (Stofleth et al. 2008).

All spawning salmonid species excavate depressions within gravel deposits, called redds, where they lay their eggs, which are then fertilized and covered by a porous layer of gravel. Salmonids often select riffle heads with downwelling hyporheic flow for digging redds and laying their eggs (Groot and Margolis 1991). The embryos incubate within these redds for several weeks to months before hatching. Newly hatched fish, called alevins, reside within the gravel pore spaces for additional weeks. Embryos and alevins depend on hyporheic flow to supply them with well-oxygenated water and carry away metabolic wastes (Findlay 1995).

When ready to leave the redd, the young fish must be able to travel up through pore spaces between the gravel particles to emerge into the stream channel (Bjornn and Reiser 1991). In addition to spawning habitat, the vigorous hyporheic flow through riffles and bars is also important for numerous species of invertebrates, many of which are food sources for animals higher up the food chain. The hyporheic zone beneath the channel is therefore one of the most important and productive stream habitats, supporting high densities of organisms (Hynes 1970). This habitat is, however, vulnerable to damage if the bar or bed topography is diminished; the seasonal mobility, size distribution, or packing arrangement of the substrate gravels is altered; or the intergravel pores become clogged by fines.

Loss of physical variability (removal of snags, loss of recruitable large wood, channelization, bank stabilization, etc.) reduces channel habitat complexity, and thus reduces the likelihood of aquatic organisms finding the specific habitat conditions they need for various life stages. Alterations to the sediment regime also can reduce variability, as habitat may be buried or stream reaches may become starved of sediment (especially downstream of impoundments). Flow regulation may reduce sediment transport, urbanization may increase sediment transport, and either condition could cause changes to sorting processes that affect habitat. The flashy flows resulting from urbanization or from rapid changes in regulated flows often result in unsorted deposits, as the flows that mobilize gravels may drop off precipitously, thereby reducing the gradual deposition by size class of bed load associated with more gradual changes in flow.

Nonanadromous salmonids primarily eat macroinvertebrates (bugs), small vertebrates (usually other fish), and amphibians and mice. When the fish are not spawning, they are eating, and when they find a reliable feeding station, may become territorial and remain there for long periods (Cushing and Allan 2001). A reliable feeding station is, first and foremost, one that provides a regular supply of food, but also one that requires little expenditure of energy by the fish to stay in place and offers some degree of cover from predators. Pools require little energy for a fish to remain stationary. Pools are typically located downstream from channel constrictions or sites of faster water, from which aquatic macroinvertebrates are entrained. Eddy pools behind obstructions such as channel constrictions, boulders, or large wood offer similar opportunities. As with spawning habitat, heterogeneous feeding habitat is most available in streams that are unconstrained and sensitive to natural disturbance regimes, and that are rich in roughness elements that provide habitat for a variety of macroinvertebrate food sources and opportunity for a variety of size, age, and species of fish. These streams offer a variety of feeding opportunities for fish as water levels and food source life histories change with the

weather and the seasons. Land use changes at the watershed scale can alter the flow or sediment regimes and either minimize or exacerbate natural disturbance processes and direct channel modifications at the reach scale. This can reduce feeding habitat and feeding opportunities by limiting variability in habitat.

For rearing age salmonids, zooplankton is the primary food source (Polis et al. 1997). Consequently, fry will seek rearing habitat that produces ample zooplankton as well as cover from larger predatory fish. Productivity is dependent on water chemistry (inorganic nutrients) and availability of organic matter (Cushing and Allan 2001). The highest productivity of zooplankton and other tiny foods for rearing fry is generally associated with slower, warmer water with more nutrients (Cummins and Klug 1979). Beaver ponds, side channels, oxbows, sloughs, and other disturbance-related features are the most common physical habitat types providing these conditions. Pollock et al. (2003) report that fish productivity is higher for all salmonid species reared in beaver ponds than in free-flowing waters. Most ideal rearing habitats are, by definition, low energy environments and therefore susceptible to naturally higher rates of infilling and sedimentation. In unconstrained, natural stream systems, rearing habitat is continually lost to infilling, but also continually created through natural responses to disturbances, such as floods and the failure and rebuilding of beaver dams, or seasonal scour and fill of pools.

Management strategies often focus on site-specific habitat elements or incorporate specific channel features to create site-specific habitat. Installation of logs, log jams, and boulders, and construction of pools and off-channel habitat are common elements in many stream projects, and may represent a significant percentage of a project budget where habitat restoration or enhancement is a primary objective.

These are important elements to consider in any stream project and they are often incorporated in response to habitat constraints and limits identified during project planning. Less common, however, is the consideration of the probable functional life of these features and the stream processes necessary to maintain them, or perhaps more importantly to continually re-create habitat in dynamically stable systems. Features such as root wads are systematically employed in streambank stabilization projects or channel reconstruction projects, theoretically to add habitat value or mitigate habitat loss.

While these elements may indeed provide bank roughness and associated scour or refuge and cover, they also often create (either intentionally or unintentionally) a hard boundary control and therefore may ultimately constrain the stream processes and morphological adjustments necessary to maintain habitat value over the long term. Static and relatively permanent habitat features, such as anchored logs, rootwads, or boulders, may have very limited functional life for creating habitat, thus their use deserves careful consideration when balancing strategies to meet project goals (see Section 4, Project Development, for further discussion of management strategies and project goals and objectives).

3.7.2. Stream Energy: Factors that Influence Primary Productivity

Energy that influences productivity in river systems comes primarily from food and is regulated by temperature. Stream channel management actions far too often overlook or neglect

to address energy, which is critical to river system health at all scales. To be effective biologically, stream management must address all aspects of the river corridor environment, from channel form and habitat to anything that affects stream energy.

In stream systems, all food energy originates from primary production of new organic matter from inorganic precursors via photosynthesis (Cushing and Allan 2001). This new organic matter—algae, mosses, and macrophytes, or vascular plants—may be produced within the stream or outside of the stream. In either case, these primary products are the origin of the food chain. They are then consumed by progressively bigger and bigger organisms, namely terrestrial and aquatic invertebrates, which are the primary food source for fish. While anadromous fishes do the majority of their feeding and growing at sea, gaining as much as 95% of their biomass from marine life (Groot and Margolis 1991), for juvenile anadromous species and native resident fish, their macroinvertebrate food source is just a few steps removed from primary production processes. Primary production in streams is affected by water chemistry, which determines the availability of inorganic nutrients, the availability of sunlight, and stream temperature.

Water chemistry is primarily a function of basin geology, an independent landscape driver at the regional scale, though climate and human actions also contribute to water chemistry characteristics (Sullivan and Adams 1991, Cushing and Allan 2001). Nutrients can also come from outside of the watershed boundaries in the form of anadromous fish (marine-derived nutrients), and can be critically important to overall stream productivity (Kiffney et al. 2005).

Key chemistry elements include dissolved oxygen (DO), alkalinity, nutrients, and anthropogenic contaminants. DO is rarely a limiting factor for food production or salmonid survival in unimpaired streams in the western United States, though can be a limiting factor in other systems, such as in the southeastern United States.¹⁰ Small, highly turbulent streams are typically at DO saturation. DO is depleted and can become limiting when higher temperatures are combined with very high levels of organic inputs from urbanization or poor agricultural practices. In such cases, reduced DO can stress salmonids and make them more susceptible to other lethal factors (NRC 2003). Alkalinity is essentially a measure of the capacity of water to neutralize acid and is controlled primarily by the amount of carbonate in the water. Alkaline streams are generally more productive than their more acidic counterparts. Natural streams are rarely acidic or alkaline enough to be limiting to fish, but mining operations can be a threat to stream pH. In natural streams, the supply of inorganic nutrients (principally nitrogen and phosphorus) is typically limited by basin geology. Smaller streams in basins with relatively insoluble rocks, such as granite, can be nutrient limited. Nutrient excesses, most commonly from nonpoint agricultural runoff and from sewage treatment, particularly in combination with high temperatures, can become problematic.

Stream temperature directly influences overall system productivity as well as the metabolic rates, physiology, and life history traits of aquatic organisms (Allan 1995, Hughes 1998). Water temperature is determined by air temperature at the watershed scale, the mixing of surface and groundwater at the reach scale, and by the reach-scale and site-scale degree of

¹⁰ F. D. Shields Jr., U.S. Department of Agriculture, ARS National Sedimentation Laboratory, Oxford, MS. Pers. commun., 11 February 2010.

shading, which depends on the type of riparian vegetation and stream size (Cushing and Allan 2001). Spring-fed streams near their source tend to have a fairly constant temperature that is close to that of the source groundwater, which is roughly equivalent to the mean annual air temperature (Laperriere 2006). Streams with a higher percentage of surface runoff–derived flow tend to show greater seasonal variation in temperature; though summer low flows may be substantially groundwater influenced. Stream water temperature generally trends away from baseline or groundwater temperatures in a downstream direction (Sullivan et al. 1990).

While external temperature factors, such as heat from the ambient air, determine the net heat energy delivered to the stream, the internal structure of the stream and its connection to an alluvial aquifer determine how heat energy is distributed and exchanged, and is often overlooked in considering stream projects and management strategies (Poole and Berman 2001). In particular, stream water that infiltrates into the alluvial aquifer travels down valley through the aquifer and later remixes with stream water in the hyporheic zone, thereby exchanging temperature and chemical qualities with the alluvial aquifer.

The hyporheic zone immediately beneath the channel includes the layer of permeable sediments that conveys subsurface stream flow and the shallow groundwater environment that stores and releases water and associated nutrients seasonally (Triska et al. 1989). This zone is known to be critical for stream ecosystems. Water in the subchannel hyporheic zone moves down valley through interstitial spaces between the streambed sediments and is intimately connected to flow in the channel. The rate of flux between the hyporheic zone and the stream is influenced by channel substrate, streambed topography, and channel pattern, as well as by alluvial aquifer characteristics such as aquifer depth and sediment size and sorting (Poole and Berman 2001). In addition to influencing stream temperature, the hyporheic zone can be an important source of nutrients, in some instances delivering a higher percentage of nutrients than surface water (Stanford and Ward 1988).

Unless the potential for damage to the subchannel hyporheic zone is recognized, acknowledged, and properly managed to avoid risk to the stream environment, any instream action can adversely affect hydrological and ecological functioning of the hyporheic zone (Smith et al. 2008). Actions that may pose significant risks include excavation that alters hyporheic flow patterns; changes to stream hydrographs or the seasonality of flows that may alter the spatial or temporal patterns of bed materials; activities in the channel that may disturb sediments; and the use, refueling, or maintenance of powered equipment in or adjacent to the channel.

Pronounced effects on water temperature also arise at the site scale from loss of shade-producing riparian trees. Important parameters include canopy cover, orientation relative to solar track, latitude, and channel width. In smaller streams, riparian vegetation may completely shade the stream, fostering stable, cool temperatures year-round (Bilby 1988). In these cases, streams acquire the majority of their energy resources from organic inputs derived from the riparian community (Cummins 1974). In fully shaded streams, midday summer temperatures rise only 1–2°C above year-round averages. Streams in clear-cut riparian forests, however, can be susceptible to significant diurnal fluctuations, rising as much as 7–16°C due to sunshine warming of the streambed (Beschta et al. 1987).

As streams increase in size, however, riparian influence on stream temperature decreases. Additionally, the mass of water and increased depth limits the degree to which solar gain affects water temperature. In larger streams, water temperature is more closely related to upstream conditions and is moderated by sheer volume of stream flow (Beschta et al. 1987). Wider or larger streams may be less susceptible to temperature impacts associated with the loss of streamside vegetation, because only a small portion of the stream may be shaded.

Beyond site-, reach-, and watershed-level temperature effects, climate change is also contributing to increased stream temperatures, as average air temperature is increasing due to global warming throughout the western United States. (Stewart et al. 2004, National Wildlife Federation 2005).

3.7.3. Ecosystem Context and Scale

An ecosystem is generally defined as a community of organisms and all elements of their physical environment, linked by the flow of energy and nutrients among them. In this document, the term refers more specifically to aquatic and riparian environments and biota, the physical and biological processes active within those elements of the stream, and the watershed controls, stream processes, and channel morphologies that form and sustain them (Beechie et al. 2003). An important feature of this document-specific definition is the incorporation of watershed controls and, therefore, land use in the ecosystem concept.

Historically, studies in ecology have considered the presence and influence of humans within a landscape variously, but generally as agents of disturbance or impact rather than integral components (Wiens 2002). As discussed earlier in this document, the influence of human actions has extended to virtually every watershed in the western United States, often leaving legacies of impact that have colored current perceptions of what constitutes a natural stream condition. While in a purist perspective this may seem disheartening, from a pragmatic management perspective it is simply a reality. Human interaction with an otherwise natural world is an unavoidable fact of contemporary ecology, and therefore of restoration science and management. Holistic management, therefore, will benefit from not only acknowledging human impacts, but also establishing means to accommodate human activities and interactions.

Aquatic ecosystems can be considered at varying spatial and temporal scales, often in the context of the realm of influence and relevance of a particular species. In the context of salmonid species recovery, an evolutionarily significant unit is the established level of biological organization applied to recovery planning (Ryder 1986, Waples 1991a and 1991b). The relevant spatial scale for this level of biological planning is a basin (Waples 1995) (Figure 30). While this spatial scale is relevant to much of the recovery planning that has been accomplished or is underway, most project work occurs at the site and reach scale, a scale of influence that may be relevant to recovery only when considered in the context of cumulative efforts, and only when considerable accumulation of beneficial work scales up to a watershed level (Beechie et al. 2008b). As Figure 30 indicates, actions at the site or reach scale may have little influence on viability at a population or species scale, except where the habitat in question represents the best or most important one for a population within a watershed.

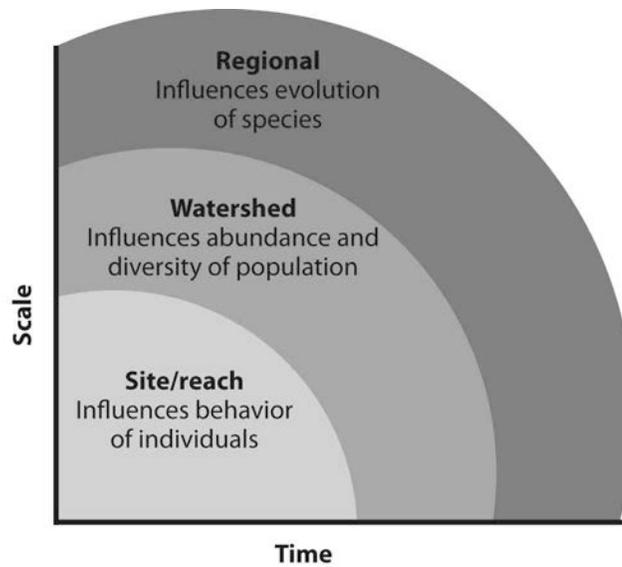


Figure 30. Levels within the hierarchy of biological organization, from individuals to populations to species, are influenced by varying spatial and temporal scales. Actions at the site or reach scale over relatively short periods of time primarily affect the behavior of individuals. In order to influence populations of a species, watershed-scale actions over longer periods should be considered. Further, when considering a species overall, a basin scale and long time frame may be necessary to affect any change.

4. Project Development

4.1. Introduction: Guiding Principles and Steps for Project Development

While stream management actions are typically conducted as discrete projects, they should consider potential upstream and downstream impacts to the stream and watershed. The fundamental purpose for a stream project might be restoration of habitat and the processes that support habitat, but stream management may also address other concerns such as development or infrastructure protection. The scale of projects may vary from small-scale, site-specific habitat improvements to a large-scale channel reconfiguration project extending for many reaches. Regardless of the project goals or project scale, all stream alterations or improvements can benefit from a set of guiding principles that promote effective project development. The following guiding principles emphasize consideration of physical processes and associated habitat, and therefore can be best applied where physical conditions have been identified as a primary constraint to ecological recovery.

The guiding principles of project development are:

1. Identify and address primary causes and processes. Identify and address the causes of the observed problem at an appropriate scale before implementing remedies to observed impacts. Problems observed are often symptoms of distant or broader causes, which may result in impacts at site, reach, or watershed scales. For example, if bank erosion is caused by an actively incising channel, bank stabilization may be futile unless bed incision and its ultimate causes are dealt with first.
2. Look both ways—upstream and downstream. Consider all stream management actions in a watershed context, which may entail looking at upstream and downstream impacts. If possible, address watershed issues prior to or in conjunction with addressing reach-scale and site-scale problems. Identify and understand the consequences that proposed projects may have on downstream and upstream reaches.
3. Do not repair what is not broken. Many channel features that appear to indicate channel instability, such as eroding streambanks, also occur in a natural channel that is dynamically stable. Do not assume that streams need to be fixed without a thorough analysis and confirmation that channel stability problems exist.
4. Keep the door open—evaluate alternatives. Ensure that the selected project does not limit future options for upstream, downstream, and floodplain restoration efforts. For example, projects that impose grade control either upstream or downstream of the project site effectively establish a base level, thereby potentially limiting options for subsequent upstream and downstream management or projects.

5. Accommodate uncertainty. Recognize that what we do not know and are unable to know are as important as what we do know. Ensure that selected alternatives accommodate the uncertainties inherent to natural systems and our imperfect knowledge. For example, management or restoration actions undertaken on alluvial fans should account for the inherent uncertainty associated with such a dynamic environment. Addressing the uncertainties about future events in an alluvial fan environment may be more important when evaluating alternatives than what is known with certainty.
6. Question constraints. Many potential project alternatives are not considered because they conflict with what are perceived as fixed site constraints (e.g., established infrastructure or lack of property easements). Failure to consider all potential alternatives limits potential project success from a habitat perspective. Oftentimes, better projects are produced by removing the constraint (e.g., moving a structure, using a wider bridge, obtaining an easement) than by trying to force a stream to accommodate a fixed constraint. Projects that remove constraints where possible and avoid introducing any new constraints are more likely to provide sustainable results. Experience shows that structurally forcing a particular channel form to accommodate existing infrastructure or property concerns usually constrains stream processes and thus is not sustainable.
7. Maximize natural stream processes. Stream projects are more successful when they restore, rather than restrain, natural stream processes. Take the long view and work with the river. Constructed features should restore process, not just form. For example, creating bars with large rock that never moves restores the appearance of a bar, but not the sediment storage and transport functions that maintain a stream. Another example is the addition of large wood, which is an important component for healthy stream habitat and sediment processes. Although adding large wood to a stream is often beneficial, better results may be achieved in the long term by incorporating revegetation that will restore processes that recruit wood naturally.
8. Do no lasting harm. Short-term project impacts, such as those associated with construction activities, are often necessary or unavoidable, but there must be no lasting adverse impacts resulting from project implementation. Evaluate all impacts associated with project implementation and understand the risk and nature of unforeseen or unintended impacts. Ensure that an adequate monitoring plan exists to identify impacts. Maintain a contingency plan or provide adaptive management to address unintended adverse impacts.
9. Invest wisely and protect the investment. Good projects are resilient; that is, they minimize the potential for future impacts resulting from natural stochastic events, land use change in the watershed, or climate change. Resilient stream projects achieve a dynamic equilibrium that allows them to respond to disturbance by adjusting the channel and floodplain boundaries without losing long-term stability. Investments in projects that cannot be designed to be resilient may provide only short-term benefits. Further, even successful and resilient projects need protection. Easements, zoning, buffer strips and riparian corridors, instream flow protection, and designs that make allowances for changes in watershed controls rather than introducing constraints on stream processes serve to protect successful projects.

In addition to considering these guiding principles, project development should ideally proceed through a logical sequence of steps from conception through postproject evaluation. The project development process presented below for successful project development (Figure 31) is also a convenient framework for project evaluation.

The project development process includes seven steps:

1. Problem identification—linking the identified problem to its underlying cause.
2. Project context—considering the project within its hydrologic, geomorphic, engineering, ecologic, and socioeconomic contexts.
3. Goals and objectives—developing an overall goal that is supported by specific objectives to clarify the project purpose, intent, and anticipated outcomes.
4. Alternatives evaluation—identifying and investigating alternative solutions, management strategies, and design concepts.
5. Project design—developing varying levels of design for the selected alternative to communicate design details to stakeholders and regulators.
6. Implementation—conducting and documenting implementation of all elements of a fully detailed project design and plan.
7. Monitoring and management—monitoring to measure success relative to project goals and objectives, identify geomorphic and ecological trends of adjustment, and inform adaptive management to accommodate unexpected outcomes and ensure continued project benefits.

While the project development process is depicted as linear, inherent feedback loops are present and iterations of some steps in the process are often necessary (Figure 31). For instance, evaluation of alternatives may reveal that stated objectives are impractical or mutually exclusive, requiring that objectives be revisited; or the design process may invalidate assumptions applied in evaluating alternatives and compel reconsideration of project details or alternatives; or, depending on regulatory evaluation, the selected solution may not be permissible, requiring significant revisions to intended project elements or selection of another alternative.

Remarkably, the four phases leading up to design are often overlooked before embarking on design. An unfortunate characteristic in contemporary river management is that project design often proceeds directly from a preconceived solution rather than from consideration of specific objectives, ecological and social context, and an analysis of potential alternatives. Similarly, monitoring is often conducted without sufficient consideration of the other elements of project development. In fact, even though monitoring should theoretically be performed on all projects to verify the attainment of project goals, in practice monitoring is often not performed, fails to relate to measurable objectives, or is only included as an afterthought.

This section details elements of the project development process starting with problem identification and leading up to project design, implementation, and monitoring. Detailed discussion of project design is provided as a resource for design evaluation in Appendix B: Design of Stream Channels and Streambanks.

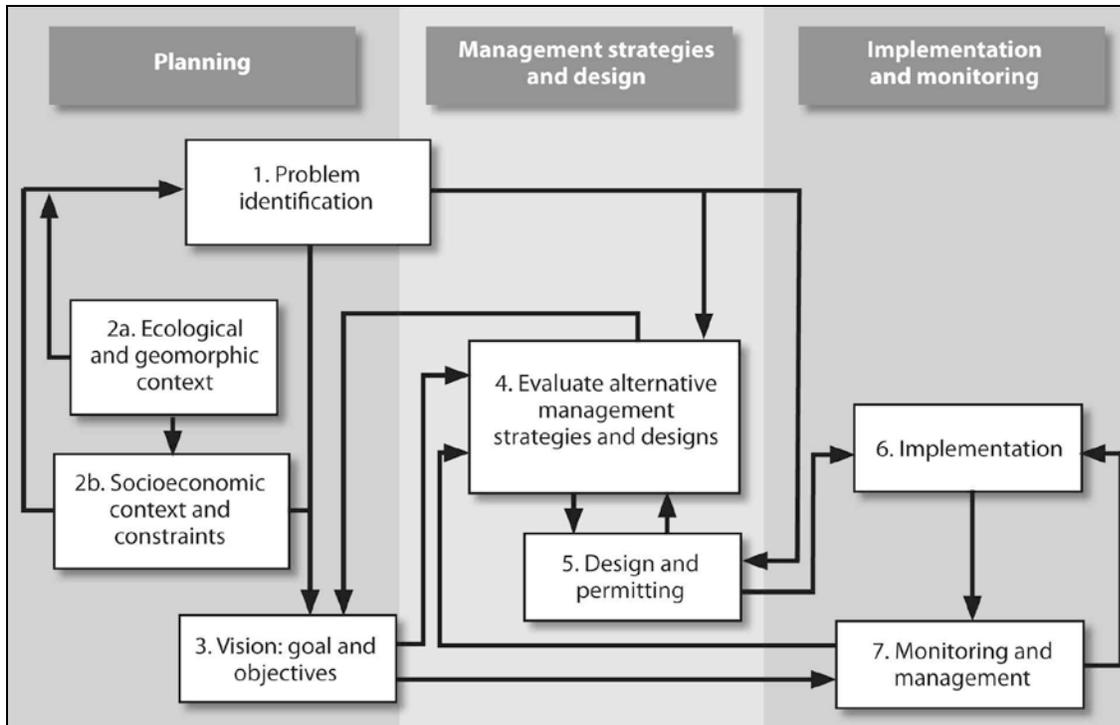


Figure 31. The project development process typically involves: 1) identification of a problem, 2) consideration of the problem in varying contexts, 3) developing a vision of project success articulated through goals and measurable objectives, 4) evaluating alternative approaches to achieving goals, 5) design and permitting of a solution consistent with a selected alternative, 6) project construction and related management actions, and 7) monitoring relative to stated goals and objectives and adaptive management to ensure success.

4.2. Problem Identification

Most stream projects are initiated to address specific problems and projects are usually initiated when problem symptoms reach unacceptable levels. The first step in the project development process is problem identification, which seeks to identify not only the symptoms of a problem, but also the underlying causes. This step often involves an interdisciplinary team of scientists and practitioners. Problem identification also involves determining the scale at which the symptoms and causes occur. Finally, the problems identified in stream projects can be categorized as related to habitat constraints, channel conditions, or water quality.

Restoration planning considers restoration goals in a landscape and watershed context. It provides a framework for evaluating the relative importance of varying restoration schemes and prioritizing restoration actions. Where restoration goals are related to improving biological populations and ecological conditions, the relevant questions to consider are 1) which restored habitats within the watershed will most improve the conditions, and 2) what restoration actions are necessary to restore habitat or access to habitat, as well as at what scale are these actions most appropriate? These questions (Figure 32) can only be answered through watershed-scale analysis (Beechie and Bolton 1999).

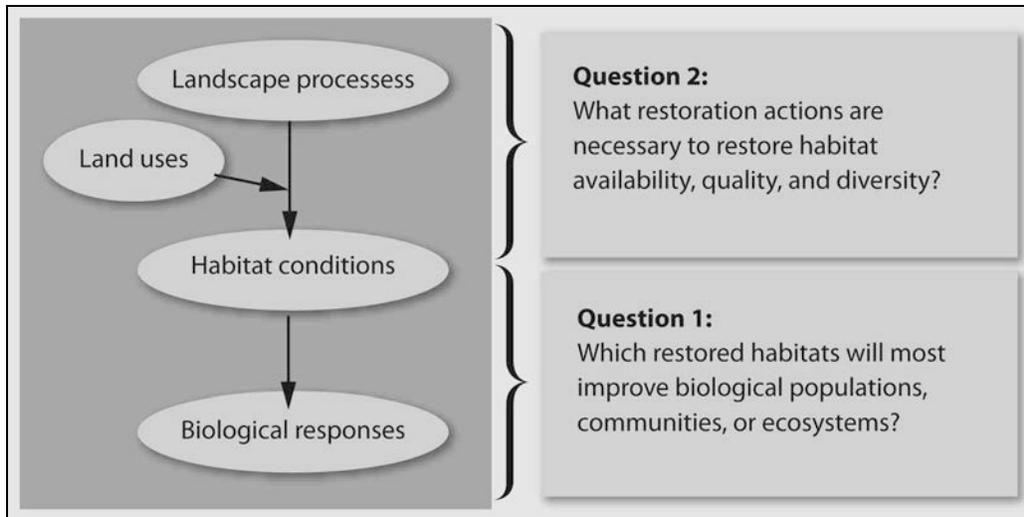


Figure 32. Two critical questions to be answered in restoration planning. In restoration planning, questions regarding what actions are necessary to restore habitat must be considered in a watershed-scale context. Questions regarding what habitat conditions are needed to improve biota can best be addressed at more local scales. (Adapted with permission from Beechie and Bolton 1999, copyright American Fisheries Society.)

4.2.1. Symptoms vs. Causes

Identifying the causes of stream problems is often undertaken by multidisciplinary teams because understanding the causes of stream problems requires insights from several fields of knowledge. Geomorphologists determine whether the cause relates to channel dynamics or to changes to the sediment regime acting at site, reach, or watershed scales. Hydrologists identify other potential watershed impacts and constraints by evaluating historical and current changes to the flow regime. Depending on the project, problem identification may require other experts, such as geologists, geotechnical engineers, horticulturists, range scientists, land use planners, and construction managers. Multidisciplinary efforts enable more informed project planning processes and ultimately lead to more sustainable projects.

Distinguishing between the symptoms of a problem and the underlying causes is critical for problem identification. Unfortunately, common approaches to project development focus on treating the symptoms, rather than identifying and resolving their underlying causes. For example, armoring a failing bank treats a symptom, while addressing the underlying causes of bank failure, which might be channel incision or riparian vegetation removal, is likely to be more effective for solving the problem. While treating the symptoms may alleviate short-term concerns and allow for rapid project implementation, the benefits of the project will generally be unsustainable in the long term and the wrong treatment may actually degrade habitat. For example, a fish biologist may conclude that the problem is a lack of rearing habitat for fish and thus that the project goal should be to create more rearing habitat. However, rearing habitat is a dynamic feature of the channel that is dependent on the flow and sediment regimes, as well as the natural disturbance regime in the watershed. Therefore, while artificial creation of new rearing habitat may be well intentioned, it will likely be only a temporary fix if stream processes cannot maintain it in the long term or re-create it naturally when the channel is disturbed.

4.2.2. Problem Scale and the Watershed Context

Problem identification should recognize that symptoms may occur at much different scales than causes. For example, poor fish habitat is a symptom that occurs at the site scale, but the cause may be 1) a site scale issue such as disconnection of off-channel habitat, 2) a reach scale issue such as flow confinement by levees, or 3) a watershed scale issue such as sediment accumulation due to upstream logging. Evaluation of problem causes and alternative solutions should take place in the context of a multidisciplinary watershed assessment.¹¹ Regardless of the scale of identified problems or their causes, a project will interact dynamically with and be influenced by watershed controls. Thus the watershed context must be considered in developing the project plan.

Watershed assessments typically:

- determine the condition of the watershed,
- identify changes that have occurred within the watershed leading to current watershed and downstream conditions, and
- translate data collected into management- and policy-relevant information that is suitable for decision making and selecting actions across a watershed (Shilling et al. 2005).

A watershed assessment gathers and translates information about the physical, chemical, biological, social, and geographic characteristics of the watershed, from which the probable causes of observed disturbance or impacts to river system habitat can be identified. Particularly, watershed assessments provide insight into potentially destabilizing phenomena that operate at the watershed scale (Table 10). An understanding of hydrologic and geomorphic processes acting throughout the watershed is essential for any scale of project in a river. Regardless of whether projects are planned for the site or reach scales, an assessment of watershed condition is crucial for the accurate evaluation of habitat concerns and the development of sustainable restoration actions to remedy the problems identified. Watershed assessments document and characterize the watershed variables influencing stream processes and morphological conditions, evaluate the extent to which they have been altered or constrained by humans, and provide the

Table 10. Watershed-scale potentially destabilizing phenomena (PDP). (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

Increased sediment supply	Decreased sediment supply
Upstream erosion	Upstream deposition
Tributary input	Bank protection
Bank retreat	Vegetation on banks
Tidal input	Dredging
Straightening	Channel widening upstream
Upstream levees	Upstream weirs/bed controls
	Sediment traps

¹¹ The following Web sites provide resources for watershed assessment: <http://www.epa.gov/emap/>, <http://www.epa.gov/warsss/>, <http://cwam.ucdavis.edu/>, http://www.nwfsc.noaa.gov/assets/4/5316_07142005_182742_chap_8.pdf, and http://www.oregon.gov/OWEB/MONITOR/watershed_assess_overview.shtml.

wider perspective necessary to determine how watershed controls are influencing downstream habitat.

Identifying systemic causes of problems is a primary objective of watershed assessment. Ideally, the influence of legacy impacts from actions taken during presettlement or early settlement periods will be revealed by this type of assessment.

Watershed assessment also provides a window into the future. Accounting for trends in land use change is often critical to developing sustainable restoration strategies, as changes in land use may fundamentally alter future flow and sediment regimes. A watershed assessment identifies not only land use conditions and impacts across the watershed, but also provides a comprehensive view of activities that may impact channel form and processes through their cumulative effects, such as channelization, channel stabilization, or groundwater extraction.

4.2.3. Types of Problems and Their Causes

Within the context of a watershed, problem identification can be categorized as predominantly related to habitat constraints, channel condition, or water quality problems. These symptoms and how to identify their causes are discussed in the following subsections. Also refer back to Section 3, Fluvial Geomorphology and Stream Habitat, for understanding of specific stream processes.

Habitat constraints

Habitat constraints are defined as restrictions on the physical, chemical, or biotic properties of the living place of an organism or community. Descriptions of habitat constraints (or lists of limiting factors) commonly provide the justification for habitat enhancement projects focused on physical improvements to the stream channel. Habitat constraints are typically expressed with respect to a single species, and can be further reduced to life stage-specific constraints for a given species. However, identification of habitat constraints generally considers only habitat condition with respect to its use by a species (the symptoms), and does not explicitly seek to identify why the habitat is limited (the cause). Identification of habitat constraints tends to focus efforts on the creation of habitat conditions that are perceived to be “good” rather than on addressing the watershed controls or stream channel processes that create and maintain a “good” suite of habitat types. Identification of habitat constraints is critical to guiding habitat restoration efforts, but it must be coupled with analysis of watershed controls and stream channel processes that have been disrupted and result in habitat loss or constraint. Thus an understanding of how habitat is created and maintained by natural stream processes at the project site must be incorporated into the solution.

Beechie et al. (2001) provide an example of how habitat deficiencies and their causes are identified at the watershed scale. Using historic reconstruction techniques such as historic maps and field notes from the early 1800s, aerial photographs, and current field habitat and fish surveys, the researchers found that the majority of habitat alteration, degradation, and loss in the north Puget Sound area occur in lowland floodplain areas. In the Skagit and Stillaguamish river systems, more than 50% of floodplain habitats and more than 70% of estuarine environments (collectively 10,040 square km) have been either filled or disconnected from their stream

channels (Beechie et al. 2001). Floodplain habitat is created and maintained by overbank flows and channel migration, both of which have been significantly reduced by diking and levees along the mainstem channels. Other causes of floodplain habitat loss are land use conversion, channelization, draining of wetlands, and beaver dam removal. The resultant habitat change has reduced the rearing capacity of these systems for coho salmon (*Oncorhynchus kisutch*) and other salmonids, who typically reside and overwinter there during the high flow season before completing their migration to the ocean (Beechie et al. 2001, Quinn 2005).

This example illustrates how historic reconstruction of habitat conditions such as floodplain extent and connectivity to the channel can aid in 1) identifying key drivers of habitat creation and loss such as channelization and vegetation removal, 2) defining the spatial and temporal extent of habitat loss such as the lower watershed, and 3) identifying which biological organisms are affected such as coho salmon and beavers. In Beechie et al. (2001), the extent of the study area was appropriately scaled for the analysis: since coho salmon range throughout the watershed, this scale was also used to examine controls on stream processes and habitat constraints. Therefore, restoration priorities and actions can also be evaluated within this watershed context.

Channel conditions

A disturbed stream channel reach may result from changes affecting watershed controls, changes in stream processes, changes in channel boundary characteristics, or direct physical alteration of the channel. Channel responses to disturbance can be simplified into four general categories:

- aggradation,
- degradation,
- width adjustment, and
- planform metamorphosis

Other types of morphological change can be described as secondary responses. Channel responses are commonly associated with disruption of the sediment regime that leads to imbalance between the supply of sediment to a reach and the local sediment transport capacity of the stream. Some of the more common phenomena responsible for changing the sediment supply are listed in Table 11.

Table 11. Reach-scale PDP. (Adapted with permission from Sear et al. 2003, U.K. Crown copyright.)

Increased sediment supply	Decreased sediment supply
Climate change (> effective rainfall)	Climate change (< effective rainfall)
Upland drainage	Dams and river regulation
Deforestation	Reforestation
Mining waste inputs	Cessation of mining
Urban development	Revegetation of slopes
Agricultural drainage	Sediment management

Making causal links between potential destabilizing phenomena (PDP), stream processes, morphological responses, and habitat impacts generally requires the involvement of an experienced fluvial geomorphologist. The Geomorphic Analyses subsection of Appendix A provides further discussion on techniques and analyses for linking watershed controls, stream processes, and morphological responses.

Comparison of existing to historic channel conditions is an excellent way to identify PDP and decipher the potential causes of channel instability. Channel response and recovery can continue for several decades after a disturbance, thus historical analysis can provide insight into the reasons for current problems and the likelihood that channel changes will persist into the future. Additionally, historical analysis can bring to light the relative rates of change, potential threshold conditions (such as channel braiding), and general postdisturbance recovery time.

Sources of historical channel data include aerial photos, survey records, and maps. While systematic air photos became available in the late 1920s, survey records may be available from the earliest settlement periods. Such records make it possible to evaluate changes in historic reference reaches relative to current conditions. Channel changes may relate to planform (number of channels, braiding intensity in braided rivers, meander wavelength, amplitude, and sinuosity in meandering rivers), channel geometry, riparian corridor condition, and other elements of channel morphology. When accompanied by adequate records or photographs of upland and watershed conditions, historical channel records can reveal much about channel responses related to land use changes. However, historical reference conditions can also be misleading. Since photographs and maps are only a snapshot in time, the channel portrayed in a map or photograph may not be stable or in dynamic equilibrium. Additionally, even the oldest of historic references may not reveal earlier, presettlement impacts from wetland drainage, mining, beaver trapping, log jam removal, logging, and splash damming (Wohl 2004). Similarly, firsthand accounts of channel condition should be carefully evaluated because many watershed scale impacts occurred well before the birth of even the oldest citizens.

Water quality

Water quality impairments may result from changes in temperature, pH, dissolved oxygen, and chemical constituents, or from the introduction of heavy metals, waterborne pathogens, or excessive fine-grained sediment. These impairments affect all levels of the food chain. Contaminants such as heavy metals also directly affect fish health and mortality. Even the best remedies for physical habitat and stream channel processes may prove futile if water quality is a dominant biological constraint.

Point source pollution is easier to identify and treat than nonpoint source pollution, but water quality is rarely just a site-scale issue. Solutions to nonpoint source water quality problems usually require much broader-based remedies such as land use regulations and other watershed-level treatment. This is simply a scale issue. For example, stabilizing a single reach of eroding bank does not typically result in a measurable reduction of the stream's fine sediment load when compared against background rates.

The geomorphic influence on water quality is often linked to the transport and deposition of fine sediments. Nutrients, metals, pesticides, and organics all bind to fine sediments, thus

becoming widely distributed throughout the stream system even if they originate from a point source. Because contaminants bind to fine sediments, they are distributed within and across floodplains and in-channel sediment deposits (Marcus et al. 2001). The geomorphic influence on water quality may also manifest in higher concentrations associated with flashy discharge regimes resulting from channel enlargement and incision (Shields et al. 2010). Therefore, any restoration activities that propose to directly or indirectly disturb fine sediment transport processes or depositional forms should be evaluated for their potential impacts on water quality.

4.3. Project Context

Project goals and objectives are only realistic and achievable if they are developed from an understanding of the geomorphic, ecological, and socioeconomic contexts at a watershed scale. Social and economic conditions may introduce obstacles or constraints on what is deemed acceptable, while geomorphic and ecological conditions restrict what is possible. Regulatory conditions may impose additional constraints on project elements and methods that may be contradictory to achieving project goals. As in subsection 4.2, Problem Identification, evaluating project context is a critical second step in the project development process. Failure to fully understand the project context leads to delays in project implementation or project failures.

Many potential social and economic obstacles exist for stream restoration projects (Miller and Hobbs 2007), including institutional and regulatory constraints. Existing legal protection of private property and water rights and the socioeconomic perspectives of landowners can be obstacles to achieving restoration objectives. Funding limitations can impose very real limits on what may otherwise be ecologically possible. These socioeconomic constraints become more prominent hurdles as the scope and spatial extent of restoration goals and objectives increase. Most stream restoration efforts to date have focused on isolated site-scale and reach-scale projects and are based on narrowly defined goals (Bernhardt et al. 2005, Beechie et al. 2008c), usually emphasizing physical habitat objectives. Moving beyond this scale to address the wider causes of habitat problems—watershed land use, dams, water diversions, agricultural and urban development—is difficult because it presents greater social, economic, and political challenges (Roni et al. 2005b).

While the majority of restoration efforts to date have been reach-scale or more local actions conducted independently of the broader watershed context (Bernhardt et al. 2005), a noticeable and encouraging trend is emerging toward restoration and recovery planning at the watershed scale. Coordinated efforts to plan for salmon recovery and stream health at the watershed scale provide a planning context that includes recognition of geomorphic, ecologic, social, regulatory, and economic constraints. Within this framework, more appropriate project goals can be developed, while the relative importance of various projects, or objectives within projects, can be determined through prioritization (Roni et al. 2002).

The importance of watershed health, restoration, and recovery planning has led to a number of state and regional watershed-scale planning efforts including:

- Washington's Watershed Planning Act: <http://www.ecy.wa.gov/watershed/Index.html>
- Columbia River Subbasin Planning: <http://www.nwcouncil.org/fw/subbasinplanning/Default.htm>

- Oregon Watershed Enhancement Board: http://www.oregon.gov/OWEB/policy_main.shtml
- California Watershed Planning: <http://cwp.resources.ca.gov/index.html>

Within the realm of restoration that is socially and economically acceptable, geomorphic and ecological conditions then dictate what is possible. The geomorphic context includes all those factors that influence channel dynamics and the processes that govern them, including human impacts that influence the hydrologic or sediment regimes, impose physical constraints on channel processes, or affect boundary characteristics. Many if not most projects do not necessarily extend the consideration of geomorphic context to the watershed scale. Changes in watershed controls (flow and sediment regime) may significantly impact geomorphic processes at a project site, but may not be readily apparent at the site or reach scale. In particular, reference reaches are often used as the basis for project development and design, yet many of the dominant elements influencing geomorphic context are not captured in reach-scale analyses. While sediment transport analyses may be essential for project design, consideration of sediment transfer through the watershed provides essential context for these transport analyses.

The ecological context, encompassing the suite of constraints on ecological processes and the physical processes that support them, to a large extent determines what it is possible to achieve through habitat restoration (Miller and Hobbs 2007). Many watershed-scale and reach-scale changes imposed on river systems, especially changes in land use, are irreversible over management time frames (Brooks and Brierley 2004, Brooks et al. 2006). For example, it is unlikely that heavily urbanized watersheds will become unurbanized or that productive farmland will ever be fully returned to a predevelopment state during the relatively short time frame of stream management. However, the condition of urban streams can still be substantially improved in terms of ecological function and habitat value (Riley 1998) and many efforts are underway to improve ecological function within agricultural landscapes (Talmage et al. 2002). Rhoads et. al (1999) put forward the term stream naturalization to characterize the variety of management actions that can be considered, particularly in human-dominated landscapes.

What is ecologically possible is often largely a function of geomorphic context. Project proponents may form a preconceived notion of a preferred stream type and social preferences may gravitate toward what is thought to be “natural” (e.g., meandering rivers with pools and riffles (Wohl 2004), yet the preconceived channel form may be unsustainable given the existing hydrologic and geomorphic controls. For example, converting a braided channel to a single thread channel, creating pools in channels crossing alluvial fans, or achieving year-round flow in intermittent or semiarid streams may simply not be possible, at least not sustainably.

Legacy impacts, or impacts that persist long beyond any remaining evidence of their causes, may limit what is ecologically possible and warrant alternative goals and objectives, or at the least a significantly different time frame for restoration. Climate change is almost certain to create and impose limitations for quite some time before the current trends cease or reverse. This means that it may not be possible to restore water temperature, the timing of snowmelt, or the seasonality of flows affected by climate change.

4.4. Goals and Objectives

The third step of project development involves developing appropriate goals and objectives. In project development common practice, the terms goals and objectives are often used interchangeably, but in this document they represent distinctly different concepts.

- Goals are outcome statements that define accomplishment. A goal should efficiently express the intent of a project, serving as the fixed vision to continually assess all project elements against.
- Objectives are statements of measurable actions that support completion of a goal within a specified time frame.

Goals are often not explicit in stating the problems to be addressed; in fact, a suite of problems at varying scales may be addressed by a single goal. Objectives are quantifiable outcomes necessary to achieve a goal, and each goal may contain many objectives. Through the attainment of objectives, progress toward a goal can be measured and plans for monitoring and adaptive management developed.

4.4.1. Project Goals Statement—A Vision of Success

Ideally, a goal statement will be unambiguous and supported by a stakeholder group representing all the people and institutions with interests in the project. Stream management or restoration goals may not be measurable or quantifiable (this is the role of objectives), but should provide a guiding image of project intent. Effective goal statements must be developed through consideration of project context, which assesses what is feasible geomorphically and ecologically, what is acceptable socially, and what is sensible economically (Miller and Hobbs 2007). Identifying what is feasible geomorphically and ecologically typically requires a multidisciplinary team of scientific specialists. Identifying what is acceptable socially and economically requires proper representation of diverse stakeholder interests. Of equal importance are goal statements that acknowledge risks inherent to the project due to scientific uncertainty and natural variability.

Through comprehensive reviews and development of regional and national project databases, Bernhardt et al. (2005) and Rumps et al. (2007) found that many projects lack clear goals. Without a clear goal statement, evaluating project relevance and success is impossible. Project goals should reflect the following four criteria:

1. Articulates a vision of a postproject stream condition that is resilient and self-sustaining.
2. Considers geomorphic, ecologic, and socioeconomic contexts and constraints, as well as the scale of probable actions and outcomes.
3. Coordinates with other planning and management efforts, current and future, within the watershed.
4. Acknowledges the risks and uncertainties inherent to intended project goals.

Examples of goals statements that meet these criteria (adapted from actual project proposals) include:

- Support recovery of all salmonids through restoration of landscape processes that form and sustain riverine habitat diversity, while minimizing impacts to local landowners.
- Restore and protect dynamic channel processes to foster sustainable riparian and salmonid habitat.
- Improve and protect water quality to promote salmon recovery.
- Maximize the area influenced by natural stream and tidal processes, and minimize anthropogenic impacts to or constraints on those processes.
- Reduce development impacts on hydrologic regime and sediment regime in order to reverse trends of stream channel instability and associated habitat degradation.
- Remedy direct or indirect human actions contributing to channel instability in order to address sources of excess sediment and associated habitat and water quality degradation.

Project goals need to be realistic and focused on identified problems within the project context. They should not be stated as prescriptive measures, such as stabilization, reconstruction, or reconfiguration. Prescriptive goals statements effectively predetermine a solution, often before the problem has been accurately identified and adequately evaluated; goals should instead follow the four criteria listed earlier in order to maximize project success. Three typical project goals statements that should be avoided because they make assumptions that lead to a predetermined project plan are:

- Restore historic planform conditions.
- Return channel bed elevation to preincision elevation.
- Stabilize streambanks.

4.4.2. Project Objectives—Defining the Actions

While goals articulate a desired end condition, they do not define the actions to be taken. Hence objectives are developed to define the actions necessary to achieve a stated goal. Appropriate criteria for developing objectives follow the acronym SMART, which is commonly used in project management training, marketing, and business development, but with variation on what the five keywords mean. Here the acronym stands for:

1. Specific: objectives are clear, concise statements that specify what you want to achieve.
2. Measurable: objectives use parameters that can be measured before and after project implementation.
3. Achievable: objectives are geomorphically and ecologically possible.
4. Relevant: objectives are clearly related to and support the project goal.
5. Time bound: objectives are bound by a specified time frame.

Objectives developed to meet these stated criteria provide a solid foundation and clear link to project design, as well as to eventual postproject monitoring. Measurable attributes combined with a specific time frame provide the context for postproject appraisal and, where appropriate, adaptive management.

For larger and more complex projects, multiple objectives may overlap or even conflict with one another. Designating primary and secondary objectives is useful in such cases. Secondary objectives should be met only if they do not conflict with primary ones. In addition, all objectives might not be achieved simultaneously. For example, expanding shallow and protected rearing habitat might increase water temperatures beyond the stated temperature objective. Prioritizing objectives provides greater clarity to project intent and facilitates development of design criteria, as well as postproject monitoring.

As with goals, objectives should not be too prescriptive. Stating objectives too narrowly closes off possible alternatives for meeting the project goals. For example, if the project goal is to increase the number of fish available for harvest, a corresponding objective might be to “increase rearing habitat.” This leads to a prescription that requires instream work as a solution. Modifying the objective to “restore geomorphic processes that create and maintain rearing habitat” is broader and allows for a range of solutions.

4.5. Alternatives Evaluation

The final step in the planning phase of project development is to evaluate alternatives. Project proponents should identify concept plans or alternatives that produce outcomes specified by the goals and objectives. The alternatives are then compared and evaluated for differences in feasibility (including costs) and probable outcomes. An alternatives analysis should always consider a no-action alternative to fully evaluate the consequences of allowing a problem to persist versus the project implementation costs (monetary and environmental) and the value of the outcome.

No project should proceed without formal consideration of alternatives. Failure to consider alternatives often results in projects that are infeasible, conflict with site or societal constraints, or need to be reworked or redesigned at great cost late in the project development process. A common problem with stream projects is that they are developed using preconceived solutions to perceived problems using actions that may be inappropriate. A common perception is that a stable channel will provide the foundation for ecological recovery, yet there remains considerable uncertainty in this hypothesis (Budy and Schaller 2007). Proceeding directly to a solution without undertaking the proper steps leading up to project design typically creates further impacts generated by the project itself, as it introduces new disturbances and constraints in the river system. Thoughtful evaluation of alternatives, in concert with careful development of goals and objectives, can make the important connections between the causes of the problems and designing a project that addresses these causes.

4.5.1. Developing Alternatives

Project investigations

Developing a set of alternatives requires first that proponents for a stream project fully investigate site conditions and constraints. This type of investigation may be performed as part of problem identification and establishing the project context. After goals and objectives are established, project proponents should revisit the investigation to ensure that they have all the information needed to fully understand the problem causes and possible constraints on project

development. The project development process shown in Figure 32 reveals that feedback in the process occurs frequently. Decisions made or information developed in later steps often require that project proponents revisit earlier steps in the process. For example, the original investigations may have focused too narrowly on the area where problem symptoms occur while the problem identification shows that the causes of the problem occur at a larger scale. Under these circumstances, further investigations may be necessary.

Understanding constraints

The range of possible solutions for a stream problem is often limited by physical or societal constraints. Project investigations should identify site constraints that potentially limit stream problem solutions. Constraints come in many forms. Some constraints are physical such as water supply, lithology, sediment supply, and terrain, while others are related to anthropogenic uses of the landscape such as existing infrastructure. For example, stream projects often involve consideration of road crossings, pipeline crossings, existing buildings, or floodplain development. Property ownership often constrains project alternatives. Some projects are limited because project proponents only have access to public lands or they do not want to develop partnerships with private landowners. Some projects are limited because they would change the way in which land has been historically managed. For example, many tidal marsh restorations are not considered because they conflict with community views that the land should not be taken out of agricultural production. Finally, constraints may relate directly to project development. Many times, the money available to support a project is not available or is limited to specific uses. The regulatory permitting process may impose restrictions on methods or land alterations that constrain the range of possible alternatives.

Check your assumptions about constraints, particularly those based on societal and anthropogenic land uses. Some constraints truly exist and are not subject to modification, while it might be possible to relax or eliminate other constraints. For example, relocating infrastructure such as power lines, sewers, or other buried utilities may be too expensive to be practical, so many assume at the start that the infrastructure represents a fixed constraint on project location. Before accepting such a constraint, verify that the costs of relocation outweigh the costs of working around the constraint, and investigate whether the infrastructure is due for replacement or abandonment. Do not assume that the situation is fixed. Failure to fully evaluate constraints may lead to rejections of beneficial project alternatives.

Identify alternatives

The process of identifying potential alternatives is the most creative component of the entire project development process. Much like brainstorming, the first step is to enumerate potential alternatives without dismissing those that appear to be infeasible or impractical. No alternatives should be rejected at this stage; enumerating alternatives often spurs the creative process and leads to development of alternatives that might otherwise be overlooked. Be sure to include a no-action alternative.

Involving stakeholders and additional perspectives is useful in identifying alternatives. Involve specialists from all technical fields related to the project to get a broad range of perspectives. Remember that an engineer is likely to propose an engineering solution, while a

stream restoration specialist is likely to suggest an instream solution. Consider nonstructural measures as well as structural measures. Be aware of artificial constraints on your thinking. For example, don't limit the possible field of action to the location where the problem occurs; consider whether other actions can take place at a larger scale that will produce the desired results.

Evaluate the feasibility of alternatives only after an initial list of alternatives is developed. As you evaluate feasibility, check your assumptions about constraints. Some constraints truly exist and are not subject to modification, but other constraints may possibly be relaxed or eliminated. Consider breaking the alternatives down into their component parts. This provides an easy way of modifying or combining alternatives to meet various regulatory, budget, and social constraints that may come to light during project planning.

Analyze and document alternatives

Feasible alternatives should next be analyzed and documented. The analysis should enumerate the potential implementation costs, benefits, impacts, and feasibility of each alternative. Descriptions of alternatives typically include the following:

- Objectives addressed by the alternative, evaluated at a number of time frames
- Range of benefits and cumulative impacts anticipated
- Consequences of failure
- Probability of meeting stated goals and objectives and relative confidence in achieving predicted outcomes
- Risk to habitat and listed species associated with implementation practices and completed project
- Regulatory constraints and feasibility of obtaining permits
- Societal benefits or risks, including public perception
- A concept level estimate of total project cost
- Difficulty of implementation
- Timetables for completion and meeting objectives
- Limits and constraints imposed by project on upstream or downstream opportunities
- Extent to which various alternatives reduce risk
- Extent of uncertainty in projected outcomes
- Sustainability and anticipated maintenance

Alternatives analysis should include stakeholders and additional perspectives. This often results in revisions to the goals and objectives or development of additional alternatives due to new information, or previously unknown constraints.

Expert review

Upon development of a set of alternatives (and at later stages of project development), it is useful to have an expert review by others not involved in the development process. Outside experts may see fatal flaws or be able to suggest additions or deletions to an alternative. Also, there are formal processes, such as value engineering, for conducting reviews. Value engineering is a systematic method to improve the value of a project by examining the function of project components and their associated costs. Project value can be increased by either improving the functionality or by reducing the cost.

4.5.2. Selecting an Alternative

After alternatives are developed and evaluated, a preferred alternative or set of alternatives is selected. A selection method commonly used on larger projects is a cost/benefit analysis, which uses a suite of sophisticated systems for estimating the value of benefits or consequences associated with environmental or ecological issues. A cost-benefit analysis is most useful when large construction costs are involved and can be accurately estimated.

However, alternatives do not have to be evaluated using a monetary metric such as a cost-benefit analysis. The use of complex methods may not be warranted for many projects. Furthermore, quantifying smaller project outcomes on a parametric basis (e.g., monetary value) is difficult and expensive. Often, alternatives can be rated on a comparative basis using nonparametric or subjective methods (Cohon 2004). Enumerating project outcomes and impacts in a tabular format or in plain text allows for a thoughtful evaluation and comparison of alternatives.

Involving stakeholders in the selection process is extremely important. Many times, the process of selecting a final alternative reinitiates the conceptual design process. The alternatives analysis or stakeholder comments may highlight the need for new alternatives or adjustments in existing alternatives. In such cases, a new evaluation of alternatives is prepared and a new alternative selected for project implementation.

Finally, the alternatives analysis and selection of a preferred alternative should be well documented. As the project progresses, keeping detailed records of the reasoning used to arrive at project decisions is important. Otherwise, as project staff and stakeholders change, the reasoning behind choices made at an earlier stage may be lost and the project success may suffer. All investigations and analyses undertaken during the planning phase should be documented and combined into a single report, typically called the concept report.

4.5.3. McCartney Creek Alternatives Analysis—Case Study

McCartney Creek is a small, perennial tributary of the Columbia River in the coulee country of north central Washington. It flows from headwaters in uplands primarily vegetated with sagebrush through an isolated agricultural valley before dropping into a basalt canyon. For approximately 1,000 meters upstream from the canyon, the stream is deeply incised into fine-grained valley fill, having been channelized through an agricultural property. The channel is in early stages of incised channel evolution, having incised and reached grade stability, but not yet begun to widen. The property is now under a conservation easement established to protect native

terrestrial, avian, and aquatic species including native redband rainbow trout (*Oncorhynchus mykiss gairdneri*).

Acknowledging the degraded conditions resulting from channelization, riparian vegetation removal, and grazing impacts, the fully developed project goal was to “reestablish and protect a naturally functioning riparian and stream system to provide enduring riparian and aquatic habitat for native species.”

A feasibility study was conducted to:

- Estimate historic undisturbed conditions to serve as a potential future desired condition (i.e., restore to historic conditions).
- Determine the probable mechanisms for observed degraded conditions in order to evaluate restoration feasibility and strategies.
- Evaluate the feasibility of restoring presumed floodplain aquifer elevations and providing natural aquifer storage and late season baseflow to benefit downstream water users.

A restoration scheme of raising the bed within the incised channel and reestablishing beaver was presented by project owners as a preferred approach. However, a reconnaissance-level review by a multidisciplinary team determined that considerable uncertainty was associated with a number of elements under consideration, and suggested a geomorphic investigation and alternatives analysis. Field studies determined that:

1. Hydrologic and sediment regimes were not significantly impacted from historic conditions.
2. The probable mechanism of incision was purposeful channelization to facilitate agricultural management and subsequent downcutting. Angular colluvium along the valley margin where the channel had been relocated was providing some measure of grade control in otherwise fine-grained valley fill.
3. A series of shallow piezometers (groundwater wells) determined that the stream was perched above the floodplain aquifer, even in its incised condition, indicating that the stream had likely sealed its bed with fine material. Consequently, the objective of filling up the floodplain aquifer proved unrealistic.
4. Field observation of soils and floodplain fill at coincidental and convenient excavations within the valley fill revealed no history of beaver in previous centuries. Furthermore, the lack of significant existing riparian vegetation would prove limiting for beaver reintroduction until a riparian forest could be established, requiring years if not decades of establishment under even ideal conditions.
5. Floodplain fill material proved to be of fairly uniform fine-grained composition. Further, indications were that the floodplain fill may be predominantly relict fill from glacial Lake Missoula floods, and as such not alluvial in relation to existing hydrology and sediment supply. The fine-grained nature of the floodplain fill makes use of this material for a new channel alignment risky without augmenting gravel supply to the channel, and the risk of avulsion is very high.

These field investigations cast doubt on many of the preconceived objectives of restoring beaver populations and providing floodplain aquifer storage. However, indications of little or no impact to hydrologic and sediment regimes and limited land use impacts within the predominantly sagebrush watershed indicated that restoration of a riparian corridor and stream system should be feasible. Three alternative schemes and a no-action alternative were then evaluated relative to the new project goals:

1. No action: Allow the project site to evolve without intervention. The no-action alternative offers no meaningful risk to property or infrastructure, as this is a remote project site, entirely owned and under easement for conservation purpose, and effectively controlled from further incision by natural downstream bedrock. Further, little or no ecological risk is involved relative to existing limiting conditions, as degradation is unlikely to worsen or continue. However, future channel evolution will likely contribute significant excess sediment to downstream reaches, as the channel migrates laterally through deep, fine-grained valley fill. The disadvantage of a no-action alternative is that it will likely result in continued limitations to habitat value for decades as the channel evolves; therefore, a time horizon of decades is needed before the project area will function as desired for ecological purposes. The advantages associated with a no-action alternative are no costs, low risks, and the potential to study natural channel evolution following incision.
2. Passive alternative, riparian planting: Provide significant riparian planting without any channel modification. The probable outcome of this alternative is that the stream will follow the sequence of changes set out in channel evolution models for incised streams. As incision appears to have ceased, the stream is likely to next migrate laterally and eventually build an inset floodplain and riparian system at a lower elevation, leaving the existing floodplain as a dry terrace. This alternative presents the advantage of being low cost, with a low degree of uncertainty in the eventual morphological outcome. The primary disadvantages of this alternative are a long time horizon for achieving the desired end condition, continuation of substantial sediment contributions to downstream reaches, and a high degree of uncertainty in mechanisms by which the outcome will be achieved.
3. Relocate the stream within the floodplain at historic channel elevation. This alternative would require construction of a new channel and backfill or check dams in the existing incised channel. This alternative presents the advantage of immediately establishing a connection between the stream and its floodplain. However, this is the highest cost alternative and is fraught with technical challenges, not the least of which is how to keep the new channel from incising into the fine-grained floodplain material, how to seal the bed to prevent loss of stream flow through its bed, how to prevent the channel from shifting to a new location and incising again, and how to establish the riparian vegetation. The more obvious solutions to many of these challenges would likely require structural controls that would act as channel boundary constraints and so be inconsistent with the project intent. Further, structural controls impose limits to project resiliency and sustainability, as they limit dynamic channel processes and channel evolution mechanisms that allow natural streams to adapt to disturbances.
4. Excavate the floodplain to match existing incised channel elevation. This scheme would involve excavation of valley fill to create a new floodplain at an elevation that allows for floodplain and stream connection at the existing channel elevation, and revegetation of

the riparian corridor and lowered floodplain. The advantages of this approach are that it essentially accelerates the natural evolution of an incised channel and as such works with the system, would not disrupt the existing sealed channel, poses few risks to the resource, and has a moderate degree of uncertainty in the outcome. The disadvantages of this scheme are a high cost of excavation (though these are less than cost of channel relocation), the need to find a waste site for the excavated material, and significant disappointment among stakeholders that the outcome would not be as they had imagined (a broad riparian complex across the valley with saturated floodplain fill).

As of 2009, this project has not been further developed, as local support for funding was in part based on the assumption that the project would provide increased groundwater storage to naturally augment downstream summer baseflows. Additionally, the recommended approach was more costly than the relatively passive reintroduction of beaver and revegetation effort that was initially envisioned. By default, the no-action alternative is now in play, though all three of the other alternatives remain viable.

4.6. Project Design

The project design process can range from a series of meetings to discuss concepts for nonstructural actions to a very complex process involving extensive engineering analyses for construction-intensive projects. The following subsections focus on the process of developing designs requiring engineering plans. Users should consult Section 3, Fluvial Geomorphology and Stream Habitat, and Appendix B, Design of Stream Channels and Streambanks, on how to design and analyze individual project elements.

4.6.1. Design Tracking and Review

Project design consists of several phases. Depending on the agency or locality, these phases may have different names, but generally the process advances as follows:

- Concept plans (or $\approx 30\%$ plans) are the first phase. These plans, along with the concept report, should indicate the general location of any activities and project elements, show overall layout of the project location, and identify any constraints. The concept report and plans should demonstrate that the project is feasible and reflect a preferred alternative. Alternatives analysis often compares a number of concept-level plans.
- Intermediate plans (or $\approx 65\%$ plans) are the second phase. They should show detailed plan views and profiles of any improvements and standard details. Individuals reviewing intermediate plans should be able to interpret exactly where the project will be built and where project impacts will occur.
- Draft plans (or $\approx 90\%$ plans) are the third phase. They should incorporate revisions to the intermediate plans and add details that are required for construction, such as survey notes, instructions for erosion and sediment control, staging areas, access, and the like.
- Final plans (or 100% plans) are the final phase. These plans should incorporate any revisions to the draft plans and represent the final set of design documents.

Project proponents and regulatory agencies should review each phase of project design. Any comments should be documented in writing and submitted to the design team. The design team should prepare a written response detailing how the comments were addressed. Failure to properly resolve comments and document the review process can lead to costly changes and delays near project completion. This is especially risky on multiyear projects where there is a strong potential for new reviewers to enter the process midproject.

4.6.2. Design Documents

Design documents required to advertise a project typically consist of three elements:

- **Plans:** a set of graphic plans which commonly include a project location map, project plan views of existing and proposed conditions, longitudinal (vertical) profiles, cross sections, standard details, property boundaries, survey controls, planting plans, and plans prepared to satisfy regulatory requirements (e.g., erosion and sediment control).
- **Specifications:** a set of written directions on how the project elements are to be constructed. They should detail acceptable materials, methods of placement, methods of measurement, and how the item is to be paid.
- **Cost estimate:** a listing of the individual project elements, their estimate unit costs, and estimated quantities.

In addition, the project team should prepare a design report that documents the design process, design assumptions, and any investigations, analyses, or modeling performed to prepare the design plans. The design report and concept report provide important documentation on the decision making process used to prepare the project. When reviewing project performance in future years, the lack of such reports makes it difficult to determine the reasoning used in preparing the project design or what the original problems were.

4.6.3. Level of Detail

The type of design documents required to implement the plan should be determined early in the design process.

- The most common type of design document is a full engineering design plan that is of sufficiently high detail so that the engineer can hand off the plans to a contractor who implements the plans. Preparing plans for stream projects to this high level of detail requires accurate surveys and is often difficult and expensive. This level of detail is justifiable if a high degree of risk is associated with the project that requires a well thought-out approach to achieve lower risk of impact. One example is a stream restoration project in an urban area with many sewer crossings and structures located in the floodplain.
- A lower detail of plan preparation can be employed if the designers or their representatives will be on site to inspect and to supervise construction activities. Under these circumstances, plans might be prepared to show the overall concept and develop good cost estimates, but specifications of fine details are left for on-site direction. This type of design document is common for habitat projects where exact structure placement is not critical for project success.

- A third approach is to employ a design-build contract. Under this approach, the project design is left for a contract team to assemble. The contract consists of specifications and deliverables that the design-build team is responsible for constructing. The design-build approach does not infer project simplicity. Rather, it is often used in rapidly changing or complex environments where the time and effort of developing detailed plans and specifications well in advance of construction is not appropriate. This approach is also valuable in situations where significant field discovery is expected (i.e., buried pipelines, unknown depth to bedrock, and culturally significant sites).

4.6.4. Permitting

Permitting should be considered from the earliest stages of project development, but will require the most attention during alternative selection and project design. Possible limitations created by permitting should be addressed to the extent feasible in the alternatives evaluation. Regulatory agencies should be consulted early in design development so that effort is not wasted preparing plans that are not permissible. Permits are a critical path item—the schedule for developing design should clearly identify dates when permits will be submitted and allow adequate time for review. To expedite the review process, engineering drawings should clearly indicate the volumes of material fill and removal, specific materials and equipment required, project footprint, staging areas, access routes, stream crossings, and other pertinent information. Permit review is often completed by those with minimal training in formal engineering, so drawings should be adapted for readability and interpretation by a broad audience.

4.7. Implementation

A good restoration design should be practical to build and acceptable to permitting and regulatory agencies. Construction impacts associated with good designs are short-lived and do not require significant mitigation or ongoing maintenance. Consequently, considerations of constructability and construction impacts are integral to and will strongly influence the design of restored channels and the sequencing of construction elements. Design teams with a strong foundation in construction administration and management will be best positioned to consider constructability through the design process.

4.7.1. Construction Planning

Ideally, construction issues are first addressed in setting the project objectives, refined during feasibility and alternatives analyses, and reconsidered frequently throughout the design process. General construction and implementation issues include:

- site access,
- sequencing of construction activities,
- dewatering and rewatering,
- sediment and erosion control,
- revegetation,
- materials sourcing,

- equipment impacts, and
- safety.

Construction logistics and sequencing are site-specific concerns for which little guidance and no comprehensive resource exists, particularly for instream projects. Local engineering and contracting companies can provide indispensable insight and perspective and their early involvement and consultation greatly facilitates project design, particularly with respect to structural elements related to construction implementation. Contractor review of preliminary designs in particular can ensure that all construction feasibility issues are addressed prior to final design and permitting.

Site access and construction sequencing often significantly affect the feasibility of design alternatives. A comprehensive design plan sheet will specify access and sequencing of construction elements and reveal whether proper consideration of construction issues has occurred. Setting the construction and installation sequence is often an iterative process, and should be undertaken alongside project design. Dewatering and rewatering operations, sediment control, materials management, fish recovery, and installation and eventual removal of access roads all influence the sequence of operations in implementing a project. For channel reconstruction projects, the intersections of existing and new channels are of particular concern because of the potential to recapture flow in the old channel. Ideally, construction should occur in dry conditions; however, when the stream is reconnected and flow is turned into the new channel, these intersections may be particularly sensitive because of the fresh disturbance. As a minimum, a narrative account of construction sequencing will facilitate consideration of construction impacts during project review.

The timing of essential biological activities within the stream will also affect construction sequencing. Spawning or incubation may periodically preclude disturbance; these periods have to dovetail with project sequencing. Dewatering and subsequent rewatering of a construction area or reach of active stream is often necessary for construction. Except for the smallest streams that may be rerouted around a construction area with a pump and pipe (even the smallest of streams at low flow require exceptionally large pumps and pipe), dewatering typically requires an alternate channel, or use of the existing channel, while a new channel is constructed.

The timing of potential storm flow or other high flows also affects project timing and sequencing. Construction is often conducted during predictable low-flow periods, which may be dry summer months or frozen winter months. However, storm flows are possible at any time of year and can inundate a project site. The probabilities, durations, and elevations of storm flow can be evaluated using hydrologic and hydraulic analyses performed during the design process. Contingency plans for storm flow will consider the probability, and hence risk, of inundation. These risks can be clarified in design and construction criteria that specify what flows will be diverted from the project to protect the area from inundation. For example, construction design criteria may specify that controls will be established to prevent all flows up to the 10-year storm flow from inundating the project during construction in order to control sediment and water quality. A 10-year construction month storm flow is a flow resulting from a 10-year storm during the anticipated month of construction, which is not the same thing as a 10-year flood. A 10-year storm flow has 10% chance of occurring during the specified month of construction.

Construction plan sheets should specify areas not to be disturbed, as well as any utilities (water or gas pipelines, power lines, buried cable, etc.) or easements that may limit the project area or pose dangers. Site access often requires temporary roads for the import or export of materials, as well as temporary storage areas for excavated materials. Temporary roads may require imported materials, such as gravels or geotextiles, which need to be removed afterwards. Geotextiles can often be placed directly on floodplain vegetation, covered with road gravel, and removed later with minimal impact to floodplain soil or vegetation. Construction on frozen soils (at higher elevations in inland areas) can greatly reduce impacts to sensitive soils and facilitate access. In many instances, the new constructed channel or a dewatered existing channel can serve as an access road as a project is constructed, particularly for streambank work, and thereby minimize impacts to adjacent floodplains. Whenever equipment, including road legal trucks, is working or traveling within a sensitive aquatic environment, fuels management and fuel leaks become a concern. Although still toxic in high doses, the expanding availability of biodiesel and biodegradable lubricants reduces the potential impacts of spills. The construction plan sheets should also include direction on the cleaning of vehicles before entering the site to reduce the potential of introducing invasive species during construction.

Construction is often thought of as ending when the equipment leaves the site. However, the design may be based on performance criteria that must be met for the design to be properly implemented. As an example, the design of channel hydraulics might assume a roughness associated with a mid-succession stage of vegetative condition. Construction of this project needs to have the roughness managed (plant growth fostered) until such time as the design roughness becomes self-maintaining. Stream projects are rarely completed in one season or one hydrologic year. As a minimum, reviewers should ask the question: When is implementation finished and when does maintenance and management start?

Questions to ask in review:

- Do project plans and narrative provide detail on construction sequence, timeline, and the monitoring and maintenance plan?
- Does the construction timeline overlap with known spawning or migration periods for any native species?
- Do contractors selected to perform the work have experience with instream projects?
- Do project plans delineate disturbance limits and materials storage areas?

4.7.2. Dealing with Uncertainty During Construction

Operational uncertainty during the construction phase stems from a number of sources including:

- inconsistencies, lack of clarity, or gaps in the contractual documents;
- inexperience on the part of the contractor;
- errors in or misinterpretation of the project design drawings and specifications or design specifications that are impractical;

- failure to perform key tasks vital to the success of the project due lack of necessary skills or human error;
- use of inappropriate materials, especially plants in biotechnical schemes;
- inadequate attention to environmental and species protection leading to unacceptable outcomes such as fuel spillage, sediment transmission downstream, or “take” of a listed species;
- bad weather, difficult stream conditions, and, particularly, the occurrence of extreme events during or immediately following construction;
- the possibility that site occupancy and groundwork will reveal unidentified hydrological, geological, geomorphic, ecological, or archaeological features that constitute constraints or opportunities requiring variations from the project design drawings; and
- changes in site conditions that have occurred in the intervening period between project design and construction.

Few academic studies have addressed these issues, but Moses et al. (1997) provide a useful guide to steps that can be taken to reduce the risks associated with uncertainty during construction of urban restoration schemes in the United States. These include:

- ensuring that contractors are fully familiar with the project aims, methods, and materials employed;
- providing on-site guidance by the designer of the project, because paper drawings and specifications may not reveal all the nuances of its construction; and
- setting realistic budgets and time scales to remove the temptation to cut corners and avoid rushed work under pressure.

Mant et al. (2008) provide an in depth treatment of the steps that can be taken to reduce uncertainty during construction to a tolerable or ideally an acceptable level. Based on a number of case studies, they conclude that uncertainty can best be managed successfully through careful planning, the creation of explicit drawings and documents, and the selection of an experienced contractor, coupled with effective communication between the project designer, contractor, work force, and stakeholders.

4.8. Monitoring and Management

The final phase of project development is monitoring and management. Monitoring is composed of two actions:

- Implementation monitoring typically occurs soon after implementation and entails some form of inspection or as-built survey to verify that the project was built according to plan and to document any deviations to the plan.
- Effectiveness monitoring (or postproject assessment) is a formal program of repetitive site assessment and monitoring performed over a long time scale (e.g., years), which evaluates how well restoration projects meet their intended objectives.

Both types of monitoring are fundamental components of the project development process. Both are required so that project developers can determine whether the completed project satisfies individual project objectives and overall project goals.

4.8.1. Implementation Monitoring

Project funders or regulatory agencies typically require some form of implementation monitoring. Funders want to verify that the work that they are funding is actually built. Regulators want to verify that the project is built in accordance with the plans and documents used and approved in the permitting process (Beechie et al. 2009).

Implementation monitoring may consist of a number of actions. As-built surveys are used to verify that constructed works (e.g., instream structures, channel profile adjustments, channel grading, etc.) are built to the tolerances specified in plans. Additional surveys might be performed to verify construction quantities (e.g., volumes of excavation or supplied gravel), number or dimensions of installed structures, or number and types of plants. This information might be used to process payments for contractors. Projects are rarely built exactly as designed, so implementation monitoring provides an important postproject baseline for future effectiveness monitoring.

4.8.2. Effectiveness Monitoring

Effectiveness monitoring, a more complex undertaking than implementation monitoring, is critical to determining whether the implemented project met its goals and objectives and guiding future management actions. Effective monitoring is typically performed over longer periods of time and employs a formal program of repeated surveys or measurements to establish the trajectory of the project as a whole or the trajectories of individual project elements. Results of effectiveness monitoring support adaptive management procedures (Walters 1986, Downs and Kondolf 2002, Roni et al. 2005a, O'Donnell and Galat 2008), which review project outcomes and, if necessary, implement adjustments to the project or to resource management. Effectiveness monitoring also provides the main scientific base for transferring knowledge gained and lessons learned so that future projects can benefit from past successes and failures (Kondolf and Micheli 1995).

Many stream projects fail to perform any type of effectiveness monitoring, which has engendered criticism about individual stream projects and stream rehabilitation practices as a whole (Bernhardt et al. 2005). Effectiveness monitoring helps determine whether an individual project was successful, provides information for guiding future management actions, and helps maintain a focus on the initial project goals. Unless the changes induced by the project are measured and evaluated, the degree of project success is largely unknown. Overall, developers of stream projects should learn from what has worked or not worked in the past and understand how previous stream projects influence ongoing adjustments in existing conditions.

Effectiveness monitoring should focus on process rather than form. From a habitat perspective, functional failures (i.e., loss of fish passage, gravel for spawning, cover) are more important than structural failures (i.e., rock displacement, large wood movement). Project design and success criteria tend to focus on a simple accounting of physical and structural elements of

the project. For example, success criteria for a structure fall within the realm of implementation monitoring, which would identify whether the structure was constructed or installed according to the design plan. Consequently, damage, rotation, or movement of any structural element may be taken to constitute a partial or total failure of the structure. However, a well-developed effectiveness monitoring program would evaluate success of a structure in terms of whether it achieves the desired stream processes, morphological adjustments, and dynamic biological outcomes for which it was designed.

Palmer et al. (2005) provide standards for establishing river restoration monitoring protocols that focus on project goals rather than specific project elements. The standards relate the measured objectives and outcomes to the project goals stated in the original proposal and design documents. They evaluate the success or failure of the project in terms of goals and outcomes by applying preproject and postproject assessment of the project reach that focuses on objectives and outcomes rather than the physical condition of specific project elements.

Effectiveness monitoring is of most value if based on predictive, quantifiable, and testable questions or hypotheses concerning restoration actions and their outcomes in terms of habitat, ecosystems, and species. In subsection 4.4.2, Project Objectives—Defining the Actions, effective project objectives that guide successful design and implementation are characterized as measurable and predictive, with a specified time frame. Project objectives that meet these criteria can serve as the basis for valuable effectiveness monitoring to evaluate the overall success of a project relative to its stated goals.

4.8.3. Considerations for Undertaking Effectiveness Monitoring

The following elements comprise a well-considered effectiveness monitoring plan:

- Project goals and objectives are clearly defined.
- The topographic and temporal scale of project elements and controlling processes is understood.
- The monitoring design plan is appropriate.
- Selected monitoring parameters and locations are appropriate.

Defining goals and objectives

Clearly defining goals and objectives is critical in developing an effectiveness monitoring plan for a project or suite of projects. Recall that goals are broad and almost strategic (e.g., increase aquatic habitat quality), while objectives are measurable and predictive and include a specified time frame for success (Roni et al. 2005a).

Scale

The next step is to further refine objectives into key questions or hypotheses (MacDonald et al. 1991, Conquest and Ralph 1998, Roni et al. 2005a) that help define the scale for effectiveness monitoring:

- Will the monitoring effort be for a single project or multiple projects?

- Will the monitoring effort include only one or a suite of project types?
- Will the expected response be at the site or reach scale (e.g., 10s of meters or 1,000s of meters)?
- Will the expected response be at the watershed or population scale (e.g., affect the entire drainage or population dynamics of the interested biota)?

The spatial scales of sampling effort vary as a function of habitat-forming processes addressed by the actions. The scale of monitoring thus depends on whether a specific action type influences river processes or conditions at the scale of habitat units (on the order of 10–100 m in length), river reaches (on the order of 100–1,000 m in length), or river subbasins or basins (greater than 1,000 square km in area) (Beechie et al. 2009).

Many biological indicators and stream channel metrics are measured at the scale of habitat units (Roni et al. 2005a), and monitoring at this scale is appropriate for restoration actions that attempt to modify the characteristics of specific habitat units, such as the construction of wood or boulder structures in streams to create pools (Beechie et al. 2009). Effects of riparian and floodplain restoration actions are most strongly expressed at the scale of the treated reach, and monitoring of out-of-stream (e.g., riparian processes, floodplain connectivity, lateral channel migration) and instream (e.g., habitat types, fish community structure) parameters should focus at this scale (Pess et al. 2003, Pollock et al. 2005). Finally, hydrologic and sediment processes occur at the watershed scale and effectiveness monitoring of those actions should be undertaken strategically at that scale (Beechie et al. 2005).

For reach-level and watershed-level actions, the critical challenges are devising cost-effective monitoring programs that explicitly recognize years to decades long time lags between certain treatments and responses, and that are designed to indicate improvements in river health long before instream biota express recovery (Beechie et al. 2009). For example, riparian forests on trajectories for recovery indicate improving river health even before stream habitats and fish communities respond (e.g., Pollock et al. 2005). Similarly, the quantification of sediment input rates into stream channels with sediment budgets completed before and after upslope restoration can identify whether sediment supply at the source has changed years to decades before changes occur within the stream channel (Madej and Ozaki 1996, Beechie et al. 2005). The assessment of temporal scale needs to be explicitly incorporated into monitoring programs; one challenge in doing this is communicating the importance of understanding long time lags between watershed processes and stream channel response.

Sampling plan design

Sampling plans should be designed to address individual projects. Each type of study design will have a different suite of strengths and weaknesses (Roni et al. 2005a) and vary with the stream action type, key questions and hypotheses, and scale (Beechie et al. 2009). Numerous texts detail various types of study design (Hilborn and Walters 1981, Hicks et al. 1991, Underwood 1994, Downes et al. 2002, Roni et al. 2005a). Each of these break down into two distinct types of study design: before-after and post-treatment designs. Before-after study designs collect monitoring information before and after the stream action has occurred, and are replicated in time rather than space (Roni et al. 2005a). Post-treatment designs focus on areas

where stream actions have already occurred, but do not include any before data. There is spatial replication, however, because additional sites that are physically and biologically similar but did not have the stream action occur are identified and used as a reference or control site. This allows for spatial rather than temporal repeatability (Roni et al. 2005a). However, the response to a stream action takes time and may be complex (e.g., change in mean density, abundance, etc.). Thus thought should be given to 1) the physical and biological processes that create the cause and effect, 2) the time required to identify a change, and 3) how to quantify the differences due to the stream action versus other factors such as natural variability (Roni et al. 2005b).

Parameter and site selection

The next consideration is the parameters to monitor and the number of sites and years to monitor to determine whether any change has occurred due to the stream action. Characterizing the condition and trend of myriad attributes of river ecosystems is daunting, yet monitoring a narrow suite of end point metrics is insufficient for ascertaining whether restoration actions are achieving their objectives (Beechie et al. 2009). Therefore, the challenge is to identify a small but comprehensive set of metrics to monitor a stream action, and to devise metrics that are diagnostic in nature and capable of detecting which aspects of the river ecosystem have been improved by various restoration actions. This suite of metrics should represent physical, chemical, and biological end points of restoration, but should also capture landscape and watershed processes that form and sustain riverine ecosystems (Beechie et al. 2009). Moreover, such metrics should consider monitoring parameters relevant to societal goals in order to increase the relevance of river restoration to the general public. For example, channel and floodplain restoration actions can include ecological and societal criteria for success, including species richness of aquatic and floodplain dependent species and the amount of land that is needed to maintain fluvial processes (Larsen et al. 2006). These additional metrics allow for balancing ecological benefits against the cost of acquiring land along rivers that naturally migrate across their floodplains.

A monitoring plan needs to quantify the ability to detect a change in the monitoring parameters of interest. To do so, the variability of a chosen parameter must be quantitatively understood, as well as how it is replicated across space or time (Roni et al. 2005a). The main question to be addressed with this consideration is: What is the sample size (either in years, number of sites, or both) needed to detect a level of response of interest from the stream management action or actions? To calculate the sample size, one must know the variability associated with the parameter, the probability of detecting a change if it truly does exist, the level of difference hypothesized to exist between groups (effect size), and the probability of detecting a difference when it does not exist (significance level) (Roni et al. 2005a).

The next step, once the parameters are identified and the number of samples is known, is determining the methods and allocation of sampling within a site or study area (Roni et al. 2005a). As stated previously, no one sample design is best for all situations (Roni et al. 2005a), and several factors need to be considered including the trade off between random versus stratified (e.g., by stream channel gradient or width) sampling, moving between sampling locations, and economic costs (Conquest and Ralph 1998, Downes et al. 2002). Another factor that should be included in this consideration is data management and quality assurance.

Data analysis and plan implementation

Data analysis should ideally be determined during the monitoring design, parameter selection, and data collection phase (Roni et al. 2005a). After analysis occurs, report writing is a critical vehicle for communicating results to funding and permitting agencies as well as the greater community. This links the action with the results and can be used to refine future actions that are similar in type or location. Thus for adaptive management to occur, the results need to be connected in some way to future actions.

Implementing the monitoring program occurs after determining the sample scheme for assessing changes in the chosen monitoring parameters. An implementation plan should include at a minimum the required personnel, equipment, temporal and spatial sampling protocols, and direction for data compilation, analysis, reporting, and storage.

4.8.4. Common Pitfalls in Monitoring

What are some of the most common problems to watch out for during the development and implementation of a monitoring program? At what stage do they occur and what can be done to avoid the most common pitfalls? Reid (2001) found that most monitoring programs that fail to deliver results have problems with either design or procedure. A design problem is defined as having flaws inherent in the overall plan, while procedural problems are those that occur with plan implementation. Of the 30 projects Reid (2001) informally surveyed, nearly 70% had a design flaw, while 50% had a procedural flaw. The most common design flaws include:

- metrics that did not directly measure variables stated in the objectives,
- a study time shorter than that needed to determine statistically significant differences,
- misidentification of the problem, and
- inappropriate study design.

Each of these could be avoided by considering the steps in the preceding section.

Common procedural pitfalls found by Reid (2001) include:

- untrained workers,
- too much of a time lag between data collection and analysis,
- missing information,
- lack of understanding of how to implement technology,
- personnel changes,
- a lack of long-term commitment, and
- protocol changes during the study that prevented comparison of data.

Avoiding many of these pitfalls is difficult, even when following the steps outlined in this section. These types of procedural pitfalls need to be identified by knowledgeable and experienced individuals early in the implementation process.

4.8.5. References to Help Guide Monitoring

The development of a monitoring scheme is a demanding but vital component of any restoration design. Excellent resources are available to support the production of effective monitoring protocols; some of the more widely used references include:

- Roni, P. (ed.). 2005. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, MD.
- Johnson, D. H., N. Pittman, E. Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil, and C. Barrett. 2001. Inventory and monitoring of salmon habitat in the Pacific Northwest—Directory and synthesis of protocols for management/research and volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Dept. Fish and Wildlife, Olympia.
- Skinner, K., F. D. Shields Jr., and S. Harrison. 2008. Measures of success: Defining the outcomes. *In* S.E. Darby and E. Sear, (eds.), River restoration: Managing the uncertainty in restoring physical habitat. Wiley & Sons, New York.
- The Monitoring considerations appendix of the Stream habitat restoration guidelines document (Saldi-Caromile et al. 2004), online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.

4.8.6. Dealing with Uncertainty Following Project Completion

Uncertainty concerning the postconstruction performance of a project arises not only because no design is perfect, but also because future events and developments are truly unknowable. The future morphological behavior of a river cannot be accurately predicted deterministically, mainly because data, models, and projects are not perfect; some amount of uncertainty always exists. Theoretically, properly designed restoration will prevent postproject changes in morphology or habitat. But even alluvial channels in dynamic equilibrium adjust in response to normal flood events: equilibrium is metastable, not static, meaning that it can adjust dramatically from one state of equilibrium to another. In fact, this dynamic condition ultimately sustains habitat value. Morphology and habitat are not static even in streams with constrained boundaries because event-driven changes in the volume of sediment stored in the bed, bars, and floodplain still alter the form and features of the channel. While stochastic or scenario-based modeling can reveal the types of evolutionary or event-driven changes that might occur, in practice, none of the modeled sequences actually will occur. The situation regarding the postproject evolution of aquatic, riparian, and floodplain ecosystems is even more uncertain as additional biotic and environmental factors come into play, precluding deterministic prediction entirely.

Postproject uncertainty cannot be entirely eliminated; however, better science and engineering can reduce knowledge uncertainty and lead to more confidence that the project will perform as expected. Perhaps more significantly, uncertainty stemming from natural variability is an attribute of the river system (not the project) and one that is to a large degree irreducible. This natural variability is vital to the natural function of the fluvial system, provides for a wide range of habitats, and sustains the aquatic, riparian, and floodplain ecosystems.

Historically, postproject uncertainties and their associated risks were dealt with by overengineering designed to put the uncertainty on the safe side of project performance. A typical example of this approach is to use a factor of safety considerably greater than one in the design of a rock revetment used for bank protection. In fact, risks are still associated with the outcomes of projects constructed using overly conservative designs. For example, protecting the banks of a gravel bed stream against extreme events by using oversized rock may focus scour on the channel bed; this produces an unnatural morphological response that undermines the bank protection sufficiently to cause surface sliding or deeper geotechnical failure. At the same time, the potential for eroding spawning gravels and destroying vital benthic habitats for listed species is increased, thus introducing the risk that the project might not be permitted, might cause unexpected take of a listed species, or might need heavy modification after construction.

Uncertainty in the postproject phase is better addressed through a commitment to monitoring, appraisal, and adaptive management. Monitoring provides the basis for this approach by providing evidence of unexpected developments or responses to the project actions. Appraisal involves assessment of project performance against designated targets and time scales, allowing river managers to identify deviations from the expected performance or unexpected changes that may constitute undesirable outcomes or welcome surprises. While the information gained from postproject monitoring and appraisal will certainly increase the knowledge base and improve future best practice, it can only be an antidote to uncertainty if it is linked to an effective program of adaptive management. This means that mechanisms are in place for river managers to 1) act on the findings of monitoring and appraisal by taking further actions to control undesirable trends of change before they constitute a serious risk to the integrity or performance of the project and 2) encourage unforeseen but desirable developments that add value to the intended outcomes of the project.

Adaptive management is a very powerful way to deal with postproject uncertainties because it need only be deployed as, when, and if necessary. Adaptive management offers potentially large savings of materials and costs compared to overengineering, and also has the potential to enhance project performance compared to the targets set during project planning and design. It does, however, require a longer-term commitment on the part of project proponents—a fact that is consistent with ideas of sustainability and after care in-river project management.

Glossary

[Editor's note: These terms are defined to the specific context of this document.]

adaptive management. An iterative process of decision making in the face of uncertainty, with the intent of reducing uncertainty through system monitoring, and continually moving toward a stated goal through ongoing actions informed by monitoring.

aggradation. The progressive increase in channel bed or floodplain elevation.

alevin. Developmental life stage of young salmonids and trout that are between the egg and fry stage.

alluvial. Deposited by flowing water.

alluvial aquifer. A body of groundwater within the alluvium.

alluvium. Materials deposited by flowing water.

amplitude. The width of a set of meander bends; the measure of distance from the crest to the trough of a wave pattern along a line perpendicular to the tangents of the crest and the trough.

anthropogenic. Caused or produced by human action.

armor. An erosion resistant layer of relatively large particles on the surface of the streambed.

aspect. Slope and orientation relative to the sun of the landscape.

ASTM standards. For *American Society for Testing and Materials standards*. Technical standards established for a wide variety of industries by the American Society for Testing and Materials, now known as ASTM International.

avulsion. A change in channel course that occurs when a stream cuts a new channel through a floodplain, as across a meander neck or an alluvial fan.

bankfull discharge. The stream discharge corresponding to the water stage that just starts to flow onto the floodplain.

bankfull width. The surface width of a stream channel when flowing at bankfull discharge as measured between banks.

base level. The elevation at the mouth of a stream channel, controlled by factors independent of the stream channel, that serves as the lowest possible elevation for that channel.

base flow. The minimum flow condition in a stream, usually consisting predominantly of groundwater inputs.

basin. The drainage area of a stream, commonly applied to larger river systems. *See also watershed.*

bed material load. That portion of the total sediment load with sediments of a size found in the streambed and derived from scour of the channel bed. *Compare bed load.*

bedform. Any deviation from a flat channel bed, generated by flow on the bed of an alluvial channel, including pools, riffles, dunes, etc.

bed load. That part of the total load that travels in constant or frequent contact with the bed and includes relatively coarse grains that roll, slide, or bounce along the bed. *Compare bed material load.*

bendway weir. A series of structures projecting out from a streambank along a bend in the channel intended to deflect flow away from the outside bank of the channel.

boundary characteristics. Those characteristics of a stream channel bed and banks that influence the erodibility of their constituent materials and which control or limit processes of erosion in alluvial streams.

boundary materials. Those materials constituting the channel bed and banks.

braided channel. A stream characterized by flow within several channels, which successively meet and divide.

capacity. The ability of stream flow within a channel to transport sediment, measured as a quantity the channel can transport past a given point in a unit of time.

channel. A physical feature consisting of a bed and banks that conveys water and sediment.

channel geometry. The shape in cross-section of a stream channel, commonly characterized by indices of depth, width, width:depth ratio, and hydraulic radius.

channel network. A set of intersecting channels and its characteristic arrangement of channels influenced primarily by geologic and physiographic setting.

channelization. The process of changing (i.e., straightening) the course of a natural stream channel.

CMZ. For *channel migration zone*. The geographic area where a stream or river has been and will be susceptible to channel erosion or channel occupation.

cohesion. The binding together of sediment particles, usually fines, due to clay bonds, and the apparent cohesion of matric suction.

colluvium. Loose material stored in and at the foot of hill slopes and deposited through mass-wasting processes.

competence. The ability of stream flow to transport sediment, measured as the diameter of the largest particle size of sediment rather than volume.

confined. Physically limited by physiography, bedrock, or other geologic features.

controls. Factors that limit the range of environmental conditions or responses.

D₅₀. Median bed particle diameter, such that 50% of particles are smaller.

debris flow. A moving mass of rock, soil, and mud, where more than half of the material is larger than sand-sized grains.

dependent variables. Variables that respond to changes in other variables and include primarily geometric characteristics of the stream—channel pattern, meander characteristics, width, depth, and slope.

deformability. The degree to which a channel bed or bank can adjust.

degradation. The progressive decrease in channel bed or floodplain elevation.

design criteria. Specific, measurable attributes of project components developed to clarify the intent of project elements and meet objectives.

discharge. The rate of stream flow measured as volume per unit time, either cubic feet per second or cubic meters per second.

dissolved load. That portion of the total sediment load that is carried in solution.

DO. For *dissolved oxygen*. The amount of free oxygen dissolved in water expressed as milligrams/liter, parts per million, or percent saturation.

disturbance regime. The frequency and magnitude of recurring disturbances within a watershed.

drivers. Landscape scale factors, including geologic and climatic factors, that determine watershed characteristics and influence river system inputs, yet are independent of watershed and river processes.

dynamic equilibrium. A condition where deformable channel boundaries adjust over time such that the bed material load transport capacity of the channel matches the supply of bed material sized sediment from upstream.

ecosystem. The dynamic and holistic system of all the living and dead organisms in an area and the physical and climatic features that are interrelated in the transfer of energy and material. In this document, it is the aquatic environment and biota, physical and biological processes active in that environment, and the landscape processes and land uses that form and sustain the aquatic environment and biota.

ecosystem services. The suite of benefits people derive from ecosystems, including food, water, water purification, nutrient cycling, natural flood control, and spiritual refuge.

eddy. A localized reversal of downstream current as often forms downstream of a riffle or obstruction.

effective discharge. The discharge that on average transports the largest proportion of the annual sediment load.

ephemeral stream. A stream channel that flows in direct response to local precipitation and whose channel is above the elevation of the water table.

energy slope. The ratio of change in elevation of the stream over a distance along the stream, commonly measured along the water surface.

entrainment. The process of picking up and carrying along sediment.

equilibrium. A condition in which a stream channel form and the processes acting on the stream channel are balanced.

ESU. For *evolutionarily significant unit*. A distinct population of a species that is substantially reproductively isolated from other populations and represents an important component in the evolutionary legacy of the species.

evapotranspiration. The combined effect of evaporation and transpiration, the loss of water from soil from the roots through leaves of plants.

factor of safety. Ratio of restoring forces to disturbing forces, where a factor greater than one indicates that restoring forces exceed disturbing forces and stability is predicted.

floodplain. The relatively flat land area adjacent to alluvial stream channels that is prone to flooding and which has evolved through the deposition of alluvial materials.

flow duration. The percentage of time a flow is equaled or exceeded.

flow field. The velocity and density of a fluid as a function of position and time.

flow resistance. Any factor that impedes flow within a channel, generally by increasing friction or disturbing flow conditions.

fluvial. Pertaining to a stream or river system.

geomorphic processes. Any processes that influence channel form, primarily including erosion and deposition.

geotechnical. Referring to the application of scientific and engineering principles to earth materials and soils, primarily those within streambanks.

groundwater. Water that is continually below the surface of the earth and stream channel.
Compare soil moisture.

habitat. The suite of physical, chemical, thermal, and nutritional resources created by and affected by watershed controls and stream processes.

headcut. An abrupt drop or change in the bed profile of a stream channel, rill, or gully, typically migrating upstream in response to change in base level or sediment transport capacity.

hydraulic. Referring to the forces of moving water.

hydraulic geometry. The cross-sectional dimensions of a channel that influence and are influenced by discharge.

hydraulic radius. The ratio of cross section area to wetted perimeter.

hydrodynamic model. Any model that characterizes the dynamic properties of flow in a channel and its floodplain, including velocity vectors and stage.

hyporheic zone. The saturated portion of an alluvial aquifer below a stream which actively exchanges alluvial groundwater and stream water.

hydrologic regime. The spatial and temporal variation in stream flow in a river system, usually characterized by magnitude, frequency, duration, timing, and rate of change statistics.

imbricated. Overlapping and tilting in the same direction (downstream).

incipient motion. Hydraulic conditions that bring a given particle size to the threshold of motion.

independent variables. Variables that are not influenced by the processes acting within the stream channel, but rather, they determine the watershed inputs to the system, namely stream flow and total sediment.

indeterminacy. The state of being impossible to determine or know in advance.

large wood. A relative expression of wood in a stream channel sufficient in size to be immobile at most flows and to interfere with channel hydraulics, commonly referred to as LWD (large woody debris) in the literature.

levee. A berm constructed parallel to a channel to contain flood flows (as distinct from a natural levee).

LiDAR. For *Light Detection And Ranging*. An aerial surveying technique using pulsed laser light reflected from ground surfaces.

limiting factor. The most constraining habitat encountered by a population, also referred to as a population bottleneck. It is that habitat type or life stage that limits the size of a population. (See Reeves et al. 1989 and 1995 for quantitative examples.)

longitudinal profile. The profile of a channel drawn along its channel bed, generally measured at thalweg depths.

mass wasting. The downslope movement of earth materials due to gravitational force.

matric suction. Negative pore water pressure applied to bank materials by partially saturated conditions, apparent cohesion between particles.

meandering. The winding of a stream channel in an alluvial valley.

natural levee. A naturally formed alluvial berm on a floodplain parallel to a stream channel.

nickpoint. The point of change or break in the slope of a river profile.

OHW. For *ordinary high water*. A statutory term whose definition and characterization varies jurisdictionally, but generally represents the stage of mean annual peak flow.

oxbow. An abandoned meander bend, when cut off completely forms an oxbow lake.

pattern. The configuration of a section of stream channel characterized in plan view.

PDP. For *potentially destabilizing phenomena*. Factors that may significantly affect channel stability.

perched water table. Unconfined groundwater separated from the underlying main body of groundwater by unsaturated rock, often a clay or lahar lens in alluvial materials.

phreatic fringe. The surface or margin of groundwater from which plant roots derive water.

piezometer. A well (pipe in the ground) used to measure groundwater elevations.

placer. A glacial or alluvial deposit of sand or gravel containing eroded particles of valuable minerals.

planform. The shape and geometric character of a channel in map view.

pool. A channel bedform characterized by relatively deep, slow-moving water with a smooth surface.

pore water pressure. The pressure produced by water in a saturated soil and transferred to the base of the soil through the spaces between soil particles (pores).

primary production. The creation of new organic matter through photosynthesis from inorganic precursors.

project elements. Distinct project components that require some degree of analysis to design which in concert constitute a complete reach-scale reconfiguration or stabilization design.

reach. A section of stream having relatively uniform physical attributes, such as slope, sinuosity, bedforms, and dominant bed material.

redd. An area of streambed gravel disturbed by fish within which eggs are laid.

reference reach. A reach of stream used as a template for design or which is assumed to be representative of desired conditions.

refuge. A place of safety where organisms can hide from predators or flood flows.

regime channel. A channel with cross section, slope, and sediment size in equilibrium with flow and sediment input.

resilience. The capacity of a system or community to resist or adapt to changes in environment (watershed controls) in order to maintain functionality/viability.

restoration. Action taken to enable physical and biological processes to operate naturally and free from artificial constraints.

return interval. The frequency of occurrence of a given discharge.

riffle. A stream channel bedform characterized by fast-moving and relatively shallow water flowing over or through gravel, cobbles, or boulders.

riparian. In close proximity to and dependent on the moisture of a stream channel, often specifically its banks.

riprap. Broken rock, cobble, or boulders placed along a streambank to protect the bank from erosion.

river system. An ecological system composed of streams and associated riparian functions.

riverine habitat. The channel form, water, substrate and debris, and associated riparian community that provides some or all life history requirements for food, shelter, and space resources.

rootwad. A mass of roots attached to a tree trunk, typically installed in a streambank or streambed to protect a bank or provide aquatic habitat.

roughness. A generalized measure of the resistance to flow as influenced by bedform, bed material, and vegetation.

runoff. Water that flows over the ground and reaches a stream as a result of rainfall or snowmelt.

saltate. To bounce along the stream channel, a form of sediment transport.

salmonid. Fish of the family Salmonidae, including salmon, trout, and char.

scour. The erosive action of running water in streams, which excavates and carries away material from the bed and banks.

sediment. Soil or mineral material transported by water and deposited in streams.

sediment continuity. The balance of transport of sediment such that there is no net erosion or deposition (aggradation or degradation) within the channel.

sediment discharge. The amount of sediment moved by a stream in a given amount of time.

sediment load. The granular material carried by a stream. *Compare suspended load.*

sediment regime. The characteristics of sediment discharge over time, including the variability in time of sediment supply, sediment characteristics, and sediment transport.

segment. A section of stream channel constituting multiple reaches.

shear (stress, force). That component of force tangential to (along) a surface such as a streambed or bank, expressed as force per unit area.

sinuosity. The ratio of channel length to direct valley length.

site. A small segment of a stream reach.

slope. The ratio of change in elevation to distance between two points.

slough. A shallow, undrained depression, often formed in a former stream channel.

soil moisture. The water stored within soils above the saturated zone. *Compare groundwater.*

solifluction. The slow downslope movement of waterlogged soil.

spate. High water, typically resulting from storm flow or snowmelt.

splash dam. A temporary dam constructed across a stream used to flush harvested logs down the channel by impounding water and logs, then releasing them in a flood.

stable channel. A dynamic channel condition in which equilibrium is persistent and channel form will recover to previous morphology if disturbed.

stage. The elevation of the water surface at a specified location above some arbitrary datum.

stationarity. A condition where data do not exhibit any spatial trend.

steady state. Not varying with time or with inputs of energy.

stochastic event. A random event, such as a landslide, fire, volcanic eruption, or flood. The occurrence of individual stochastic events cannot be predicted, but the probability can be described by statistical means.

stream. A channel that conveys water and sediment from its contributing watershed to a larger downstream river system.

streambed. The unvegetated portion of a stream channel.

stream habitat. The physical, chemical, thermal, and nutritional resources created by and affected by watershed controls and stream processes.

stream power. The rate of energy supply at the channel bed, useful for describing erosive capacity.

suspended load. That portion of the total sediment load that is suspended in the water column.

Compare sediment load.

sustainable. A condition where processes and state persist indefinitely without maintenance.

terrace. A horizontal surface above the elevation of a floodplain, generally a result of an abandoned floodplain surface in alluvial systems.

thalweg. The line drawn along the deepest points of a channel.

total sediment load. The total load of stream sediment including that derived from bed material load.

turbulent flow. A characteristic of fluid flow having variations in local velocities and pressures, where fluid moves erratically.

unconfined. Not limited by physiography or geologic features.

velocity distribution. A measure of variability in velocity within a column of water in a channel expressed as the range of velocities along a vertical line normal to the direction of flow.

velocity profile. The range of velocities across the channel.

watershed. The total land surface area that drains to a point in a stream. *See also basin.*

water table. The surface between a saturated zone and an unsaturated zone, synonymous with the elevation of groundwater.

weathering. With reference to rock, it is the physical or chemical breaking down of rock into mobile particles.

weir. A structure to control water levels in a stream.

wetted perimeter. The cross-sectional distance along a streambed and banks that is in contact with water, generally measured at a bankfull stage.

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Appendix A: Investigative Analyses

Hydrologic Analyses

Hydrologic investigations characterize, usually through statistical analyses of historical records, the primary descriptors of the flow regime, including the magnitude, frequency, duration, timing, and rate of change of stream flow at gauging stations (Poff and Ward 1989). Hydrologic analyses characterize seasonal and interannual variation in the timing and volume of stream flow, and provide insights into how the regime has changed over time, as well as how it may change in the future under alternative scenarios for climate and land use change. Understanding changes in the flow regime may be a crucial element in identifying the causes of existing problems and possible future stresses on river ecosystems. For example, evaluating historical flow records may reveal trends of change in the frequency or duration of channel-forming flows. Such trends may explain observed channel instability or indicate the susceptibility of the channel to future instability.

Design criteria for various project elements may be defined relative to specified flows extracted from the results of hydrologic analyses, such as channel-forming flow for channel dimensions, base flow for instream habitat, and flood flow for channel stabilization structures. Similarly, the probability of any particular flow occurring in any given year, expressed as the inverse of the return interval, is useful for evaluating the risk associated with failure of project elements related to that flow. For example, a design criterion for a recently constructed, bioengineered bank that mandates bank stability up to a 20-year flow for a period of 2–3 years implies a 5% chance of failure in each year (5% chance is the inverse of a 20-year return interval). Table A-1 describes the relevance of commonly applied return intervals.

While flow probabilities can be useful for design and consideration of risk, it is equally important to consider the uncertainties inherent in hydrologic analyses. Uncertainty is described generally in the Uncertainty and Risk subsection of Appendix C, and many of these principles are relevant to hydrologic analyses. Uncertainty in this context stems from unknown

Table A-1. Return intervals and associated probability of occurrence. The inverse of a return interval is a probability of a given flow occurring in any given year. Specific return intervals are commonly applied in restoration and stabilization planning and design, but often without indicating the associated probability of occurrence, which is often more informative.

Return interval (years)	Probability of occurrence	Relevance
1	99%	Mean annual peak flow, “ordinary high water” in some states
2	50%	Commonly applied as equivalent to bankfull or channel-forming flow
25	4%	Commonly applied for stability criteria in natural channels and stream banks
100	1%	Flood delineation for the Federal Emergency Management Agency

measurement inaccuracies, data limitations, and inconsistent data quality; natural annual variability in stream flow; unknown future impacts of land use and climate change; and model uncertainty. Specifically with respect to the determination of return intervals, we must consider the length of discharge records. The period of record for discharge may range anywhere from a few recent or historic months to a century or more. The uncertainty in calculating the return period for widely used design flows, such as the 2-year event, is high for short records but decreases markedly as records increase in length. A long record will also enable consideration of extreme events such as droughts or wet periods, as well as provide the basis for evaluating land use impacts through a sensitivity analysis of selected statistics for different segments of the record. Conversely, calculating the 100-year flow is statistically uncertain even from 100 years of record. Experience shows that the magnitude of the theoretical 100-year flood has had to be reevaluated frequently in light of the many so-called 100-year floods observed recently in western states. Similarly, natural variability in channel form and dimensions at bankfull stage within a reach can lead to considerable uncertainty in estimates of bankfull discharge based on field measurements and hydrologic records (Heil and Johnson 1995).

One of the most widely employed discharges for the design of naturally functioning channels is channel-forming flow, which forms the primary independent variable input to hydraulic geometry equations. Channel-forming flow in stable alluvial streams can be estimated by the bankfull discharge, a discharge with a recurrence interval of about 2 years, or the effective discharge, which transports the most sediment over a prolonged period (Copeland et al. 2000). However, none of these candidate discharges ideally represents the channel-forming flow in most circumstances. For example, where the channel is incised or aggraded, the bankfull discharge may no longer represent a channel-forming discharge. Similarly, the use of a return period flow such as the 2-year flow, while convenient because it is easily derived from a flow record, is often inappropriate. While numerous studies (Wolman and Miller 1960, Williams 1978, Andrews and Nankervis 1995) have indicated a strong correlation between the 1- to 2-year flow and channel-forming discharge in natural alluvial rivers, the data represent primarily larger streams with perennial stream flow and may not apply to smaller streams, especially if they are ephemeral (Castro and Jackson 2001). Computation of the effective discharge is commonly regarded as the preferred method for establishing channel-forming flow for stable channel design (Biedenharn et al. 2000, Doyle et al. 2007), particularly where watershed hydrology is known or suspected to have changed due to land or water resource development.

An important trend is developing that relates return interval flows to ecological criteria; for example, scientists are now identifying the return interval flow that is significant during spawning periods, that is associated with the lower limit of woody vegetation, or that is significant for recruitment of woody debris. This characterization leads to better understanding of hydrologic statistics across disciplines and reinforces the concept that various design discharges are relevant to a variety of project elements and project objectives.

Another output from hydrologic analyses that is often used in a regulatory context is ordinary high water (OHW). While of regulatory significance, the OHW term is of little practical value in restoration design, as its definition is ambiguous and varies among and within state and federal regulatory agencies. Consideration of various OHW definitions reveals that they often rely on streambank descriptors that will lead to substantially different designations of OHW stage (water elevation) and associated discharge within the same channel. While the

intent of most definitions appears to indicate the average annual high water elevation, which may approximate a channel-forming discharge, the lack of strong correspondence between bankfull discharge and channel-forming discharge in many systems calls into question the utility of this term. In any case, services staff (e.g., National Marine Fisheries Service and U.S. Fish and Wildlife Service) would need on-site definition of OHW when evaluating the use of OHW as a means of defining flows for restoration planning and design.

Most hydrologic investigations are based on statistical analyses of flow records. Where a project reach has a flow gauge nearby with a significant period of record, deriving most hydrologic design inputs is a fairly straightforward exercise in statistics, for which there are sophisticated but accessible tools.

Flow statistics such as mean low flow (applied to evaluation of extent of the low-flow habitat and habitat design), the 100-year flow (applied to flood inundation risk), maximum peak flows for any given month (applied to determine risk of construction inundation during construction months), or minimum flows for any given month (applied to passage design), can all be statistically derived from existing flow gauge data. However, many streams are ungauged, or the period of record may be insufficient to derive significant statistics. In such cases, hydrologic investigations will also involve modeling stream flows from precipitation records to develop a synthetic flow record. The Tools and Resources subsection below provides a summary of common hydrologic analysis tools and flow-simulation models, as well as their appropriate applications and limitations.

The flow regime is a function of the regional landscape drivers of geology and climate, but is strongly influenced by watershed controls including soils, vegetation, and land use (Figure 3). Analysis of discharge records and storm hydrographs over a prolonged period of record will often reveal the influence of changes to watershed vegetation or land use. Development that involves replacing natural soils with impervious surfaces over even a relatively small percentage of a basin can greatly affect the runoff regime, often leading to more frequent, higher magnitude, and shorter duration flows associated with storm events. In semiarid climates, irrigation return flow can alter summer hydrographs, while impoundments established to store irrigation water greatly affect runoff in winter and spring. Climate change also is affecting the timing and distribution of precipitation and snowmelt, thereby altering hydrographs even in undeveloped basins. These hydrograph impacts create inherent challenges in determining appropriate design flows for restoration programs.

One of the most common errors in hydrologic analysis is the derivation of hydrologic statistics from an entire period of record when mean values are nonstationary. In watersheds impacted by climate or land use change, use of the entire period of record will distort the values derived for event return intervals and the associated values for the probability of occurrence. This is particularly relevant to higher frequency flows, such as the 2-year flow values that are commonly used as the basis for channel design. In watersheds subject to urbanization in particular, the frequency of a given discharge may increase dramatically and what was once a 2-year channel-forming flow in an alluvial channel may now occur many times a year. In such cases, it becomes imperative to segment the flow record to identify land use change as a cause of channel instability and derive design values only from that portion of the record that represents existing hydrologic conditions.

Considerations for Design Review—Hydrologic Analyses

This brief review of hydrologic investigations leads to several key considerations for design review (i.e., questions to ask):

1. From what type of hydrologic data are design hydrologic statistics, and thereby design discharges, derived? For gauge data, what is the period of record and where is the gauge relative to the project site? For synthesized data, what tool or model was used to derive synthetic hydrographs, and over what period of record? What statistical methods were used to derive design flows? For regional regression derivations, how geographically relevant are the regional regression equations used?
2. Has the natural hydrologic regime been altered? Has the hydrologic data record been segmented to distinguish between the historic/natural regime and the portion of the period of record affected by, for example, land use impacts on the watershed controls? What portion of the record is being used as the basis for determining design flows—natural only, impacted only, or the entire period of record? Can impacts to flow regime be reversed? If they can, over what time frame? Does the derivation of design discharges take this into account?
3. Is a natural/historic hydrologic regime the current, impacted regime, or a future/anticipated flow regime used as the basis for project designs? Do project objectives address observed or expected future changes to the natural or impacted flow regime?
4. What stated project objectives are related to or impacted by the flow regime? What project elements have established design criteria related to specific design flows?
5. What specific flows are being used for particular project elements and how were these selected? In particular, how was the channel-forming flow determined? Do design criteria for different project elements specify different design discharges?

Tools and Resources for Hydrologic Analyses

- Overview of hydrologic analyses and methods
 - The Stream Habitat Restoration Guidelines document (Saldi-Caromile et al. 2004) provides a thorough review and resource list for hydrologic analyses. Online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.
- Hydrologic statistics from gauge data
 - Indicators of hydrologic alteration (IHA) is a comprehensive flow-data statistical software tool developed by the Nature Conservancy to evaluate deviation from normal hydrologic conditions. Menu-driven, IHA is sufficiently sophisticated to be defensible, sufficiently user-friendly to be practical, and provides virtually all the statistical derivations needed to develop design discharge from stream gauge data.
 - Program PEAKFQ performs hydrologic statistics based on U.S. Geological Survey Bulletin 17B (USGS 1982), the federal standard protocol for flood frequency derivation.

- The Hydrologic Engineering Center Flood-flow Frequency Analysis (HEC-FFA) Program performs frequency computations of annual maximum flood peaks in accordance with USGS 1982.
- Derivation of flows from precipitation (simulated runoff models)
 - Menu-driven software, roughly equivalent to DOS version of HEC-1, HEC-HMS software simulates runoff from precipitation at any point in a watershed for a given storm.
 - In DOS format, HSPF software simulates precipitation runoff from mixed pervious and impervious surfaces and from continuous precipitation data to compute a basin hydrograph and water quality parameters.
 - The Storm Water Management model (SWMM), a menu-driven model of water quantity and quality developed by the Environmental Protection Agency, simulates precipitation runoff primarily in urban catchments.
- Regional regression equations (estimation of flood flows)
 - Jennings et al. (1993) provide a nationwide summary of USGS regional regression equations for estimating magnitude and frequency of floods for ungauged sites.
- Effective discharge calculation
 - Barry et al. (2008) relate effective discharge calculation to prediction of bed load transport rate.
 - Biedenharn et al. (2000) provide guidance on estimation of effective discharge.
- Software sourcing
 - Abstracts for utility and limitations of most resources listed above are online at http://www.dodson-hydro.com/software/hydro-cd/cd_org_list.htm.

Geomorphic Analyses

The dominant processes of concern to fluvial geomorphologists are erosion, deposition, and transport of sediment. These processes are governed by flow and sediment regimes, influenced by boundary characteristics, and result in characteristic channel forms, sediment features, and habitat. In this sense, geomorphic analyses are integrative, drawing on hydrologic, sediment transport, and boundary characteristics analyses to characterize the stream processes within a project reach, as well as to predict probable responses to proposed management or restoration actions. Ultimately, the fundamental function of geomorphic analyses is to determine whether a channel is stable or unstable, causes and degrees of instability, and whether instability is inherently natural or a result of anthropogenic disturbances.

Geomorphic analyses are used to:

- Characterize historic conditions and establish an historic baseline or equilibrium condition. Not all natural channels are naturally in equilibrium condition. Streams in many arid regions, as well as those that cross alluvial fans and deltas, are all inherently unstable in that they are either perpetually aggrading, incising, or avulsing as natural

functions of sediment exchange and channel evolution. In such cases, efforts to stabilize channels often prove futile.

- Evaluate the departure from historic conditions. Geomorphic analyses can quantify the absolute difference between historic and existing conditions, as well as characterize the trajectory of change.
- Understand causes of change or instability. Geomorphic analyses evaluate changes to independent variables and boundary conditions that may be causing change or instability. Such analyses can also determine whether causes are direct (local, acting at the site) or indirect (acting on flow or sediment regimes).
- Evaluate potential restoration trajectories. Analyses can be used to predict response to management actions, including the probable system trajectory under a no-action management scenario.

The ability to characterize historic conditions to establish a baseline or equilibrium condition is entirely dependent on availability of historic resources, primarily including air photos and surveys. Historic descriptions of conditions and actions can be enlightening and offer a generalized perspective on conditions, but may be of little value in quantifying departures from normal. With sufficient air photo or survey data, however, it is possible to quantify departures from historic conditions as well as rates of change for many channel characteristics, including primarily channel pattern.

A generalized characterization of key indicators of geomorphic instability includes evidence of incision, aggradation, lateral migration, or planform metamorphosis. While each of these processes occurs naturally in alluvial channels, the occurrence of persistent trends or excessive rates of change relative to natural variability in the fluvial system constitutes a river “problem.” Hence, the significance of channel change must be gauged, as well as its existence, before deciding whether the channel is dynamically stable or unstable. Further, lateral migration may occur in concert with either aggradation or incision, and so in and of itself may not be a strong indicator of the type of geomorphic instability. Incision and aggradation, while sometimes readily observed in the field, are best detected and evaluated through longitudinal profile surveys of the channel bed and banks.

Common indicators of incision are:

- Low width:depth ratio.
- Continuous oversteepened or vertical streambanks with evidence of retreat due to erosion or mass failure along both sides of the channel simultaneously, slumped trees from higher bank positions.
- Abrupt break in channel profile (headcut or nickpoint) of the primary channel, demarcating the upstream extent of incision. This may be indicated by an overfall in a channel with a cohesive bed, a perched culvert or an exposed bridge apron, but it can also be a subtle feature, especially in coarse-bedded streams, that is only discernable from a surveyed profile.
- Presence of artificial grade-control structures or heavy armoring of the bed.

- Exposed bridge piers and piles, abutments, pipelines, or other static structural features that should be below bed level.
- Excessive bank erosion where overbank flood flows reenter the channel.
- Changes in points of diversion to increasingly upstream positions.
- Exposure of rock or clay layer and lack of gravel/cobble features on bed.
- Lack of pool habitat in an otherwise pool/riffle-dominated system.
- Transition of vegetative composition in channel banks from moisture-dependent species to drought-tolerant species as the depth to channel bed and associated groundwater table exceeds rooting depth.
- Extensive exposed and undercut tree roots.
- A narrow riparian zone, exists only or primarily within channel banks, and associated loss of riparian vegetation on floodplain.

Common indicators of aggradation are:

- Very high width:depth ratio.
- Poorly sorted bed material and low elevation bar forms.
- Frequent overbank flooding, exceeding common annual flood frequency.
- Recent and prevalent channel avulsions associated with channel filling rather than mature meander bends and neck cutoffs or the development of flanking subchannels in braided systems.
- Excessive in-channel bar development, particularly mid-channel bars.
- Depositional lobes of coarse sediment (sand and gravel) on the floodplain.
- Excessive bank erosion associated with very high rates of channel widening or lateral shifting.
- Poorly sorted substrate within channel bar deposits and bar elevations exceeding floodplain elevations.
- Loss of flow capacity at bridges and culverts.
- Death of vegetation that is saturation intolerant.
- Adventitious roots in trees subject to sedimentation around their stems.

In addition to evaluating channel stability problems and the causes of those problems, geomorphic analyses are also used in project design. Geomorphic elements of the design may rely on analogs or empirical relations (see the Technical Basis for Design of Project Elements subsection of Appendix B) or may employ geomorphic theory and modeling to develop channel designs. In essence, geomorphic analyses complement hydrologic and hydraulic analyses in the design of multiple project elements and forms, including cross-sectional dimensions and geometries, channel planform patterns and attributes, in-channel features and habitat, and floodplain elevations relative to the channel bed.

Considerations for Design Review—Geomorphic Analyses

This brief review of geomorphic investigations leads to several key considerations for design review (i.e., questions to ask):

1. Is the channel at the project site truly alluvial and governed by dynamic channel processes, or does it feature natural (colluvial, bedrock) boundary controls that are the dominant controls on channel character?
2. Has a watershed assessment indicated any historic, current, or future impacts to flow or sediment regimes?
3. Has the channel been physically altered through resectioning, enlargement, embanking, encroachment, or channelization?
4. Are there artificial constraints to natural dynamic alluvial process, such as bank protection works, weirs, or grade control structures?
5. Is there any indication of persistent aggradation or incision, or excessive channel migration or avulsion? Are there legacy impacts (e.g., beaver removal, logging, mining) that have likely influenced historically recorded and current conditions?
6. If channel instability is a problem, have its causes been determined? Are the causes direct or indirect, where direct is a local feature causing local instability, and indirect is a change in watershed controls causing system-scale instability? Are there ongoing impacts that may lead to further changes in the flow or sediment regimes (and continued stability problems) if they persist?
7. Have the causes of contemporary or potential future channel instability been remedied, or is the project design intended to address the causes as well as their symptoms? Does this extend to indirect as well as direct causes of instability? If it is intended to treat the causes; over what time frame should the solution become effective?
8. Are the channel form elements in the project design (hydraulic geometry, planform, habitat) based on analog, empirical, or analytical design approaches (see the Technical Basis for Design of Project Elements subsection of Appendix B)? If using an analog approach, have all the conditions for valid application been verified (i.e., Are the problem causes local and direct, is the reference reach stable, and are the reaches upstream and downstream of project reach also stable?)? Additionally, if using an empirical approach, are the empirical data sets geographically and geomorphically relevant to the project site?

Tools and Resources for Geomorphic Analysis

Geomorphic analysis is more of an integration of analyses from multiple disciplines than a distinct suite of analyses that are specific to channel form. Appendix D, Annotated Bibliography, provides a comprehensive listing of common guidelines, many of which describe geomorphic analyses and methods. However, the fundamental geomorphic investigation of determining channel stability relative to watershed inputs is subject to such a wide range of potential variables that no single approach developed to date provides an adequate method of assessment. Most professional geomorphologists rely on techniques and methods described in a

broad suite of individual technical papers and on independent, custom-developed analytical tools (e.g., spreadsheets based on empirical equations) that are not distributed or publicly available.

A few commercial enterprises have developed packages of assessment and analysis techniques (e.g., Rivermorph, <http://www.rivermorph.com/>, or WARSS, <http://www.epa.gov/warsss/index.htm>), but these have not necessarily achieved any degree of sanctioning from academic or federal agencies, may be heavily reliant on comparison to reference conditions rather than absolute or inherent measures of stability, and are therefore limited in application. Following is a partial listing of some useful tools or resources.

- Geomorphic analyses overview and methods
 - The Stream Habitat Restoration Guidelines document (Saldi-Caromile et al. 2004) provides a thorough review and resource list for geomorphic analyses, online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.
- Field methods
 - Stream Channel Reference Sites: An Illustrated Guide to Field Technique (Harrelson et al. 1994) provides methods for measurement of static stream channel characteristics, but does not provide analytical techniques for evaluating stability or trends.
- Channel stability analysis.
 - The Pfankuch method (Pfankuch 1978), a method of rating stream stability using 15 stability indicators for mountain streams in the northwestern United States, provides users with a tool for determining a subjective description of channel stability, rather than a quantitative evaluation of change in condition.
 - Channel Evolution Models (CEMs) are any of a number of conceptual models that relate observed channel condition to a phase in the process of adjusting to system inputs. CEMs, described in subsection 3.6.3 of this technical memorandum, are useful tools for establishing geomorphic trends and likely outcomes.
 - Rapid Assessment of Channel Stability in the Vicinity of Road Crossing (Johnson et al. 1999) provides a rapid assessment method for determining site-scale and reach-scale channel stability based on indicators of geomorphic and hydraulic processes at play. This method provides a relative ranking, rather than a quantitative evaluation of magnitudes of change.

Channel Classification and Geomorphic Analysis

The development of stream channel classification systems began decades ago for a variety of applications, but most commonly in an effort to explain the wide range in observed channel forms and patterns. Classification of the project and surrounding reaches is now commonly employed as an investigative tool and is useful as a step along the way to building the foundations for a sound design. Classification is useful for communicating information concerning observed conditions and establishing the context for assessing the response potential of the stream to disturbance. However, classifying the channel does not in itself provide a sufficient basis for identifying the dominant processes at play or predicting the type of channel response likely to result from disturbance. Classification, while occasionally required by project

sponsors (Simon et al. 2007), is not actually an essential step in either geomorphic investigation or channel design (FISRWG 1998). However, the parameters required for classification by any of the published and more widely used classification systems will typically be measured in any geomorphic investigation, so classification can be seen as a low cost option that may add value and insight on preproject conditions in the project reach. Considerable discussion of the utility and limits to channel classification as an aid to investigative analysis and channel design is provided in recent literature (e.g., Naiman 1998, Montgomery and Buffington 1998, FISRWG 1998, Shields et al. 2003, Simon et al. 2007, Roper et al. 2008) and these issues are further discussed in subsection 3.6.2, Channel Classification.

Hydraulic Analyses

Channel hydraulics result from interactions between the flowing water and the channel boundaries. The resulting velocity distributions are complex and three-dimensional, and are influenced not only by channel morphology and boundary conditions in the project reach, but also by conditions in the reaches immediately up and downstream. The velocity distribution, or flow field, determines the mobility of bed and bank materials, the sediment features that develop, and the nature of the instream environment, including the habitat that the channel provides. However, flow field details are difficult to measure, let alone model or predict. Still, hydraulics tools and models are available to simulate and evaluate open channel flows in one, two, or three dimensions and these may be applied to investigate existing conditions, support the design of project elements, and predict postproject conditions. Thus the ability to model and predict channel hydraulic characteristics is vital to a successful project outcome.

Hydraulic analyses provide the analytical foundation for many approaches to channel and streambank restoration design. They are used to establish the water surface profile through the project reach, the velocity distribution, and the fluid shear stresses and drag forces acting on the streambed, banks, and any engineered structures under the design flows (low flow, channel-forming discharge, design flood).

While hydrologic and geomorphic analyses relate mainly to the flow and sediment regimes and the watershed controls on those river attributes, hydraulic analyses allow the design team to focus on the project reach, examining relevant site- and reach-scale flow phenomena, sediment dynamics and continuity, and how any structural elements in the channel such as weirs, engineered log jams, bank stabilization, or grade control structures interact with the flow. Further, hydraulic analyses provide a means of examining the extent of secondary channel and floodplain inundation at selected design flows, as well as the basis for designing microhabitat elements or fish passage structures (culverts, ladders).

Several options are available for performing hydraulic analyses. The level of analysis selected should be appropriate to the problem being investigated, the project element being designed, or both. Typically, analysis may be performed to produce at-a-section, one-dimensional, two-dimensional, or three-dimensional simulations of the velocity field. The models available to perform these analyses may be hydraulic models, which assume steady flow—dealing with a hydrograph as a series of discrete steps in the discharge—or hydrodynamic models, which account for unsteady, gradually varied flow. When selecting an appropriate type of model, practitioners should consider the availability of data and the funds, expertise, and time

available to build and run the models, as generally the cost of modeling increases in a nonlinear fashion with the complexity of the model. Above all, the levels of detail and accuracy required of the output must be matched to specific project needs, especially the design of specific project elements, to avoid modeling for its own sake.

Hydraulic modeling is a useful tool for examining a number of conditions or alternatives, as individual model runs are relatively inexpensive once the model is developed. While it is tempting to take model results at face value because they represent numerical values derived from meticulous methods utilized by skilled and trained technical persons, model results typically report much greater precision than is warranted in the application to design or the interpretation to physical and biological processes. The reasonable use and interpretation of hydraulic model output is discussed in the introductory chapters of the HEC-RAS manual (<http://www.hec.usace.army.mil/software/hec-ras/>). In general, the best use of model results is often in the comparison of alternative conditions or alternative projects, where the differences between model runs is given more credibility than the actual values of the numerical output itself.

At-a-section Analysis

At-a-section analysis examines velocity in one dimension (downstream) at a cross section only, without consideration of upstream or downstream influences on flow (e.g., convective accelerations or backwatering). This type of analysis is an appropriate and relatively simple approach for investigative and design applications involving relatively uniform channels (cross-sectional dimensions and slope do not change along the channel) in unconfined reaches with no downstream controls such as weirs, bridges, aprons, or culvert inverts. At-a-section analysis is generally based on the empirically derived Manning flow resistance equation, which predicts the cross section averaged stream velocity as a function of the cross section area, hydraulic radius, slope, and roughness. The outputs of this type of analysis include width, average depth, and mean velocity, which may be sufficient to support some basic investigation of existing conditions (e.g., incipient motion of the bed material, instream habitat) and options analysis in the early stages of the project design process. WinXSPRO is a public domain software package (<http://www.stream.fs.fed.us/publications/winxspro.html>) that facilitates at-a-section analysis. However, while applications of this simple approach are common, the uncertainties involved are considerable. For example, accurate estimation of the roughness coefficient for at-a-section analysis and how this varies as a function of flow stage are vital to obtaining reliable results and this remains a challenge in applying this approach.

One-dimensional Models

One-dimensional (1-D) models compute hydraulic conditions along a reach for a specified discharge; outputs include the water surface profile, mean depth, and mean velocity in the downstream direction. The advantage of 1-D models over at-a-section analyses is that they consider upstream and downstream influences on the flow and can account for the effects of convective accelerations or backwatering on the water surface elevation at each cross section.

Application of 1-D hydraulic or hydrodynamic models typically require channel cross sections, a longitudinal profile of the bed, roughness values, and some observed discharges and

water surface elevations for model calibration. One-dimensional models define the water surface elevation and extent of inundation at each cross section, and more sophisticated models allow extrapolation between cross sections along topographic contours to provide maps of inundation and section-averaged downstream velocity along a reach. Consequently, they are powerful tools for 1) investigating how and where local controls may be contributing to the problems addressed by the project and 2) simulating selected design flows and the potential impact of the proposed project on instream conditions and the extent and frequency of flooding.

One-dimensional models should be used wherever the flow is nonuniform (where downstream constrictions exist that may cause backwatering), whenever infrastructure is involved, and where water surface profiles must be evaluated. When used with care, they are useful for modeling the extent of overbank flow for floodplain design and for wetland inundation. However, 1-D models are generally not the best option for reaches with side channels, complex cross sections including multiple benches, floodplains, terraces, or estuaries and bays with tidal influence.

The HEC-RAS model is one of the most widely used 1-D tools in stream channel design. Recent versions may be run in steady state or hydrodynamically and have sediment transport functions. MIKE-11 is another commonly applied 1D model, though for more specific applications (see Tools and Resources subsection below). While 1-D models typically require more time and expertise to employ than at-a-section analyses, the level of effort required has been greatly reduced by improved computer programs. These 1-D models often require little or no more survey data inputs than would be necessary for at-a-section analyses, and the added power of analysis they provide is usually well worth the additional resources.

Two-dimensional Models

Two-dimensional (2-D) models compute either depth-averaged (2D-V) velocity and direction at the network nodes throughout the model mesh, or width-averaged (2D-H) depth, velocity, and flow directions across each cross section. While 2-D models typically require greater sophistication in input data and experience to set up and run, their use is now becoming common in certain realms of restoration design, including tidal and estuarine applications and for detailed design of channels with compound cross sections, highly irregular bank lines, secondary channels, and complex floodplain interactions. Two-dimensional flow computations are important for these applications because the flow field is too complex to be adequately represented by downstream averages.

Two-dimensional models are also useful when presenting the results of modeling, because they generate colorful graphics and maps which more clearly display the way that depths and velocities vary through the channel at various selected design flows. Two-dimensional modeling can also provide added value where eddies and other secondary currents are important to the evaluation of instream conditions. Locations where secondary currents are important include meander bends, tributary junctions, bifurcations leading to secondary channels, flows around spurs and groins, and where it is necessary to evaluate microhabitat velocities around obstructions such as log jams. In many cases, 2-D modeling is the only practical way to evaluate the hydraulic impacts resulting from intervention such as habitat enhancement structures.

However, while they are more powerful, 2-D models require substantially more input data (xyz topographic data from total station or bathymetric surveys, LiDAR topography of the floodplain, etc.) and cost substantially more to employ than 1-D models. Also, 2-D models cannot be run over long reaches or long time scales in continuous simulation. Hence 2-D modeling often compliments 1-D modeling where specific questions arise about flow field behavior. Commonly used 2-D models include MIKE-21, RMA-2 (packaged in Surface Water Modeling System [SMS] software), River2D, and FLO2D (see Tools and Resources subsection below).

Three-dimensional Models

Three-dimensional (3-D) models can simulate and evaluate the flow field in three dimensions by producing downstream, horizontal, and vertical velocity components at every node in the model mesh. Three-dimensional computer models use computational fluid dynamics to solve the equations of motion for fluid flow. These models can be run on any powerful workstation or minicomputer although long runs or complex channel geometries may require access to a super computer.

Three-dimensional models can be used to evaluate probable or potential problems associated with particular elements of the restoration design or, exceptionally, at the scale of the restoration site. Typical applications include detailed evaluation of complex local distributions of velocity, fluid drag, or boundary shear stresses; determining site-specific habitat potential or designing site-specific habitat; investigating the potential for local scour, sediment transport, and sedimentation; and evaluating the influence of, impact on, and constraints due to infrastructure features. At present, high resource demands limit the application of 3-D computer and physical models to well-funded projects where very sophisticated investigations and design analyses are warranted, such as in the design of fish passage structures for dams where sediment transport complicates the operation and maintenance of passage facilities.

Physical Models

Physical models are physical scaled-down replicas of the stream system that can only be built at a few specialized research and university facilities across the United States. Physical models are typically meters to tens of meters in length and require specialized and spacious facilities. At present, the application of physical models is limited primarily to research and to a select few projects where sophisticated investigations are warranted.

Considerations for Design Review—Hydraulic Analyses

This brief review of hydraulic investigations leads to several key considerations for design review (i.e., questions to ask):

1. Have hydrologic and sediment analyses and topographic surveys been conducted such that hydraulic models can be built with reasonable confidence in input parameters? What project elements, specifically, are designed in a hydraulic model space?
2. Are input cross section data derived from surveyed cross sections, a surveyed topographic map, or from LiDAR, and what is the resolution of the topography? Are

cross sections specifically georeferenced to each other, and to what vertical precision? What is the resolution of the survey provided, and was it ground truthed?

3. What design flows are used in the models? Are the design flows applied relevant to the project element context of the hydraulic analysis; for example, is the 100-year flow used for flood mapping, and is a channel-forming design flow used for channel design?
4. What hydraulic or hydrodynamic model was used, if any, and was it appropriate for the application? How far upstream and downstream of the project area does the model extend (boundary conditions)? Do roughness values (Manning's equation) and other inputs to the model represent existing conditions, design conditions (at implementation), or future conditions (under full vegetative growth)?
5. Is the design reach potentially affected by downstream constrictions (bedrock walls or canyon, bridges, culverts, diversions)? Will the project be conducted in a reach where flooding is a concern? (A yes answer to any of these questions may warrant a 1-D model as opposed to at-a-section analysis.) Is the project area in a tidally influenced or estuarine area? Does it involve floodplain habitat elements, side channels, off-channel habitat, or beaver dams? Does the project involve design of specific and discontinuous (as opposed to continuous riprap for example) structural elements protecting infrastructure? (A yes answer to any of these questions may warrant a 2-D model as opposed to at-a-section analysis or 1-D modeling.)
6. What effect will project evolution, including the growth of vegetation, have on future water surface elevations, flood inundation, and sediment transport? Will the project as designed influence velocities or water surface elevations outside the project area?

Tools and Resources for Hydrologic Design Analysis

- Overview/summary of hydraulic design for natural channels
 - The Stream Habitat Restoration Guidelines document (Saldi-Caromile et al. 2004) provides a thorough review and resource list for hydraulic design. Online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.
 - Hydraulic Design of Stream Restoration Projects. Copeland et al. 2001.
- Comprehensive documentation of river hydraulics design considerations
 - River Hydraulics: Technical Engineering and Design Guides as Adapted from the U.S. Army Corps of Engineers (ASCE 1996).
 - Hydraulic Design of Flood Control Channels, EM 1110-2-1601, online at <http://140.194.76.129/publications/eng-manuals/em1110-2-1601/toc.htm/> (USACE 1994).
- At-a-section hydraulic computation
 - XSPRO Channel cross section analyzer, menu-driven software that provides stage:discharge calculations, allows analyses of existing and design iteration conditions for at-a-section cross section geometry.
- 1-D Hydraulic/hydrodynamic model

- HEC-RAS is a 1-D model that enables calculation of stage-discharge with backwater effects, as well as readily derived values for hydraulic forces. This menu-driven software has the capability to route sediment and perform sediment budget calculations using the Sediment Impact Assessment Method module.
- HEC-Geo RAS (<http://www.hec.usace.army.mil/software/hecras/hec-georas.html>) is a GIS based tool that meshes a digital terrain model with HEC model results and generates illustrative inundation maps.
- MIKE-11 is a 1-D model that enables calculation of stage-discharge and water quality monitoring. It has good applicability for hydrodynamics related to complex integrated channel-floodplain analyses and to drive sediment transport and water quality modeling, but is complicated to operate.
- Scour computation
 - HY-9 software, designed to assist users in using equations presented in HEC-18 (Hydraulic Engineering Circular 18, Richardson and Davis 2001), has application to derivation of scour for design of structures.
- 2-D Hydraulic model
 - MIKE-21 is a 2-D model that enables calculation of stage-discharge relationship and flow direction and velocity. It is also applicable to water quality monitoring and groundwater interchange, and a strong application for estuarine and tidal applications and complex floodplain analyses.
 - FLO-2D is a 2-D model that enables calculation of stage-discharge relationship and flow direction and velocity. It has applications to estuarine, tidal, and floodplain analysis and design.
 - 2-D Hydraulic model–River 2D (<http://www.river2d.ualberta.ca/>).
 - RMA2 is a 2-D model within the SMS software graphical interface that enables calculation of stage-discharge relationship and flow direction and velocity. It is a strong application for estuarine and tidal applications and complex flow field and channel and floodplain flow analyses.
- 3-D Hydraulic model
 - CORIE (<http://www.ccalmr.ogi.edu/CORIE/>)

Sediment Transport Analyses

Sediment transport analyses are used to investigate the nature and significance of sediment dynamics under existing conditions, identify the causes of sediment-related problems associated with either excess or insufficient sediment supply due to upstream land use or channel impacts, and evaluate the sediment performance of alternative restoration designs in light of geomorphic and biotic design criteria and project objectives.

Usually, sediment analyses are conducted with a view to assessing whether sediment transport connectivity exists in the project reach and assisting designers in achieving sediment balance (i.e., matching sediment transport capacity to supply) as part of stable channel design.

However, achieving sediment balance is not always a sustainable project goal, as some streams are inherently unbalanced with respect to sediment input and output. Typical situations where a non-zero sediment balance may be an appropriate design criterion include streams crossing alluvial fans, deltas, headwater streams, and ephemeral gullies or washes (especially in semiarid areas).

The simplest sediment transport analyses are conducted for a single design flow, usually the channel-forming discharge, though it is becoming more commonplace to evaluate sediment transport over the entire range of flows experienced in the project reach. The design of a naturally functioning channel is an iterative process based on adjusting initial estimates of design channel dimensions and slope to achieve the desired sediment balance for the selected design discharge or range of discharges. Sediment transport analyses for stable channel design can be generally categorized as either incipient motion analysis or sediment discharge analysis.

Incipient motion of stream sediments, the subject of intensive research for nearly a century, is summarized in Buffington and Montgomery (1997). Incipient motion calculations yield the maximum size of particle that can be transported by a specified design flow as a function of the channel dimensions, roughness, and slope. Customarily, the designer then lines the restored channel with sediment that is as large as or larger than the maximum transportable size for the highest design discharge, so that channel stability is assured. This analysis is then useful for sizing bed material in newly constructed channels or assessing the susceptibility to bed erosion in existing channels. More recently, incipient motion calculations have been used to determine the discharges at which the bed will become mobile, or conversely to identify the smallest size of sediment able to resist entrainment at a given flow.

Incipient motion analysis alone is adequate for some design applications where bed material loads are low or zero and the risks associated with imbalance between sediment supply and transport capacity are acceptable or at least tolerable (Newbury and Gaboury 1993).

Sediment discharge analysis, in contrast, will be necessary 1) in most cases where sediment loads are substantial, sediment balance is required, or downstream sediment connectivity is an issue, and 2) in all cases when proposed projects affect hydraulics at a multireach scale. Sediment discharge analyses are based on the use of sediment transport equations and used to calculate the rate and size distribution of bed material transported by either selected design flows or the range of flows experienced at the study site. The results of sediment transport calculations integrated over the range of flows experienced within a specified period of time allow the computation of the volumes of sediment transported into and through a project reach, thereby allowing the design team to determine the reach-scale sediment balance. In cases where the balance is not zero, the difference between the incoming load and the local transport capacity indicates the potential for the reach to scour or fill with sediment during the modeled period and under the specified flows.

Sediment transport analyses require measurements of the size gradations of bed material and substrate sediments in the project reach and in the supply reaches contributing sediment load to the project reach from upstream. In this context, sediment gradations for coarse bedded streams can be measured by pebble counts, with bulk sampling and sieve analysis used for sand bed streams, and core sampling and Coulter counter analysis used for silt and clay bedded

streams (Church et al. 1987). Although more sophisticated methods exist (Rice and Church 1996), pebble counting continues to be widely used and accepted due to its ease of application and repeatability. Sieve analysis of bulk samples collected from active channel bars or bed substrate is necessary where these sediment bodies include significant proportions of sand and fines (Church et al. 1987).

Sediment transport equations also require hydraulic inputs, usually including channel dimensions, slope, and discharge, though the exact nature of the hydraulic data required varies between different equations and approaches to the sediment transport problem. While sediment calculations can be performed on the basis of data defining channel hydraulics and bed materials, it is highly desirable that at least some measured sediment loads are available to allow the calculated rates to be calibrated against rates actually observed in the project stream. Experience shows that uncalibrated sediment transport calculations are prone to large errors, being within $\pm 50\%$ of the actual load for only about 70% of the time.

Sources of uncertainty in sediment transport analyses stem from data uncertainty, a lack of understanding of sediment transport process, regional and stream specificity of sediment and transport processes, and model specificity. Models are most robust when using data sets from which they were developed (Gomez and Church 1989).

Considerations for Design Review—Sediment Transport Analyses

This brief review of sediment transport investigations leads to several key considerations for design review (i.e., questions to ask):

1. Is the rate of bed material transport in the project reach zero or negligible? If so, an incipient analysis may be sufficient.
2. What indications exist, if any, of reach-scale sediment imbalance (aggradation or degradation) within or through the project area, or upstream or downstream of the project area? Evidence of sediment imbalance will warrant a sediment transport analysis.
3. For project reaches found to have a sediment supply that is artificially elevated (land use) or depleted (dams, gravel mines), are measures being taken or planned to remedy this? If the cause of imbalance is not being addressed, what project elements account for either transport deficiency or excess, and sediment scour or storage, within the project reach? That is, for stream systems found to be degrading, what project elements control grade or reduce excess transport capacity? In overloaded streams, what project elements store excess sediment, such as overbank flows?
4. Can the project area be characterized as an alluvial fan, delta, headwater stream, or ephemeral gully or wash? If so, then follow up with questions as in number 3 above.
5. What methods were used to characterize sediment gradation and sediment flux? If the catchment sediment yield was estimated, from what area were sediment volume yield estimates computed?
6. How is sediment transport addressed in design? Was an incipient motion analysis, a sediment budget, or a sediment discharge analysis used? For discharge analyses, what transport equations were used and how were they selected? Were hydraulic data derived

from field measurements or from modeled designs? Does the sediment transport analysis evaluate existing transport conditions, design conditions, or anticipated future conditions? What design discharge (flow) was used for analyses? Have the sediment transport computations been calibrated using local measured loads?

7. What are the project objectives and design criteria with respect to the sediment balance in the project reach? What design criteria have been applied to design development? What specific predictions have been made regarding anticipated outcome with respect to sediment continuity?
8. How will predicted future conditions (e.g., vegetative regrowth within the project area, changes in land use, changes in sediment storage) affect sediment transport and the sediment balance for the project reach?
9. Have the large uncertainties inherent to sediment transport analyses been acknowledged, and how have they been incorporated in design? Are the risks associated with sediment transport acceptable, or at least tolerable?

Tools and Resources for Sediment Transport Analysis

- Sediment transport analyses overview
 - The Stream Habitat Restoration Guidelines document (Saldi-Caromile et al. 2004) provides a thorough review and resource list for sediment transport analyses, online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.
 - Accounting for Sediment in Rivers—A Tool Box of Sediment Transport and Transfer Analysis Methods and Models to Support Hydromorphologically Sustainable Flood Risk Management in the UK (Wallerstein 2006).
- Summary and overview of sediment analyses
 - HEC-6 is a 1-D sediment transport model that calculates water surface and sediment bed surface profiles by computing the interaction between sediment material in the streambed and the flowing water-sediment mixture. HEC-6 is a legacy model, though still widely used. The U.S. Army Corps of Engineers has incorporated similar sediment transport functions in Version 4.0 of HEC-RAS (<http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm>).
 - The HEC-RAS sediment transport/movable boundary computations model simulates long-term trends of scour and deposition over moderate time periods (years) that might result from changes in hydrologic regime or channel geometry.
 - Incipient motion analysis—Shields equation, Richardson equation (see Julien 1995).
 - Selection of appropriate transport equation (see Barry et al. 2004).
- Sediment measurement techniques
 - Guidelines for sampling bed material (see Copeland et al. 2001).
 - Sampling Surface and Subsurface Particle-size Distributions in Wadable Gravel and Cobble Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed

- Monitoring (Bunte and Abt (2001). This report is a compendium of field and methods used to sample sediment and analytical methods used to analyze field data.
- Relation of effective discharge calculation to prediction of bed load transport rate (see Barry et al. 2008).

Geotechnical Analyses

Serious bank retreat is generally driven by a combination of fluvial processes and geotechnical mechanisms, although their relative importance varies greatly from site to site (Thorne 1982). Retreat is initiated when the shear forces exerted on the bank material by turbulent flow close to the bank exceed the resisting forces of friction and cohesion that hold particles in place (Lawler et al. 1997). For noncohesive banks formed in coarse sediments such as sand, gravel, cobbles, and boulders, the balance of erosive and resistive forces acting on individual grains can be analyzed to predict the onset of erosion using an approach similar to that developed by Shields (1936) for grains resting on the bed of the stream, but with the destabilizing effect of the down slope component of the submerged weight of the particles taken into account. Consequently, all else being equal, particles are more easily entrained from a sloping bank than from the level bed of the channel and, as the bank angle approaches the friction angle for the particles, less and less fluid shear force is required to erode the bank.

However, in nature very few bank materials are truly noncohesive. While banks formed in soils that contain an appreciable quantity of clay are intrinsically cohesive, even banks formed in silt and sand have some apparent cohesion when they are partly saturated due to pore suction or meniscus effects in soil pores that are partially filled with water. The erosion of cohesive materials usually takes place through the removal of small pedes (aggregates or crumbs) of soil and is not amenable to analysis using a Shields-type approach. In fact, the onset and rate of erosion is better predicted on the basis of the clay mineralogy of the soil and the chemistry of the pore and eroding fluids (Arulanandan et al. 1980), although no strong theory or empirical basis exists from which to predict the erosion threshold or rate for cohesive bank materials.

In natural watercourses, fluvial bank erosion is usually concentrated in the lower half of the bank profile. This is the case for a number of reasons including:

- action of secondary currents in the near bank flow field, which steepens the velocity gradient adjacent to the lower bank and bank toe and so increases local boundary shear stresses (Bathurst et al. 1979, Thorne 1982),
- higher frequency with which the lower bank is attacked by the flow,
- the tendency for materials lower in the bank profile to be more erodible than those higher in the profile because they are less cohesive or wetter (Thorne and Tovey 1981),
- lack of vegetation cover on the lower bank due to its more frequent inundation, and
- limited root penetration and reinforcement low in the bank by bank top vegetation (Thorne 1990).

Preferential erosion of the toe and lower bank thus sets up a cycle of erosion involving phases of toe scour, oversteepening, bank weakening, geotechnical failure, debris accumulation

at the bank toe, and basal clean out (Figure A-1). Therefore, the origin of geotechnical instability in streambanks is usually fluvial scour or lateral erosion of the lower one-third to one-half of the bank. The actual timing of failure is not only dependent on fluvial erosion, however, and other phenomena that often trigger geotechnical failure include:

- rapid draw down in the channel at the end of a flood, which generates high positive pore water pressures in the bank if it is poorly drained,
- heavy and prolonged rainfall that saturates the bank,
- intense drying that leads to soil desiccation and cracking,
- surcharging by single rows of tall, heavy trees on the bank top that are vulnerable to wind throw,

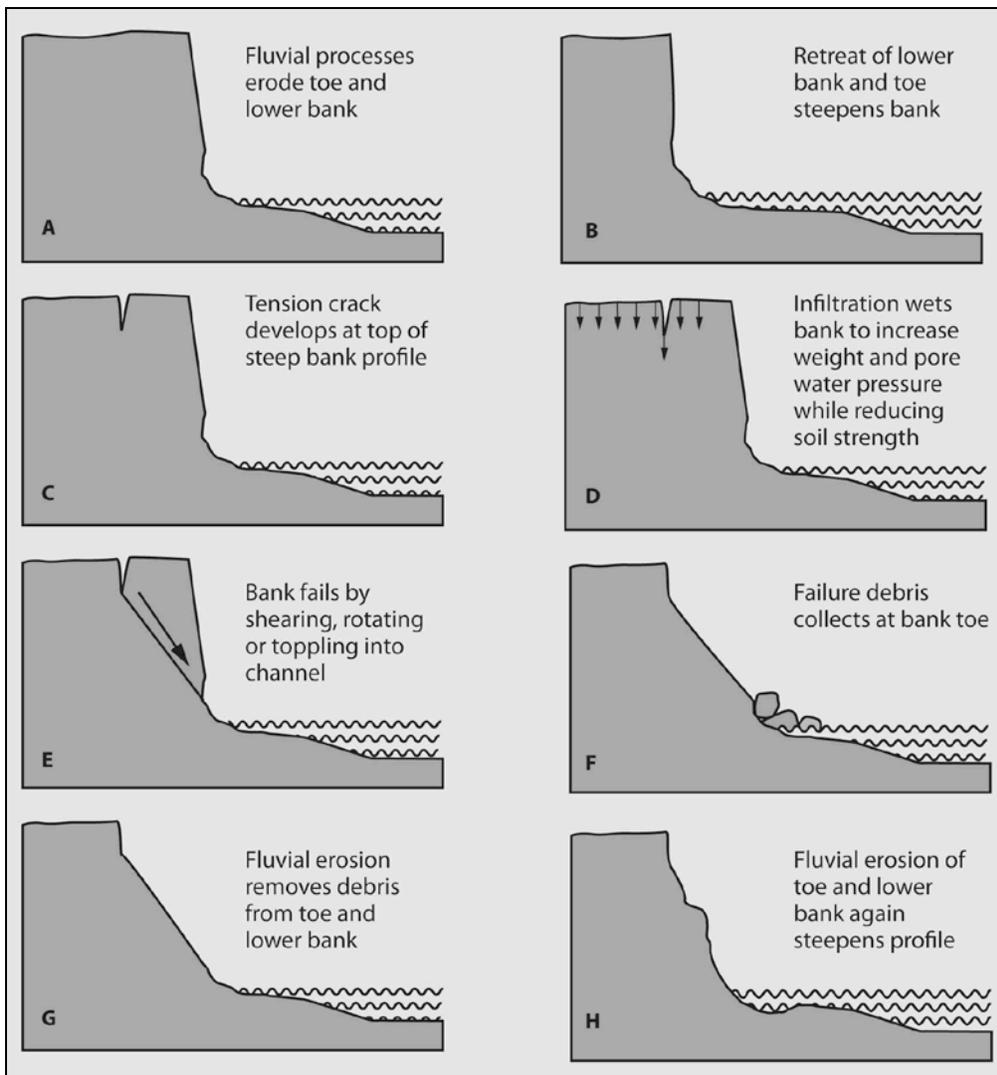


Figure A-1. The streambank erosion cycle resulting from hydraulic forces at the toe of the streambank typically follows the progression depicted. (Modified from Thorne 1978.)

- artificial clearance of natural bank or riparian vegetation, and
- soil compaction near the bank.

Conversely, collapse of the bank may be delayed by:

- dense vegetation on the bank and in the riparian corridor that provides effective root reinforcement, buttressing, and surface protection,
- negative pore water pressures that increase effective cohesion in well drained bank materials, and
- log jams on the lower bank and at the bank toe that provide surface protection and local flow retardation.

Once the bank is brought to a condition of limiting stability, it may fail by any one of a number of mechanisms. Three of the most commonly observed modes of failure (rotational slip, planar slip, and cantilever failure) are illustrated in Figure A-2.

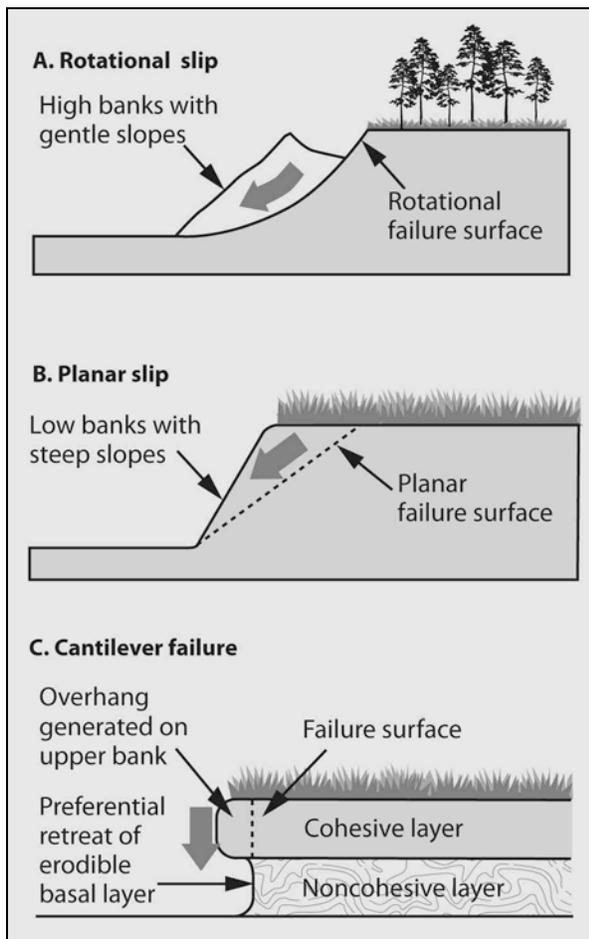


Figure A-2. Common modes of geotechnical bank failure. This differs from streambank erosion in that the forces leading to erosion are within the bank, rather than from the hydraulic conditions within the channel. (Modified from Thorne 1978.)

Bank Stability Theory

The type of geotechnical failure that actually occurs is that with the lowest ratio of restoring to disturbing forces as defined by the factor of safety,

$$F_s = \frac{F_R}{F_D} \quad (6)$$

where F_s is the factor of safety, F_R is the sum of restoring forces, and F_D is the sum of disturbing forces. If the factor of safety is greater than unity ($F_s > 1$), the restoring forces exceed the disturbing forces and the bank is stable. If the factor of safety is equal to one ($F_s = 1$), the bank is on the point of failure. If the factor of safety is less than unity ($F_s < 1$), the disturbing forces exceed the restoring forces and the bank should already have failed.

Restoring forces are generated by the shear strength of the bank material, which is made up of frictional and cohesive components. The basis for representation of the soil shear strength is the Mohr-Coulomb equation (Lambe and Whitman 2007),

$$S_s = c + \sigma \tan \phi \quad (7)$$

where, S_s is shear strength, c is soil cohesion, σ is the normal load on the failure surface, and ϕ is the friction angle. However, in nature the state of drainage of the bank also affects the shear strength of the soil and this is taken into account in the modified Mohr-Coulomb equation:

$$S'_s = c' + (\sigma - \mu_w) \tan \phi' \quad (8)$$

where S'_s is effective shear strength, c' is effective cohesion, μ_w is pore water pressure and ϕ' is the effective friction angle.

In well-drained banks with partially saturated soils, the pore water pressure is negative (termed matric suction), so the effective shear strength of the bank material is enhanced. However, in poorly drained banks with fully saturated conditions (for example during rapid drawdown in the channel, often occurring downstream of reservoirs), pore water pressures are positive and they significantly reduce the effective strength of the bank material. For this reason, geotechnical failures are most likely to occur during rapid drawdown following a high flow event that has saturated a poorly drained bank. Drawdown events are frequently repeated, or rates are commonly exacerbated in regulated river systems downstream from reservoirs, particularly when flows are moderated to meet electricity generation demand.

Motivating forces are generated by the tangential load on the failure surface, which results from the weight of the bank material plus any surcharge associated with buildings, vehicles, or other heavy infrastructure on the bank top. In this respect, the surcharge weight of vegetation has been found to be negligible compared to the weight of the bank material except where heavy wind loads are transmitted to the bank by single rows of tall trees.

Bank Stability Analyses

To understand and predict bank instability, the balance of forces with respect to the most likely mode of failure must be analyzed. Since multiple failure mechanisms are possible in streambanks, scientists have developed different analyses to deal with rotational, planar, and cantilever modes of failure.

Geotechnical engineers have paid close attention to the stability of slopes with respect to rotational slip and the “method of slices” has long been used to reliably predict failure by this mode (Thorne 1982). Modern, computer-based methods of analysis are available for rotational slips in geometrically simple slopes formed in soils of known physical properties, though their application to the more complex geometries and soil conditions found in eroding streambanks requires sound insight and experience on the part of the modeler (Abramson et al. 2001).

Many retreating streambanks have steep or vertical slopes described as river cliffs. Such banks are commonly found at the outer margins of actively migrating meander bends and at the edges of incising channels that are entrenched into their floodplains. These very steep banks characteristically fail along almost planar slip surfaces. The upper part of the failure block is usually separated from the intact bank by a deep tension crack that seriously weakens the bank and may extend down to half the bank height. In such cases, failure occurs when a slab of soil detaches from the bank through tension cracking before toppling forward into the channel. The stability of streambanks with respect to the slab or toppling failure mechanism was analyzed by Lohnes and Handy (1968). Later, Osman and Thorne (1988) extended their analysis and produced a Microsoft Excel-based, spreadsheet stability analysis that can be used for preliminary and screening analysis of bank stability (Thorne and Abt 1993). More recently, researchers at the U.S. Department of Agriculture’s Agricultural Research Service National Sedimentation Laboratory, Oxford, Mississippi, have developed an advanced computer model that accounts for the effects of soil layering, stage change in the channel, pore water pressures in the bank, and root reinforcement by bank top vegetation (Simon and Pollen 2006).

Cantilever failure is widely observed in layered banks, especially in gravel bed river systems. Fluvial erosion of the lower bank leaves an overhanging block of soil in the upper bank (often bound by roots) that subsequently collapses by shear, beam, or tensile failure (Thorne 1982). Thorne and Tovey (1981) analyzed the stability of cantilevers from first principles to produce dimensionless charts for the limiting dimensions of overhanging blocks based on the balance between the weight of the block and the tensile strength of the soil.

When a retreating bank must be stabilized because it is a threat to life or vital infrastructure, the designed solution should deal with all of the issues responsible for bank retreat. In selecting a solution to a bank retreat problem, some of the issues to be considered include:

- Is the spatial extent of the problem site specific, reach specific, or system wide?
- Is bank retreat being driven by toe scour, lateral erosion of the bank, or both?
- Is toe scour or lateral erosion related to channel incision?
- Is geotechnical instability a factor?

- Does bank hydrology and drainage play a role?
- Are the activities of people, livestock, or wildlife part of the problem?
- If so, should they be part of the solution?

Experience shows that to be successful, the type, strength, and length of bank covered by the stabilization works must be matched to the cause, severity, and extent of the problem. Local scale treatments of reach- or watershed-scale instability are unlikely to provide a long-term solution. Good solutions are ones that deal with the problem, cover its spatial and temporal extent, and are designed to withstand all relevant erosion processes, weakening factors, and potential geotechnical failure mechanisms.

With respect to geotechnical instability, field reconnaissance and at least a screening-level stability analysis should be performed prior to selection of options in order that the role of toe scour can be established and the requirement for measures to enhance soil strength or reduce internal loadings to help stabilize the bank can be ascertained. This is particularly the case where field observations suggest that the bank is poorly drained or compacted. Many otherwise well-designed bank protection schemes have failed in the past due to the effects of positive pore water pressures or seepage related piping within the bank.

In summary, some of the key points relating to bank stability include:

1. Rapid bank retreat usually involves a combination of fluvial erosion and geotechnical failures.
2. Toe erosion is especially effective at destabilizing the bank.
3. The mode of failure can be identified during stream reconnaissance.
4. Positive pore water pressures and tension cracks seriously weaken the bank.
5. Vegetation strengthens the bank, but in some circumstances can trigger failure of marginally stable banks due to wind loading or mortality.
6. Models for bank stability are available and relatively easy to apply when analyzing channel stability or designing a stable channel.

Considerations for Design Review—Geotechnical Analyses

This brief review of geotechnical investigations leads to several key considerations for design review (i.e., questions to ask):

1. Is observed bank erosion indicative of channel instability or is it occurring as part of natural adjustment and lateral migration in a previously narrowed, channelized, encroached upon, or dynamically stable channel? Would attempts to stabilize the bank contribute to restoration of a stable channel condition, or potentially risk transferring bank retreat to another location?
2. What are the erosion processes and mechanisms of failure responsible for bank instability and what do they imply about the cause of bank retreat? What does the cause of retreat suggest concerning alternatives to stabilizing the bank?

3. Will stabilization of the bank constrain natural processes of lateral migration and recruitment of sediment and wood material? Will stabilization impede channel evolution to a more stable and more ecologically valuable form?
4. Have deformable and biodegradable bank treatments been considered as alternatives to hard protection? Is the stabilization proposed isolated or will it contribute to cumulative impacts of other stabilization measures in the river system?
5. What is at risk if the bank is not stabilized? What are the risks if an attempt to stabilize the bank is unsuccessful or transfers the problem elsewhere?

Tools and Resources for Geotechnical Analysis

- Overview and comprehensive resources for design of streambanks
 - The Integrated Streambank Protection Guidelines document (Cramer et al. 2002) provides a thorough review and resource list, online at <http://wdfw.wa.gov/publications/00046/wdfw00046.pdf>.
- Resources for bank stability analysis
 - Osman-Thorne Bank Stability Analysis is a simple spreadsheet method suitable for screening assessment and indicative calculations of the factor of safety with respect to shear and slab-type bank failures (Thorne and Abt 1993).
 - Bank Stability and Toe Erosion Model (BSTEM) 5.0 (Simon et al. 2000) is a model for predicting bank instability and designing stable bank geometries, described at <http://ars.usda.gov/Research/docs.htm?docid=5044>.

Appendix B: Design of Stream Channels and Streambanks

Site- and reach-scale projects exhibit a wide range of design levels and typically regulatory agencies with project review responsibility or authority will review project designs. Dozens of existing guidelines (see Appendix D: Annotated Bibliography) address channel design, but none address the full suite of considerations relevant to Pacific Northwest and California streams, and none were developed specifically to assist services staff (e.g., National Marine Fisheries Service, U.S. Fish and Wildlife Service) in reviewing project designs.

Currently, no universally accepted standards of practice exist for the design of restored channels (Miller and Skidmore 2003, Palmer et al. 2005). In the absence of a standard of practice, the design team must provide a clear foundation that relates the proposed design to identified problems and has a thorough justification for the choice of design approach and design features, reported through comprehensive design documentation. To provide a sufficient basis for design, it is not enough to consider the findings of the individual components of the background investigations in isolation. In practice, various components of the investigation should be performed and reported within a multidisciplinary and multiscale framework that allows their results to be fully integrated and utilized in all aspects of the design process.

The design process (Figure B-1) includes selecting an alternative, specifying project elements, establishing design criteria for project elements, and developing designs to meet those design criteria. Each of these phases is informed by investigative analyses. A detailed discussion of each type of investigative analysis listed below,¹² including common methods of analysis and relevance to design, are detailed in Appendix A, namely,

- hydrologic,
- geomorphic,
- hydraulic,
- sediment transport, and
- geotechnical.

A sound design solution will be based on the findings of investigative analyses at appropriate scales:

- climate, geology, hydrology, and geomorphology at the river, watershed, or regional scales (as appropriate to the extent and potential impact of the restoration scheme);

¹² Fisheries and biological analyses are not included in the appendices, as it is assumed that readers have a strong background in biological and fisheries sciences.

- flow and sediment regimes at the river or watershed scales;
- hydraulics, stream processes, sediments, channel boundary conditions, and physical constraints at the reach scale; and
- habitat, aquatic, riparian, and floodplain ecosystems, and fisheries at the reach and project site scales.

Investigative analyses are an important component of identifying a problem, from which goals and objectives are derived; they inform the evaluation of alternative approaches to achieving the desired goals and serve as the foundation for project design. For example, investigating watershed hydrology will determine whether land use changes in the watershed have impacted the rainfall-runoff relationship and altered the river’s flow regime in ways that may be contributing to the reach-scale problems that the project seeks to solve. If a change in watershed land use is identified as a primary, or even a partial cause of the problems, this will influence selection of the preferred alternative solution and provide valuable information to support detailed design of multiple project elements. Conversely, if no investigation of watershed hydrology is performed, changes to the flow regime may be missed, leading to selection of a design alternative based on a historic reference condition that is no longer applicable to the stream processes that operate under the modern (postdisturbance) flow regime.

The design process is often initiated during feasibility and alternatives analyses. Even at these early stages in a project, some investigation of watershed hydrology and sediment dynamics is typically required to identify opportunities and constraints associated with the major watershed controls. In this respect, the establishment of design criteria also plays an important role in fully understanding problems to be addressed. While project goals often stem from social

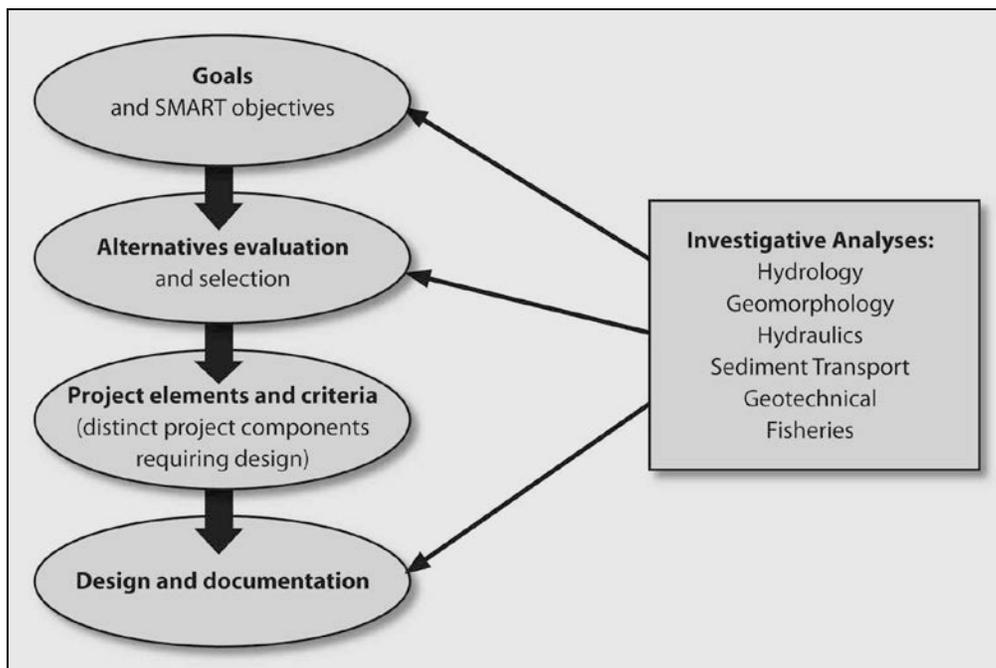


Figure B-1. All phases of the project design process are informed by investigative and design analyses.

priorities, as part of a watershed or recovery planning process, or from an intuitive sense of what needs to happen to promote species recovery in a river, problem identification and the development of explicit objectives to turn these goals into actions often require investigative analyses to understand the stresses responsible for environmental degradation, the sources of these stresses, and the ultimate causes of the observed problems.

Establishing the relationship between these investigative analyses and the project design process is important. Investigative analyses serve multiple purposes throughout the design process, but do not themselves constitute the design process. Rather, they establish the foundation for design by explaining the stream processes at play in the project area and its contributing watershed, identifying the causes of observed problems, establishing the existence of any constraints on the alluvial channel, and evaluating the potential and limitations of alternative solutions. These insights are vital to developing the analytical framework for project design.

Project Elements and Design Criteria

In project review, deconstructing the final design into its constituent project elements is useful to evaluate whether each element contributes to the project goals and objectives, review the design basis for each element, then reconstruct the design to evaluate how well the elements are integrated. In doing so, clear links should be identified between the findings of the investigative analyses and the purpose of each proposed element. For example, if investigative analyses indicate that development within the watershed has permanently altered the hydrologic regime, then project elements that aim to replicate historic channel configurations may be inappropriate and unlikely to persist.

Project review should also determine whether proposed designs first adequately address the problems they are intended to solve, and second, add to the probability of the project achieving overall success. For example, streambank stabilization measures may be designed to meet specific stability criteria based on a design discharge and factor of safety derived from investigative analyses of hydrology, hydraulics, and bank characteristics at the project site, and attuned to the design criteria (designed for failure) and project objectives (time span to allow revegetation to provide natural bank protection). The degree to which these linkages are established in the design process and made clear defines the quality and clarity of the design documentation.

Projects involving physical changes to the stream channel to meet stated objectives commonly employ a suite of constructed or structural features, each of which is intended to address and meet a specific objective. The detailed design of these features determines how the project will seek to achieve each of its objectives. In this context, the design criteria provide a vital link between detailed design and project objectives. Hence design criteria are specific, measurable attributes of the project features that clarify the purpose of each project element and state how each element will act to meet one or more of the project's objectives (Miller and Skidmore 2003).

While they are seldom stated explicitly in the design documentation and are often implicit to the design process for stream channels and banks, design criteria are valuable not only

to project designers, but also project stakeholders, sponsors, and services staff responsible for project review. For example, development of design criteria will involve discussions among stakeholders, sponsors, and designers that assist in developing a shared vision of how the project is intended to work. Such discussions can be a clarifying and unifying process and are especially useful if they extend to preconsultation with regulators under the U.S. Endangered Species Act or state laws. In particular, for agencies responsible for review of design documents, design criteria greatly facilitate review because they make explicit the design intent for each project element.

Additionally, design criteria:

- clarify project objectives and ensure that project objectives are fully considered in project design,
- establish measurable attributes for project elements that serve as the basis for postproject monitoring,
- define risk in terms of probabilities of occurrence and consequences of various possible outcomes associated with the design of different project elements,
- provide acceptable or allowable tolerances for uncertainty concerning the performance of different project elements,
- provide project designers with explicit design targets,
- facilitate mutual understanding of expectations and inherent project risks among project sponsors, property owners, designers, and regulatory agencies, and
- provide professional design engineers and scientists with explicit design objectives for which they can provide stamped designs within the context of risk analyses that account for uncertainty concerning project performance and future conditions.

In summary, “by gearing designs to satisfy specified criteria, engineers will be able to use all of the relevant methods that have withstood the scientific rigors of peer-review to better manage risk and improve project success” (Slate et al. 2007).

An associated benefit of the development of explicit design criteria is that they may be used within the project design team to bridge knowledge gaps between professionally licensed engineers and scientists with different disciplinary backgrounds and professional standards. For example, professional engineers are bound by the professional Code of Ethics for Engineers (ASCE 2006, <http://www.asce.org/Content.aspx?id=7231>) to ensure the safety and stability of any project elements they design. This may lead them to be overly conservative in the design of the structural components of a restoration project, introducing new and artificial constraints on stream processes and limiting the potential for adjustment of the channel boundaries in ways that run counter to the general principles of sustainable restoration of channel forms and habitat. In this context, design criteria should explicitly state that structural project elements are only expected to withstand the flows or environmental conditions specified, beyond which they are designed to adjust or perhaps even fail with consequences that are acceptable, or at least tolerable. This allows professional engineers to stamp or seal designs with elements that are designed for adjustment or even designed for failure under specified conditions, and to embrace

uncertainty in predicting project performance by managing the risks rather than just putting them on the safe side through the use of an excessively high factor of safety and an overly conservative design.

The great advantage of the use of design criteria is that, by freeing designers from the yoke of having to overengineer project elements, they allow professional engineers to use their education, training, practical skills, and experience to design structural elements that will not act as long-term constraints on natural stream processes and morphological adjustments in restored channels. For example, a bioengineered streambank stabilization project may be based on design criteria that state the bank will withstand all flows up to the 100-year flood for a period of 5 years, after which the bank will be allowed to fail (from an engineering perspective) or adjust naturally (from a natural process-form perspective). This may lead to a design that incorporates biodegradable elements that hold the bank together under all anticipated flows long enough for planted and volunteer bank vegetation to become established and provide natural protection. The biodegradable fabrics, soil placements, and other structural elements used in this type of streambank restoration can all be designed using established engineering and American Society for Testing and Materials standards for materials including fabric, soil compaction, and rooting strength (Miller and Skidmore 1998), as required by the relevant codes and practices for professional engineers.

Though design criteria are specific and measurable, they are also an invaluable tool for addressing uncertainty in design and can be used to reduce the risks and limit the liabilities associated with remaining uncertainties. This is the case because design criteria can cover a range of acceptable values, rather than a single target value, and still be quantifiable. In this context, a project is successful provided its outcomes fall within a band defining the allowable variation from target conditions during the project's life.

A categorization of design criteria for common natural channel project elements is provided below (adapted and expanded from Miller and Skidmore 2003) with abbreviated examples to aid project sponsors, reviewers, and designers in addressing key project elements for instream management actions, particularly those involving channel or streambank construction or reconstruction.

Common categories of project element design criteria are:

1. Channel form and geometry—specify the design discharge that the channel is intended to contain; define reach-averaged values and local variability in width, depth, and width/depth ratio; and specify a range of values for planform characteristics (pattern, sinuosity, meander wavelength, braiding index, etc.).
2. Vertical stability—design basis for substrate gradations, allowable range of bed scour and fill, specify whether grade control is allowable or required. Additionally, vertical stability criteria may specify sediment continuity objectives.
3. Lateral channel stability and bank stability—allowable range of channel shifting, discharge criteria for bank erosion and criteria for geotechnical bank stability, duration for which artificial bank protection and stabilization measures are required.

4. Floodplain inundation—areal extent and location of floodplain inundation, duration, and frequency of inundation; allowable fluvial processes on the floodplain (overbank scour and sedimentation).
5. Revegetation—acceptable plant species and plant forms, time to maturity, maintenance and irrigation expectations, density, and percent cover required.
6. Instream habitat—area and type of habitat at specified flows, structural stability of habitat elements, and expected design life.
7. Infrastructure protection—flood frequency for stability and protection, impact to flood hazards, and water surface elevations.
8. Construction costs and impacts—allowable duration and standards for water quality degradation, allowable disturbance area, cost limits, construction period restrictions, and time frame.
9. Sustainability criteria—maintenance requirements, project life expectancy, susceptibility to floods and droughts, and resilience to climate change.

Design criteria may be either prescriptive or performance. Prescriptive criteria specify how a specific element of a project will be constructed or implemented, and may be regarded as means and methods. In contrast, performance criteria may specify the intended outcome of a project element. They describe the required performance or service characteristics of a project element without specifying in detail the methods used to obtain the end result (Miller and Skidmore 2003). Performance criteria, while often offering a more direct link to project objectives, may be difficult or impossible to monitor or measure. This is particularly true for performance measures that mandate a biological response, as biological response may take many years and is generally subject to multiple uncontrolled variables that affect outcomes. Whether design criteria are framed in terms of prescriptive or performance attributes, they must specify the time frame within which to achieve the desired outcome. The expectations associated with design criteria can be defined as either static or dynamic, that is, they may refer to a particular channel feature or to a specified channel process. In many cases, the explicit objective relates to a change in the instream environment, and where this is the case, design criteria must explicitly address this as a dynamic outcome of the project.

In developing a comprehensive restoration design, these project elements will typically require design details such as drawings that illustrate the composition and arrangement of the elements, and from which a reasonable understanding of the design intent can be achieved. For any single project element, there may be a number of variations (e.g., bank design for an outside bend, bank design for an inside bend, bank design for a straight length of channel, and bank design details that incorporate habitat elements) and a number of details to illustrate the intricacies of building or installing the element. For example, a bioengineered bank stabilization design may require details of how a biodegradable fabric will be staked down, how plantings will take place, the arrangement of soil lifts, and the structures to be used to protect the bank toe, all with dimensions and materials specifications.

To further illustrate the types of design details that should be included in project documentation, the following subsections describe common project elements for restoration of

stream channels and streambanks, their relevance to natural processes, drivers and controls, and key design considerations.

Technical Basis for Design of Project Elements

While the relation between form and process in natural stream systems has been the topic of regular study for more than half a century (Leopold and Maddock 1953), the application of this science to designing channels and banks with the intention of re-creating lost habitat or other ecological value continues as an emerging science. Stream channel and bank restoration design is commonly based on the premise that natural alluvial channels tend to evolve toward a condition where the channel form and dimensions are delicately adjusted to the flow and sediment regimes as they interact (through stream processes) with boundary conditions and controls (Leopold and Maddock 1953). The challenge in stable design then is to identify a channel form that is appropriate for the channel boundary materials and setting, while being consistent with sediment continuity under the flow and sediment regimes.

Categorizations of stable channel design methods (Shields 1996, FISRWG 1998, Watson et al. 1999, Fripp et al. 2001, Skidmore et al. 2001) indicate three generalized approaches to design:

1. Analog approach: This adopts templates from adjacent or historic channel characteristics as the basis for design. It is also referred to as the reference reach, cognitive, carbon copy, intuitive, or template approach.
2. Empirical approach: This uses empirically derived equations that relate channel dimensions to various parameters defining the flow regime, sediment regime, and boundary material characteristics derived from local, regional, or global data sets. It is also referred to as the regime theory or hydraulic geometry approach.
3. Analytical approach: This applies process-based or theoretically derived equations for flow hydraulics and sediment transport to derive a solution for channel geometry that supports sediment continuity under acceptable hydraulic conditions. It is also referred to as the predictive or process-based approach.

Perhaps the most intuitive approach to design is to copy nature by using a reference reach that appears to be in equilibrium as a template or natural analog for the restored reach. An analog or reference reach may be an upstream or downstream reach, an historic representation (air photo) of the predisturbance channel in the same location, or even a reach selected from a similar stream in a nearby basin. Analog approaches can be applied with a minimum of quantification and analysis, at virtually any scale from multiple reaches down to site-specific features, as fundamentally they are copying a known condition. The assumptions inherent in the analog approach, acknowledged or not, are that the reference reach is in fact in equilibrium and is representative of flow, sediment, and boundary conditions at the project site.

The applicability of analog approaches to design of project elements is limited to situations where watershed controls, stream processes, and boundary characteristics and controls are essentially equivalent between the analog and project reaches (Skidmore et al. 2001, Hey 2006). However, a significant discrepancy between any of the major independent variables

governing channel form in the analog and project reaches generally invalidates the approach. Further, while analog approaches can be efficient in terms of design costs and expertise required, they are only appropriate where:

- the river upstream and downstream of the restored reach is in equilibrium,
- the problem to be addressed has a local cause,
- the adverse impacts associated with the problem can be addressed adequately at the site or reach scale, and
- boundary conditions are comparable between the design reach and analog reach.

These limitations on the utility of the analog approach stem from the fact that the restoration design treats the observed morphological effects of adverse impacts rather than identifying the causes of the impacts. Hence, unless the problem can be solved solely through reconstruction of the channel based on a stable template, the problem remains and the design is unlikely to be sustainable. Further, the analog approach often bypasses many of the investigative analyses that would otherwise help to identify problem causes at the river and watershed scales. These investigations are vital and should not be bypassed as they can reveal important inconsistencies between existing conditions in the project reach and reference conditions taken from the analog reach.

A related and widely employed application of the analog approach is in deriving a design discharge for the project reach. In this context, an upstream or downstream reach with desirable, natural attributes can serve as an analog from which to derive a discharge value for the bankfull or effective discharge. This is especially useful where the physical characteristics of the channel in the project reach are unsuitable, having been heavily modified by, for example, channelization or resectioning for flood control. The basic principle here is that the design discharge appropriate to representing channel-forming flows in the project reach can be derived from a reference reach, provided that the reference reach is in equilibrium. Once the design discharge has been defined, empirical or analytical approaches may be applied for restoration design (Knighton 1998).

The most common method to deriving the design discharge in an analog reach is to apply Manning's equation or other hydraulic calculations (see the Hydraulic Analyses subsection of Appendix A) to a field-measured, bankfull channel cross section. This requires accurate identification of the bankfull stage, care in measuring the bankfull dimensions, and skill in estimating the roughness coefficient—all of which call for the involvement of an experienced river engineer or fluvial geomorphologist. While derivation of a design discharge from a reference reach is often the best practicable approach to establishing flow-related design criteria, designers and reviewers must take into account the substantial uncertainties introduced by having to select a representative cross section, identify the bankfull stage, measure the bankfull dimensions, and estimate the bankfull roughness value (Williams 1978, FISRWG 1998), all of which are susceptible to the judgment and perspective of the field investigator. Bankfull stage, in particular, is notoriously difficult to define and identify consistently, as the literature offers a wide variety of field indicators for the bankfull condition (Wharton 1995, Knighton 1998).

In an empirical approach to stable channel design, the functions, constants, and exponents are derived from experimental or observed data, rather than being derived theoretically. Empirical equations represent average conditions by reducing the range of variables from multiple observations to derive predictive formulas. The approach is similar to the analog approach, the difference being that the data set used as the basis for the method consists of a population of analogs rather than an individual analog or reference reach, with the population parameters used to derive average values. This is a logical extension of the analog approach, because it adopts the intuitive approach of replicating equilibrium conditions observed in nature, but the values derived are theoretically more defensible since they are based on a larger data set.

Empirical equations generally relate various attributes of channel form including width, depth, flow velocity, slope, meander wavelength, and amplitude to independent variables defining the channel-forming flow (usually bankfull discharge) and the boundary conditions (bed material size, valley slope, bank characteristics, and bank vegetation). The resulting hydraulic geometry equations are based on either regional or global data sets. The more advanced forms of these equations include indicators of local variability around reach-averaged values as well as the mean values of the various channel parameters. This allows designers to build in some of the local variability that is a characteristic of naturally stable channels but often lacking in constructed channels.

The empirical approach is convenient and may be appropriate in regions that are well represented by existing hydraulic geometry equations. Essentially, the limitations on application of the empirical approach are similar to those on the analog approach; that is, the project stream must be in equilibrium and conditions in the project reach must match those in the streams from which the hydraulic geometry equations were derived. Therefore, the empirical approach is appropriate where the causes and adverse impacts being addressed in the project are localized (being due, for example, to a poorly designed culvert, local channelization, or unmanaged bank grazing and trampling), and where sediment and flow regimes are relatively undisturbed.

Experience shows that selection of the appropriate empirical equations is crucial as, once selected, their apparent surety can give a false sense of security. In this regard Williams (1986), in describing his empirically derived relations, summarizes the availability of a wide range of empirical equations as “represent[ing] problems more than they do conclusions.” Furthermore, even when conditions for regionally derived empirical relations are appropriate for the design application, the 90% confidence intervals for most formulas are wide—approaching an order of magnitude in many cases. This limits the confidence that can be placed in the precision of the equations, though it does represent natural variability. Therefore, it is especially important that design teams fully consider the range of values and associated confidence limits generated when applying empirical equations.

Questions to ask when either an analog or empirical approach is applied include:

1. Is the reference reach (or project reach) in equilibrium or has it been affected by changes in river conditions or watershed controls? Is either the project or reference reach within an alluvial fan or other inherently unstable channel system?
2. What is the cause of the adverse impact being addressed in the design reach? Is the cause local, such as unmanaged grazing and trampling in the riparian corridor, channelization, a

stream crossing structure, or localized placer mining? Or is the cause of impact related to a change in watershed controls?

3. How closely does the local and watershed context of the reference reach (or source of the empirical data set) match that of the design reach? Will the restored channel experience the same controls and processes as the reference reach? For example, are sediment supply and hydrology the same? Are boundary conditions (bed material size, bank characteristics, vegetation, valley slope), and characteristics of the contributing watershed area (vegetation, geology, hydrology) taken into account?
4. Does the reference have natural or human constraints that may be protecting it from degradation or lateral shifting?
5. If empirical hydraulic geometry is used, what are the confidence intervals associated with the equations?
6. Are there local constraints in the project reach that will constrict its behavior, making it nonalluvial and making reference or empirical approaches inapplicable?

Analytical approaches differ fundamentally from analog and empirical relations in that they are based on the theory of open channel flow in channels with deformable boundaries and require the quantification of the independent variables governing alluvial channel form. Further, analytical approaches are capable of simulating dynamic process-response mechanisms in unstable channels, whereas analog and empirical approaches assume equilibrium conditions and therefore are unable to represent the processes and forms associated with channel adjustment. Analytical or predictive design makes use of the equations for continuity, flow resistance, and sediment transport to derive equilibrium channel dimensions for specified values of water discharge, sediment supply, bed material, and bank characteristics (Shields 1996). However, because there are four unknowns in defining the stable channel (width, depth, velocity, and slope) but only three theoretical equations, an iterative approach is necessary to solve the channel design problem. A good example of this approach is the Copeland Method (Soar and Thorne 2001).

Limitations on the applicability of analytical methods are less restricted than for analog and empirical approaches because these methods are not dependent on the existence of equilibrium conditions. Hence, they are particularly well suited to restoration or stabilization projects where the current or restored channels are not stable. In practice, the use of analytical methods is limited, however, by the availability of the input data required, the quality of the data that are available, and scientific uncertainty in the models employed. Further, analytical models may still contain empirical components, such as the Manning roughness coefficient, which has no basis in theory.

In practice, the application of analog, empirical, and analytical approaches to restoration design need not be mutually exclusive. In fact, a hybrid approach, where different approaches are used for different components of a design, is commonplace in contemporary channel design practice. For example, all three approaches were employed in designing a reconstructive restoration of Silver Bow Creek in Montana following a century of mining contamination and physical disturbance (Miller and Skidmore 2003). In this hybrid approach, the channel-forming discharge was derived from a reference reach where the historically disturbed channel had

evolved sufficiently to be in equilibrium with the present flow and sediment regimes, analytical methods were used to test for sediment continuity through multiple reaches and to develop hydraulic cross sections, and regionally derived empirical relations were used to develop designs for the channel planform geometry.

Project Elements that Require Design

The following subsections provide specific considerations for common and important project elements that require design. They are presented in a sequence that starts with the broadest scale design considerations—floodplains—and progresses down to site-scale in-channel project elements such as structural habitat features or stabilizing structures. Project elements and associated design considerations are described assuming that readers have a working knowledge of the principles and methods of the full suite of foundational investigative analyses. These investigative analyses and their component methods are detailed in the Investigative Analyses subsection of Appendix A.

Floodplains

A floodplain is the relatively flat land area adjacent to alluvial stream channels that is prone to flooding and has evolved through the deposition of alluvial materials. Many river projects focus narrowly on the design and construction of the active river channel and treat floodplains only as the horizontal limits for the channel. Thoughtful projects recognize that channel and floodplain processes are interdependent and integrate the design of channels with floodplains. In addition to providing relief for flows that exceed channel capacity, floodplains provide areas to temporarily store sediment transported by the river and for important habitat processes. Hydraulic and hydrodynamic models (see the Hydraulic Analyses subsection of Appendix A for detailed discussion) provide information on the extent and depth of inundation for any design discharge throughout the channel and floodplain, and the extent of flow on the floodplain. This information is essential to designing the project and evaluating the benefits and risks posed by floodplain inundation.

Consideration of flood benefits and risks should extend not only throughout the project reach, but also to adjacent reaches upstream and downstream, and they should include benefits and risks to floodplain and off-channel habitats, property, infrastructure, and revegetation strategies. One-dimensional modeling will be adequate for most applications, but it should always be borne in mind that interactions between channel and floodplain flows are problematic and that flow paths across the floodplain can be complex. Hence two-dimensional modeling is desirable and may be essential when more accurate representation of the flow field is required. For example, two-dimensional modeling is necessary to predict and evaluate flows and habitats in floodplains with secondary channels.

While most projects are conducted within an existing floodplain, in some projects, new floodplains must be constructed. In situations where extensive contamination of floodplain sediments has occurred (downstream of mine operations) or the floodplain topography has been extensively disrupted by filling or mining, a new floodplain may have to be constructed, sometimes requiring substantial excavation, redistribution, or import of fill. In cases of floodplain contamination, the existing floodplain may be an appropriate analog for physical

reconstruction, greatly simplifying the design process. However, where the form of the floodplain has been significantly disrupted and no appropriate reference exists, an analytical design approach may be required and hydrodynamic flood modeling becomes an indispensable tool, allowing designers to design the channel and floodplain as a unit and accounting for the risks and benefits associated with the predicted extent and duration of overbank flows. Key considerations when designing new floodplains include the composition and compaction of subgrade alluvium, which ideally should approximate that established for the channel bed, soil development, revegetation, habitat creation, and grade control.

Design criteria for a new floodplain should accommodate overbank flow without concentrating it (increasing the risk of avulsion), provide spatially diverse and species diverse niches for native vegetation, provide complex topography, and allow for gradual channel migration while avoiding risks to life and keeping risks to property, infrastructure, and habitat acceptable or at least tolerable. The challenge in developing design criteria capable of meeting these and other project objectives lies in providing initial stability and protection from the erosive effects of flood flows long enough for floodplain and channel bank vegetation to establish and provide natural resistance to erosion of the floodplain surface and bank. Strategies for reducing the erosive forces exerted by overbank flows on newly constructed floodplains include 1) establishing floodplain vegetation 1–2 years prior to launching hydraulic connection, 2) blanketing the floodplain with biodegradable fabric, 3) use of slash, straw bale sills buried at floodplain grade (effectively biodegradable floodplain elevation valley-wide grade control), or 4) use of buried grade control structures at streambed grade to protect against incision below constructed channel grade if an avulsion does occur.

In designing streams and floodplains where significant risk of channel avulsion and damage to adjacent infrastructure exists, low constructed terraces can be employed along the floodplain margins, extending out into the floodplain. Terrace design may allow for inundation at higher flows, such as the 5-year flood (natural terraces are typically not inundated by such short-return period floods). A key design objective of these features should be to minimize the run length of unimpeded overbank flow across the newly constructed, unvegetated floodplain, and thereby reduce the potential for avulsion until floodplain vegetation becomes fully established (Miller and Skidmore 2003). Or floodplain vegetation can be established 1–2 years prior to launching hydraulic inundation, thereby managing risk of erosion and retaining desirable ecological function (this would require some means to control flow into the project area).

Incised Channels

Incised channel restoration is a special case that requires careful consideration of the floodplain, as ultimately the goal for most incised channels is to reestablish a hydrologic connection with the floodplain. Three general restoration approaches are used for incised channels.

1. Lower the abandoned floodplain (terrace¹³) to an elevation that allows hydraulic and sediment coupling with flow in the existing (incised) channel.

¹³ An abandoned floodplain that is no longer susceptible to overbank flows due to channel incision is technically a terrace; however, because this discussion focuses on restoring floodplain function to a historic floodplain, only the floodplain term is used.

2. Raise the streambed to its preincision elevation to restore hydraulic and sediment coupling with the existing floodplain.
3. Relocate the channel within the floodplain at the desired bed elevation to allow hydraulic and sediment coupling with the floodplain.

Site conditions, project goals, and physical constraints will determine which of the three approaches is most feasible. All approaches require that additional space for the channel and riparian zone be incorporated into design and ongoing land management.

A number of conditions exist where lowering the floodplain may be an appropriate solution:

- lowered base level,
- deep incision relative to stream size,¹⁴
- large or high-energy streams,
- significant progression through channel evolution evidenced by lateral migration of an incised channel and formation of an incipient inset floodplain or actively stabilizing bank toe (Beechie et al. 2008a),
- significant change in stabilizing boundary characteristics, especially vegetation that is providing considerable lateral stability, and
- lack of woody vegetation where beaver formerly played a role in maintaining channel elevation (where beaver cannot reasonably be expected to contribute to maintaining dams due to lack of vegetation).

If the stream has incised because its base level has been permanently lowered, such as in a tributary where the downstream main river system has lowered its bed, restoring the elevation of the tributary streambed to its former level may be impractical. Similarly, if incision occurred because beavers were removed and their dams had previously provided grade control, raising the streambed may be impractical unless beavers can be reintroduced and protected and sufficient woody vegetation is available for them to do their work.

If a stream incised due to a fundamental change in the flow or sediment regimes (common in urbanized and agricultural watersheds), restoring the bed elevation to its predisturbed condition may be impractical. In such cases, excavating the floodplain to a lower elevation that allows recoupling with the incised stream channel may be effective. This process essentially accelerates a natural process of channel evolution (see subsection 3.6.3, Channel Incision and Evolution), whereby channels first incise, then migrate laterally, eroding into the terrace (perched/abandoned floodplain), and ultimately create new floodplain surfaces at

¹⁴ While no general guidance exists regarding stream size and approaches to addressing channel incision that can be safely applied to all alluvial streams, stream size is highly relevant to considering alternatives, as it relates to rooting depth of riparian vegetation and the feasibility of the excavation and export of floodplain material (Beechie et al. 2006a). Caution is necessary when incision has been characterized in reporting by the phrase “entrenchment ratio,” a dimensionless ratio of flood-prone valley width (floodplain) to bankfull width (Rosgen 1994). Values for dimensionless ratios remove reference to physical dimensions and may lead to inadequate consideration of the absolute size of the stream.

elevations adjusted to the new channel elevation. Natural channel evolution of incised channels may take decades and cause significant environmental degradation including loss of habitat, loss of riparian vegetation, and significant sedimentation to downstream reaches. Active management can effectively bypass the long and environmentally disruptive processes of natural incised channel evolution by excavating new floodplain surfaces and jumpstarting the establishment of channel and riparian habitat.

A number of conditions exist where raising the streambed may be appropriate:

- small streams with limited stream power or very infrequent overbank flows,
- minimally or moderately incised channels,
- localized incision and local causes of incision,
- no change in stabilizing boundary characteristics (especially riparian vegetation), and
- no change in flow or sediment regimes.

Investigative and alternatives analyses may indicate that raising the streambed elevation of an incised channel to its historic grade is practical. Such situations include stream systems that incised following channelization (straightening) or encroachment, systems where beavers were removed but sufficient woody vegetation remains for them, or in smaller stream systems with limited stream power. The generalized approach to raising streambeds is to install check dams at intervals along the channel. Each of numerous check dams raises the bed at a point in the stream causing a backwater that traps sediment, thus establishing a new bed profile with elevation at or near the historic, predisturbance elevation. Through time, sediment trapping behind dams builds up the streambed to its predisturbance level. Consequently, the channel reconnects hydraulically to its floodplain and flows in excess of the channel-forming flow spill out to interact with the floodplain.

This approach does not necessarily provide immediate streambed function and habitat value, but does relieve the in-channel pressures associated with having long return period events retained within the channel, and restores the ecological processes derived from floodplain inundation. As the streambed between grades fills with sediment, hyporheic connection to groundwater in adjacent floodplain will increase and restore aquifer recharge and storage and contribute to higher summer base flows, though this may require years to decades.

A design challenge implicit to this approach lies in ensuring that the grade control structures are designed to be stable under all flows and that they are not flanked or end-run, meaning the stream does not erode laterally around the structure. Design will require hydraulic analysis of all flows up to and including the design flood, scour analysis, bank stability analysis, stability analyses for the structures, and analysis of fish passage through the structures. Analysis must also extend to sediment dynamics and storage potential within the incised reach, and a very sophisticated analysis of sediment supply, transport, and storage will be required. This will be necessary to predict infill rates between structures and the expected time frame for recovery of the bed profile to its predisturbance elevation.

In small streams, it may be appropriate to use permeable brush dams to replicate beaver dams and avoid the import of rock, steel, or concrete into otherwise gravel or sand bed channels.

Beavers are naturally compelled to repair and extend dams where flow end-runs a dam, in effect to maintain and manage the site. Attempts to replicate this process in the absence of beavers should consider the probability of streams flanking or end-running the dams, and the need to continually add wood to the dams to replace that washed out by storm flows.

Example design criteria for floodplain project elements:

- The channel migration zone (CMZ) will be designated to allow the maximum possible dynamic channel processes and unconstrained floodplain evolution given defined site constraints.
- Constructed floodplain surface materials will resist entrainment by flows up to the 10-year flow for a period of 3 years.
- Floodplain elevation will coincide with the water surface profile for the channel-forming flow over a minimum of 50% of the channel margins at the time of construction.
- Floodplain elevation will be no more than 0.5 m higher than water surface elevation under the channel-forming flow at any point along the channel.
- Terraces will contain a minimum of the 5-year flow for a period of 5 years following construction; for example, all flows under the 5-year flow will be contained within the boundaries of the floodplain defined by constructed terraces.
- The alluvial floodplain, within which the channel may migrate, will be a minimum of three times the maximum meander amplitude at the time of construction.
- Imported floodplain fill will approximate the size gradation of alluvial channel materials and will not limit hyporheic zone function or potential.
- The floodplain surface will be graded to prevent flow concentration and channel initiation, or over flow channels will be designed to resist erosion during the design flow.

Questions to ask in review:

1. What is the relevance and function of overbank areas in this stream? Is the stream alluvial, colluvial, or bedrock controlled?
2. Has a CMZ been defined for the project area? What are the property and infrastructure constraints on the extent of the floodplain and CMZ?
3. What is the condition and successional stage of existing floodplain vegetation and what impact does that have on alternatives?
4. Will overbank flows likely lead to avulsion in relic channels, topographic low points, or as overbank flows reenter the stream channel downstream? Are the risks associated with these possibilities acceptable, tolerable, or even desirable?
5. How soon will the project reestablish hydraulic connection to the floodplain?

Potential risks to resource:

- Recently reconstructed floodplains or alluvial channels within floodplains bear considerable risk of avulsion following construction until stabilizing riparian and

floodplain vegetation is in place. While avulsion is a natural dynamic channel process, in newly constructed stream and floodplain environments, it can cause significant sedimentation problems and channel stability issues. This risk will diminish as riparian vegetation becomes established on the floodplain. Where a mature riparian community exists, the risk may be minimal. This risk can be reduced through protection of floodplain surfaces with biodegradable fabrics or placement of vegetative debris to increase roughness.

- There is substantially greater risk in raising the channel bed of an incised stream than in lowering the floodplain, particularly where incision has effectively run its course. The risk of raising a bed or constructing a new channel at an historic elevation is related to the probability of recurrence of incision, which would likely have dramatic impacts to the resource. However, where a perched floodplain retains a mature riparian community, the loss of this associated with excavation of the floodplain would present significant loss of resource value in the short to long term.

Key design references:¹⁵

- Floodplain and incised channel analysis and design are typically conducted using hydraulic and hydrodynamic models. Refer to the Hydraulic Analyses subsection and Sediment Transport Analyses subsection of Appendix A for hydraulic modeling and sediment transport analysis methods.

Site Constraints and Infrastructure

While not necessarily a project element, existing constraints (e.g., roads, pipelines, levees, power line poles, buildings, railroads, and bridges) can limit and influence the design of many project elements if their removal or reconfiguration is not economically or technically viable or not acceptable to stakeholders. In such cases, these anthropogenic constraints effectively become imposed geologic features in that they influence the design options as much as bedrock outcrops might, but require additional diligence in ensuring proposed actions do not pose unacceptable risks to the constraints themselves. Wherever infrastructure is present, it is prudent to establish a baseline of existing hydraulic conditions including a detailed survey and hydraulic model. As part of the design process, an existing conditions model will establish the current extent of inundation, the magnitude of velocities and hydraulic forces to which infrastructure are presently exposed, and the existing risks borne by the owners of the infrastructure. All subsequent design scenarios may then be compared to this baseline situation.

Example design criteria:

- Infrastructure that can be moved or removed will be relocated such that it increases the available CMZ to 75% of the historic CMZ. (CMZs are discussed further in the Stream Corridor Management Strategies subsection of Appendix C).

¹⁵ For many project elements, common or appropriate design methods and tools are the same as those developed in Appendix A and are not repeated in these subsections. Where design methods are appropriate and specific to a project element and not otherwise described in the appendices, they are provided in these subsections.

- Channel bed elevation will be maintained for a distance of 100 feet downstream of all stream crossings (bridge footings, abutments, culverts) under all flow conditions up to the 100-year flow for a period of 50 years.
- Water surface elevations under constructed conditions will not increase at any flow relative to existing conditions for a period of 5 years.

Questions to ask in review:

1. Did the alternatives analysis consider options to remove, relocate, or improve existing site constraints and infrastructure, such as road rerouting, structure relocation, levee setback or removal, or replacement of culverts with spanning bridges?
2. To what extent do existing site constraints limit the width of a CMZ, the location of the channel, or the elevation of a channel, and have these been considered in design?
3. Do hydraulic models include all existing and planned infrastructure constraints?
4. Will the project as designed increase water surface elevation at any location, increase velocity or shear stresses on existing infrastructure, or otherwise increase risk to any existing infrastructure?

Potential risks to resource:

- Constraints to natural processes imposed by existing infrastructure limit the full extent of dynamic processes and related habitat values. Evaluating the potential consequences to the resource may be impossible, but limits on habitat sustainability imposed by infrastructure may present a significant concern.
- Existence of infrastructure in proximity to or within the CMZ invariably leads to channel and streambank stabilization where it would otherwise be unwarranted, and where it may diminish the ecological value of dynamic stream processes.

Slope

The slope of a channel is the ratio of change in elevation to distance along the channel, represented as a percentage. The energy slope is measured at the water surface and is a critical design parameter, because it determines the rate at which energy is supplied in overcoming flow resistance and transporting sediment. In steady, uniform flow, the energy, water surface, and bed slopes are all the same and in many applications the bed slope (usually measured from riffle crest to riffle crest along the channel) is used to represent the energy slope, especially at the reach scale and in geomorphic analyses.

In restoration design, the project elements involving channel slope cannot be considered separately from those concerned with cross section dimensions and planform pattern, as these three elements together define the three-dimensional geometry of the channel. Slope, cross section, and planform project elements, presented in this and following subsections, are iteratively manipulated to achieve the desired balance between the sediment supply from upstream and the sediment transport capacity of the project reach. Slope is a driving variable in this regard, as it must be delicately adjusted to achieve the desired balance between transport capacity and upstream supply over a range of design discharges.

A design consideration particularly related to the channel slope is whether grade control or stabilization of the channel slope is necessary. Grade control is commonly incorporated in project design to ensure that the design slope is maintained during the period following construction when the new channel is vulnerable to floods and to guard against possible future channel instability associated with slope adjustments in the postproject alluvial system. Regularly spaced grade controls are commonly, often unnecessarily, featured in newly constructed channels where the risks associated with drastic channel changes, particularly in the first few years following construction, are deemed to be unacceptably high. This is despite the theory that, if an alluvial channel is adequately designed to be in dynamic equilibrium, grade control should not be necessary.

Even where designers are confident in their designs, a design team or stakeholders may choose to protect their investment from destabilization due to channel instability emanating from outside the project reach by installing grade controls at the upstream or downstream boundaries of their project reach or both. Often, grade control is incorporated in design to accommodate risk-averse project designers in an effort to ensure stability, even if it is artificial stability and despite the constraints that it poses on natural process.

Where grade control is unavoidable, design should focus on ensuring the stability of the structures by installing their foundation materials at or below the maximum depth of scour and the extent of possible lateral channel migration that might flank the structure. The possibility of a channel avulsion bypassing the structure should also be assessed. In many circumstances, it will be unacceptable to constrain the channel laterally so that it cannot flank the grade control structures, because it would be necessary to install grade control across a significant proportion of the width of the floodplain. The risks created by grade control structures limiting future adjustments of the channel to maintain equilibrium as well as acting as barriers to the passage of fish or other wildlife must also be considered and reduced to an acceptable level.

Example design criteria:

- Grade control structures will protect against channel incision without impeding natural dynamic channel processes associated with lateral migration anywhere within the designated CMZ.
- Channel grade will ensure modeled sediment continuity at the established design discharge such that the channel does not aggrade or degrade for a period of 5 years under all flow conditions up to the 50-year flow.
- Grade control structures will remain effective during all flows up to the 50-year flow for a period of 5 years.

Questions to ask in review:

1. What project elements are most influenced by channel slope? Does design documentation explicitly explain or justify the design slope?
2. Were slope and stability of existing bed materials evaluated by sediment transport analysis?
3. What is the risk to the resource of implementing a project without grade control?

4. Is grade control justified by a high probability or severe consequences of channel grade instability within or outside of the project area? Has the probability of grade instability been reduced to the extent possible by other project elements?
5. If a grade control structure fails, will it result in a passage barrier to aquatic species? Who is the responsible party for repair if the structure fails?

Potential risks to resource:

- Slope that is not designed in concert with channel geometry and sediment transport analyses can lead to aggradation or incision and related habitat and resource degradation.
- Grade control, by definition, constrains vertical channel adjustment processes, but often constrains lateral migration as well (where structures are designed to prevent end-running). As such, they may limit dynamic channel processes and limit habitat development.
- In alluvial systems, failed grade control structures can become barriers to passage, aggravate lateral channel migration and bank erosion, or become unintentional hard points in the channel. The probability is that grade control structures will ultimately fail or be abandoned in an alluvial system.

Key design references:

- Channel slope analysis and design are typically conducted using hydraulic and hydrodynamic models in concert with sediment transport models. Refer to the Hydraulic Analyses subsection and Sediment Transport Analyses subsection of Appendix A for hydraulic modeling and sediment transport analysis methods.
- Grade control design is typically conducted using scour analysis. Refer to the Hydraulic Analyses subsection of Appendix A for scour analysis methods.

Cross-sectional Geometry

Design criteria and project objectives concerning the cross-sectional geometry of alluvial channels are focused on achieving dynamic stability while providing specific levels of habitat quality and diversity (Shields 1983, Shields et al. 2003). Channel slope is an integral component of cross section design, as the capacity of a channel, typically defined as the channel-forming discharge, is determined by the relation of cross-sectional area and channel slope. Cross section design usually rests on three generalized design approaches (analog, empirical, or analytical), as described earlier.

Within an alluvial channel, the shape of the cross section varies with position in the planform. For example, the cross section at the apex of a meander bend is typically triangular and asymmetrical, with a deep pool adjacent to the outer bank, while the cross section at riffles is more rectangular and symmetrical. Hence in designing an alluvial channel, practitioners commonly specify a minimum of three cross-sectional templates corresponding to pools, riffles, and transitional reaches. While the width, mean depth, maximum depth, and asymmetry vary between templates, all are sized to contain the channel-forming discharge. A robust design will

specify allowances for variation of width and depth for each template to provide for habitat variability.

In nonalluvial channels, specifying a channel-forming discharge may be less important, as channel boundaries are not readily deformable. Nonetheless, variation in channel cross section shape and dimensions will add value to habitat by providing a range of velocities and depths (Madej 1999). Design criteria for channel geometry parameters generally relate to the channel-forming flow and express the allowable or desirable range of variation in dimensions, so that the constructed channel is not unnaturally uniform.

Example design criteria:

- Channel cross section geometry will contain the channel-forming discharge (derived from investigative analyses) and provide for channel stability on the completion of construction. Discharge that exceeds the channel-forming discharge will inundate the adjacent floodplain.
- Channel width will vary up to a factor of two, such that the widest sections are no greater than two times the width of the narrowest sections at the completion of construction.
- Channel bed and bank composition will allow for gradual deformation and evolution of complex and variable hydraulics, sediment sorting, and associated habitat values.
- Water surface elevations on the floodplain will not increase under constructed conditions (relative to existing condition) at any flow between the 10-year and 100-year flood for a period of 10 years following construction.

Questions to ask in review:

1. What design discharge is cross section design based on, and how was the design discharge derived?
2. What design approach (analog, empirical, or analytical) was used to develop hydraulic geometry designs?
3. What type of hydraulic model is employed in cross section design?
4. Were floodplain and adjacent area topographic features included in hydraulic modeling?
5. Was sediment transport analyzed, either as the basis for design or to confirm design based on other approaches?
6. Do design channel roughness values reflect existing conditions, constructed conditions, or predicted future conditions (e.g., future bank and floodplain vegetation)?
7. Does design include variability in channel dimensions? Are variations in cross section geometry explicitly related to channel planform (e.g., are pools on bends)?
8. Are adjustments of channel dimensions immediately following construction anticipated? Are they planned for?
9. How will reconstructed channel banks resist erosion while vegetative elements mature?
10. How has uncertainty in sediment supply and transport been described and addressed in design?

Potential risks to resource:

- Sediment continuity is a key design consideration for reconstructed or reconfigured stream channel located in transport reaches. Channels that do not balance supply and transport capacity may adjust vertically (e.g., scour or fill) or armor if sufficient large bed material is available. Both adjustments may result in degradation of intended habitat and excessive bank erosion.
- Channel reconstruction designs often incorporate elements (artificial constraints) to protect against lateral or vertical adjustments in an effort to reduce the risks to infrastructure, or to safely compensate for lack of sediment transport analyses or lack of relevant design experience and confidence. Alluvial channels that are constrained from lateral shifting and vertical adjustment, inherent to dynamic stability, will not achieve sustainability or full habitat potential.
- Reconfiguration and reconstruction, even when most elements of uncertainty have been reduced, are subject to uncertain future hydrologic and sediment inputs. During the first years following construction, before subtle channel adjustments have occurred and before vegetation matures, projects may be very vulnerable to destabilization by infrequent large floods. Dramatic, destabilizing channel adjustments may result in more degraded conditions than prior to project implementation. This is particularly true for project designs based on reference or empirical conditions that include mature vegetation. Most constructed projects start with little if any significant vegetation, and so have different physical properties than the reference or empirical conditions from which designs may have been derived.

Key design references:

- Cross section geometry analysis and design are typically conducted using hydraulic and hydrodynamic models in concert with sediment transport models. Refer to the Hydraulic Analyses subsection and Sediment Transport Analyses subsection of Appendix A for hydraulic modeling and sediment transport analysis methods.
- The Federal Interagency Stream Corridor Restoration Working Group manual (FISRWG 1998) presents a comprehensive review of available empirical equations and references.

Planform

Planform refers to the channel configuration in plan view, as seen in a map or from the air. Planform design can be approached using analog, empirical, or analytical methods, a combination of two, or all three approaches. The advantages and limitations of each of these approaches are discussed in the Technical Basis for Design of Project Elements subsection of Appendix B. Planform is directly related to channel slope, as changes to planform affect channel length and slope is a function of channel length. As such, planform must be designed in conjunction with slope or following the establishment of design slope.

One critical planform parameter in meandering channels is the ratio between the bend radius of curvature (R_c) and the channel width (W) (Nanson and Hicken 1986, Harvey 1989). Theory and empirical observation indicate that meanders operate most efficiently (in terms of

energy loss) and tend to migrate rapidly (downstream) without changing their shape substantially when the R_c/W value is approximately 2.5. This is significant for newly restored stream channels that have relatively nonresistant, unconsolidated, unvegetated streambanks immediately following construction. While the design and construction of meander bends that approach this ratio may mimic natural meanders, meander values that approach this value increase the probability that rates of bend migration may be unnaturally high before vegetation has fully colonized the banks and riparian corridor.

The risk associated with accelerated bend migration often prompts designers to artificially harden the outer banks in constructed bends. Hardened banks at the outer margins of meander bends, whether reinforced with rock or rootwads, may be helpful in maintaining a desirable initial cross section and planform, but if they are overengineered (that is they prevent bank erosion rather than mitigating it), they constrain natural bend migration processes in what are intended to be dynamic alluvial river systems. In circumstances where the risk of bend migration immediately following construction and prior to the establishment of a mature riparian corridor is unacceptable, a better approach is to use biodegradable materials and deformable bank construction techniques (e.g., coir fabric encapsulated soil lifts) that will protect channel bends only for a defined number of years following project completion, while riparian vegetation takes root, after which time riparian vegetation can provide natural stability to the banks (Miller and Skidmore 1998).

Example design criteria:

- Risk associated with bend migration will be reduced because the reconfigured channel and bank will not be located within 20 m of existing structures, infrastructure, or public rights-of-way.
- Channel planform will remain nondeformable under all flows up to a 25-year flow event for a period of 3 years following construction, but will allow deformation through natural erosion processes and rates after riparian vegetation matures and as initial bank materials decay.
- Planform design criteria will be secondary to sediment balance and associated cross section geometry and slope criteria.

Questions to ask in review:

1. Is the channel alluvial, colluvial, or bedrock controlled?
2. Is channel planform design based on an analog, empirical, or analytical approach? What range of variability has been included in planform characteristics including width, meander wavelength, amplitude, and radius of curvature? What design basis was used to put boundaries on the range of values for these planform parameters?
3. Has an hydraulic model been developed for design conditions? Where in the existing planform are values for boundary shear stress predicted to be the highest?
4. Are channel banks designed to be deformable or nondeformable, and under what flow conditions over what period of time?

5. How are habitat elements related to proposed planform? Will planform deformability provide for habitat sustainability? Alternatively, will planform rigidity in confined reaches constrain the desired habitat?

Potential risks to resource:

- Risks (to riverine ecological systems and associated habitat) with planform design relate primarily to how the planform design contributes to dynamic stability and whether it allows stream processes to maintain channel form and sustain ecological function. If planform shifting and evolution do not permit the natural adjustments that are inherent to dynamic stability, it introduces risks that unexpected instability through aggradation or incision, channel avulsion, or planform metamorphosis may occur—degrading or destroying habitat. Alternatively, if the channel is fixed in place due to the overdesign of boundary erosion-resistance characteristics, this will limit the effectiveness of natural processes of planform adjustment that allow the channel to respond to disturbances and natural variability in the flow and sediment regimes and, in doing so, create and renew habitat.

Key design references:

- Planform design may be based on reference or historic conditions, empirical relations, or derived analytically. The Federal Interagency Stream Corridor Restoration Working Group manual (FISRWG 1998) presents a comprehensive review of available empirical equations and references to assist in establishing planform design.
- Soar and Thorne (2001) describe analytical design approaches.

Bed Materials and Substrate

In stable alluvial systems, bed material is mobilized during flows approximating bankfull flow, and over a period of years the average volume of material mobilized and transported downstream from the reach is replaced by an equal volume and similar character of material transported into and deposited within the reach. In theory then, a channel constructed within alluvium that meets criteria for dynamic stability will not need to be concerned with the size and character of alluvial material. However, alluvium is rarely of a consistent gradation, so sediment continuity through a designed reach cannot be assumed.

To meet design objectives, the sizes of existing sediments making up the surface and substrate of the bed should be compared to the sizes that will be mobilized under implemented project conditions (under design flows), as determined through incipient motion calculations (see the Hydraulic Analyses subsection and Sediment Transport Analyses subsection of Appendix A). If incipient motion calculations indicate that a different size of bed material is appropriate under implemented project conditions (under design flows), it will be necessary either to introduce appropriately sized bed material or reconfigure the design channel geometry to achieve the incipient motion conditions desired.

In designing schemes that require coarsening of the bed material, an option that may seem attractive is to allow stream processes to coarsen the bed by the input of gravel or coarser-

sized sediment moving into the newly restored reach from upstream, even as the constructed streambed is coarsening through selective removal of the finer fraction of existing bed material. However, before deciding to rely on stream processes, practitioners should recognize that flows of sufficient magnitude and duration to sort gravel in the project reach and deliver it from upstream in significant quantities may not occur for years or even decades following construction. Hence the risks associated with waiting for stream processes to develop the bed gradation required by the restoration design criteria and project objectives must be evaluated and compared with the advantages of allowing nature to form the bed and substrate rather than importing sediment artificially.

In this context, assessment of the risks and benefits of design alternatives will demand a sophisticated sediment transport analysis. Where the risks of allowing stream processes to form the bed are unacceptable, imported gravels must be used, generally to a minimum thickness that is greater than maximum scour depth predicted using an appropriate mobile-bed hydrodynamic model. When modeling scour in artificially placed gravels, the particles will be less densely packed than alluvial sediments, will not be imbricated, and will typically contain finer grained materials mixed in, making them more mobile and easily scoured than bed sediments of equivalent size that have been naturally deposited.

Example design criteria:

- The D_{50} of specified imported bed and alluvial materials will be mobile at the specified channel-forming flow.
- Specified bed substrate with a D_{50} mobile at design flow (for channel-forming flow) will consist of rounded particles (as opposed to angular or crushed, if imported) and be installed to a minimum depth of 1.5 times the depth of scour at any given channel cross section.
- Imported bed material will contain no particles greater than the D_{100} of native alluvial fill.

Questions to ask in review:

1. Will the project be conducted within native alluvium and to what extent has that alluvium been disturbed, as through mining, grading, or other redistribution? Does the design channel differ significantly in transport capacity from historic channel conditions under which native alluvial fill was deposited?
2. Under what conditions and design flows are the proposed channel bed materials intended to be mobilized? Are they intended to remain immobile at all times and design flows?
3. Were the current and with-project states of sediment balance in the project reach investigated and, if not, is this acceptable given the design criteria and project objectives? If the sediment balance was investigated, how were data characterizing the bed material, sediment supply, and sediment transport rate derived?
4. Has a hydraulic or hydrodynamic model been developed capable of simulating current conditions and those associated with all design discharges? Are the boundary shear stresses on the bed and banks likely to mobilize the boundary materials, and at what flows? If so, where in the proposed channel are boundary shear stresses expected to be greatest and is this allowed for in the design?

5. What is the expected maximum scour depth? Has this been allowed for in the design criteria for bed materials and the footings of any in-channel structures?

Potential risks to resource:

- The size distributions of the sediments making up the bed surface and substrate are important project elements in establishing sediment balance in the project reach, matching channel morphology to stream processes, and so designing a restored channel that can provide the desired habitat sustainably as part of the alluvial system. Risks to habitat and the aquatic and riparian ecosystems it supports stem primarily from failure of the bed sediment surface and substrate as designed to deliver sediment transport continuity and the degree of dynamic channel stability appropriate to the morphological setting. For example, in situations where the sediment balance should be neutral but this is not attained due to a design flaw or due to insufficient information (uncertainty) in the design process, an imbalance between sediment supply and transport capacity may drive aggradation or degradation, or excessive rates of lateral shifting. Both can substantially degrade habitat.
- Imported sediment may contain seeds of invasive or undesirable plants, introduced species (e.g., zebra mussels [*Dreissena polymorpha*]), or other pathogens and biological threats (e.g., whirling disease [*Myxobolus cerebralis*]). The provenance of imported sediment must be known and any residual risks associated with the material must be deemed acceptable.
- Introduced gravel will be more mobile than the same gradation of gravel that has been transported, sorted, and deposited by flowing water, allowing additional scour and hence creating an attractive nuisance. For example, if fish use the gravel for spawning and it is then transported downstream during the first high flow event, those deposited eggs will be lost.

Key design references:

- For sizing bed materials, refer to the Sediment Transport Analyses subsection of Appendix A.
- For bed material sampling methods:
 - Copeland et al. (2001) provide discussion of methods for sampling bed material.
 - Bunte and Abt (2001) provide methods for sampling particle size distributions in wadable streams.

Streambanks

Streambanks may be one of many project elements in a comprehensive reconstruction or they may be the primary focus of a project. In restoration projects in alluvial systems, where ideally a dynamic and deformable channel system is sought, streambank design criteria may call for immediate or future deformability. However, in cases where addressing streambank erosion is the focus of a project, streambank stabilization or protection may define project goals and objectives.

Streambank stabilization refers to actions taken to prevent further erosion of streambanks by checking the processes that result in erosion, namely entrainment of bank materials and mass failure of the bank. Bank stabilization is usually justified as an effort to reduce sedimentation in the channel resulting from apparently excessive bank erosion rates or to protect some form of property. Long-term bank stabilization may be desirable to protect infrastructure that could not be relocated out of the CMZ, as part of removing constraints. In these cases, an appropriate design flow and maintenance schedule must be specified within the design criteria in order to reduce the erosion risk to the infrastructure to an acceptable level.

In all other situations, the ideal design objective for the banks of a restored channel is a dynamic, deformable channel that is free to migrate in the context of a stable channel. Therefore, bank design criteria should allow for bank migration at moderate (pseudo-natural) rates under channel-forming flows. However, newly constructed banks formed in unvegetated alluvium are prone to erosion. Typically, it takes years for the seedlings or cuttings planted on them to develop the mature root structures and quantities of above-ground mass sufficient to develop the same degree of natural resistance. Bank design criteria must include the temporary bank protection required to provide a stabilizing influence immediately following construction. Design criteria should specify the desired degree of erosion resistance and period of time over which that protection should remain effective; that is, the design flow should be specified, as well as the period of time necessary to allow riparian vegetation to mature and provide natural bank protection.

A wide spectrum of bank design criteria exist, ranging from immediately deformable under channel-forming flows to permanently stabilized for all design flows. Unprotected banks are highly vulnerable to erosion following construction and risks arise because of the possibility that even frequent floods may cause excessive erosion, leading to actual or perceived failure of the restoration scheme. In contrast, armored banks are usually intended to be nondeformable under all flows. They fix the channel in place using bank alignments that are relatively permanent, so that it is unable to adjust in response to naturally variable stream processes and subtle changes in the flow and sediment regimes. This introduces risks to habitat sustainability and the long-term success of the restoration scheme, as well as creating a huge burden on those responsible for ensuring channel stability to maintain, and in due course rehabilitate or replace, the bank protection structures.

In the middle of the spectrum between banks that are continuously and permanently protected and those that are entirely unprotected are restoration objectives that require channels that are dynamically stable but which are able to migrate laterally at pseudo-natural rates under specified, channel-forming design flows, allowing for controlled failure. This requires bank design criteria that provide for stability during base flow and moderate in-bank flows, but allow for controlled failure under flows equal to or greater than the channel-forming discharge. For example, project objectives may require that the newly constructed banks in a restored reach must be stable until vegetation matures, after which they will be deformable under flood conditions (Miller and Skidmore 1998).

Many restoration designs involve discontinuous bank protection using structures installed at intervals along the bank line that protrude into the channel to deflect flow away from the bank. Depending on the details of their design and operation, these structures are variously termed

groins, barbs, or bendway weirs. In the short term, the impacts of discontinuous bank protection on habitat may be beneficial. For example, various designs for these structures have been shown to create and maintain pool habitat through scour processes and accumulate sediment along the protected bank. Some designs may incorporate large wood or other porous features that provide added value of refuge and may trap additional wood and organic debris. However, the intent of these structures remains to permanently train the stream and prevent erosion of the protected bank. Consequently, these still constitute a constraint on stream processes, and unless they are designed for failure, either under high flow or over time, in this context their long-term impacts are not substantially different from a channel that is stabilized using rock with rootwads protruding from it. In summary, the use of discontinuous structures for bank protection is advantageous in that they provide potential for habitat enhancement through deposition of sediment between structures, riparian colonization, and deeper scour holes. However, if oversized or built from nonbiodegradable materials, they still introduce risks to natural maintenance and renewal of habitat through their constraining effects on stream processes and natural channel adjustments.

Restoration research and practice has given considerable attention to the application of bioengineering for bank protection, and these approaches are often promoted as a nature-friendly alternative to hard engineering solutions. In the context of design criteria for the banks of restored channels, bioengineering refers to the use of living plant matter in structural designs. This does not, however, necessarily imply any lesser impact to geomorphic process, as a bioengineered bank may be as structurally sound and nondeformable as a traditional riprapped bank. Bioengineered designs typically employ native riparian plants, but they may still introduce risks to the long-term success of a restoration scheme if they prevent the bank from deforming under the action of the channel-forming flow.

In essence, bioengineering technologies can be used to deliver any standard of protection or deformability required by the bank design criteria and project objectives, from deformable over time to permanently armored. Where they differ from traditional engineering practices is in their capacity to address vegetation objectives simultaneously. Consequently, the responsibility of the design team is to select an appropriate design ranging from one that resides at the upper end of the stabilization spectrum (e.g., a rock toe with vegetation incorporating internal structural components on the remainder of the bank—essentially a “bio veneer” over an otherwise nondeformable bank), to one at the other end of the spectrum (e.g., a bank constructed entirely from potentially mobile, alluvial materials and soils protected by vegetative fascines, live stakes, mattresses, or biodegradable fabrics that provide initial stability and protection, but degrade as vegetation matures). The great advantage of using biodegradable materials lies in the fact that the materials employed have a life expectancy that may be as short as 2–3 years in humid environments or as long as 10 years in semiarid environments, and which can be attuned as appropriate to the design criteria.

Example design criteria:

- Channel banks will be nonerodible under all flows up to the 25-year flow for a period of 3 years following construction (or alternatively until bank and riparian vegetation reaches a predefined maturity threshold), after which the installed bank protection will degrade

and the banks will erode at natural rates under discharges equal to and exceeding the channel forming flow.

- Materials used to construct the channel banks will consist only of biodegradable materials, locally derived alluvium, and native plant species.
- For lengths of streambank that must be stabilized to protect infrastructure, the bank toe will be designed to be nondeformable and simultaneously allow for bed scour adjacent to the toe, for all flows up to the 100-year discharge. The remainder of the bank from the lower limits of vegetation to the top of bank will be stabilized using structural elements to guard against mass failure and bioveneered (minimum 75% cover) with native vegetation.

Questions to ask in review:

1. Is observed bank instability due to anthropogenic impacts, such as channel modifications or changes in hydrologic or sediment regime and associated incision or aggradation? Have ultimate causes of instability been addressed? If anthropogenic impacts do not explain instability, is observed instability explained by natural dynamic channel processes?
2. Is the proposed streambank part of a restoration effort where natural dynamic stream processes are an ultimate goal, or is the proposed streambank strictly an effort to stabilize an eroding bank?
3. Do project objectives explicitly state the degree of lateral mobility required for the channel within the CMZ?
4. Has every attempt been made to remove constraints on lateral shifting by relocating infrastructure out of the CMZ as an alternative to stabilization?
5. Where streambank design criteria mandate permanent or long-term stability, what is the justification for constraining natural dynamic processes?
6. Do design criteria explicitly state the design flow for any bank protection structures and the period over which protection is required to persist?
7. Do designs for bank elements use continuous or intermittent structures? Are different protection materials used below and above the water/vegetation lines? How was the water/vegetation line determined?
8. Has the possibility that protecting one length of streambank may transfer erosion from that location to another been investigated? If not part of the intended design, are the risks of transferring erosion acceptable, or at least tolerable?

Potential risks to resource:

- Stabilization of streambanks eliminates the lateral flexibility characteristic of dynamically adjustable alluvial streams. In addition to any loss of habitat associated with bank stabilization, fixing the planform pattern reduces or limits the ability of stream processes and morphological adjustments to sustain and renew habitat, and the loss of sediment input and wood recruitment from retreating banks can cumulatively impact habitat resources. Cumulative impacts are of particular concern, as a single isolated

stabilization effort may establish precedence that leads to considerable constraint of natural process in the future.

- Lack of attention to detail in the design of the banks may jeopardize project success. Failure to provide adequate temporary protection using biodegradable materials may expose a newly constructed channel to severe erosion by moderate flows with unacceptable risks to the project. Conversely, overengineering bank protection risks constraining stream processes and morphological adjustment, limiting the quality and sustainability of habitat in the long term.
- Many streambank stabilization efforts incorporate elements or features that are not native to the stream, such as large or angular rock or large wood. When these banks ultimately fail, either by design or by a failure in design, these elements will affect stream processes. Often they create obstructions or constraints to flow in unintended locations with undesirable effects, such as exacerbating erosion at other locations or preventing migration of the channel within a CMZ.

Key design references:

- The Integrated Streambank Protection Guidelines (Cramer et al. 2002) provide a comprehensive review of analysis and design methods for many different types of streambank protection, online at <http://wdfw.wa.gov/publications/00046/wdfw00046.pdf>.
- For bioengineering techniques, refer to Gray and Sotir (1996).
- Many methods discussed in the Hydraulic Analyses subsection of Appendix A are relevant for deriving channel velocity and shear along banks. For prediction near bank velocities, scour depths, and boundary shear stress at meander bends, refer to Bathurst et al. (1979) and Thorne and Abt (1993).

Vegetation

As a component of restoration design influencing channel boundary characteristics, vegetation design criteria should consider what the native riparian community can support—trees, shrubs, or herbaceous plants—and what vegetation is necessary to provide the degree of natural protection required by the restoration objectives.

Important steps in designing the vegetation elements in a restoration project include selecting suitable species and assemblages, specifying their growth stage (seed, seedling, rooted stock, etc.), and setting the timing for planting and delineating the planting zones. The planting zones should extend beyond the channel and riparian corridor to encompass the entire floodplain or at least the CMZ. Species selection and the building of assemblages are best based on native local riparian systems; seeds and rooted stock should be derived from locally adapted native species whenever possible.

In selecting plants and assemblages, the role of vegetation in providing natural bank protection should also be considered. In this context, the vegetal and rooting characteristics determine the resistance of plants to fluid forces of shear and drag at high flows (Hoitsma and Payson 1998). If plants are to be part of bioengineered bank protection, then further factors come into consideration and plant selection may be conditioned by the requirement to include

some plants that provide short-term cover and bank stabilization in the knowledge that they will later disappear as natural succession replaces them with other species. In many cases, ecological function may be best advanced by planting a mix of riparian species that includes seral-stage trees that optimize site potential, such as redwoods or the giant fir species.

Consideration of natural successional processes will also influence selection of the growth stage for planted vegetation. Many shrubby species can be effectively propagated using cuttings from local sources. In such cases, soil characteristics and depth to groundwater or the phreatic fringe during all seasons must be considered, as cuttings typically need access to saturated soil in order to establish roots, and roots need access to soil moisture. For larger projects involving large amounts of rooted stock, 2 to 3 years advance notice may be necessary for nurseries to collect and propagate plants from local sources.

Once the initial steps set out above are accomplished, a revegetation plan must be configured for each of the planting zones. This must specify the planting densities, soil amendments, and specifications developed for each zone. Revegetation plans must take due consideration of inundation frequencies and durations, the possibility of drought conditions, the lower elevation limit of vegetation on a bank, and the magnitude and duration of fluid shear and drag forces to which the plants may be exposed during the higher design flows.

Design criteria for vegetation elements of a restoration scheme require development of a postproject monitoring and maintenance schedule, particularly in watersheds prone to drought and locations susceptible to excessive browsing or grazing. Because riparian vegetative growth and success is so dependent on local soil moisture and streamflow conditions, seasonal and interannual variation in precipitation and discharge can make or break a revegetation effort. Planting zone delineation defines appropriate locations for varying species and growth types through analysis of inundation frequencies and durations (derived from hydrologic and hydraulic analyses). Hydrologic analyses may indicate that temporary irrigation is essential to allow plants to become established and self-sufficient. First and second season monitoring of soil moisture will guide the need for irrigation. Monitoring will also reveal the extent to which browsing (deer [*Odocoileus* spp.], elk [*Cervus elaphus*], moose [*Alces alces*], beaver [*Castor canadensis*], cows [*Bos* spp.], sheep [*Ovis* spp.]) affects establishment and growth of installed plants, and whether browsing controls are necessary.

Vegetation elements must be dynamic and their design will benefit from modeling the expected succession of vegetative communities and the corresponding adjustment and evolution of channel form. Interactions between channel morphology and plant growth and succession can be investigated by varying roughness characteristics within hydraulic models to simulate vegetative succession, and varying channel geometries to reflect postproject adjustments to channel form related to growth of vegetation on specific surfaces within the channel.

Example design criteria:

- Vegetation will cover 90% (with explicit cover measurement protocol) of streambanks and 75% of floodplain within 3 years of construction.
- Floodplain vegetation will consist of 100% native species for a period of 5 years following construction.

- Planted tree and shrub species will have a 75% survival rate 5 years following installation.
- Species composition will approximate desired (historic or site potential) floodplain and riparian community structure, and the plants and seeds used will be propagated or collected, respectively, from sources within the same stream system or basin.

Questions to ask in review:

1. What is the probable mature native plant community for the project area? How much do existing conditions diverge from this, considering species composition and age class? Are existing conditions on a natural, successional trajectory to return to historic conditions? Is there a site potential condition that would provide greater ecological benefits, such as old growth riparian forest?
2. What role will vegetation play in long-term channel and bank stability?
3. Where and how will plant and seed stock be obtained?
4. What level of postproject irrigation and maintenance is anticipated to meet project objectives and associated design criteria?
5. How will the succession of plant communities be accommodated or facilitated?

Key design references:

- For vegetation considerations in design, particularly for streambank design, refer to the Integrated Streambank Protection Guidelines (Cramer et al. 2002), online at <http://wdfw.wa.gov/publications/00046/wdfw00046.pdf>, and the Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004), online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.
- For a comprehensive listing of publications relating regional vegetation to geomorphic or other site conditions, browse <http://www.reo.gov/ecoshare/Publications/searchresults.asp>.

Instream Habitat

Instream habitat elements include primarily channel bed features or installed structures intended to provide forage, refuge, or cover for aquatic organisms. Habitat design criteria will cover the species, life stage, and biologic function intended to benefit the selection of materials used to create habitat, the deformability/rigidity of constructed habitat elements, the cost effectiveness (because the functional life of constructed elements may be short), and the habitat complexity at multiple scales.

Ideally, materials used for constructed habitat elements should be locally derived and consistent with natural materials already in the project or adjacent reaches. For example, the introduction of large boulders would be inappropriate in an alluvial gravel bed stream, while the use of large wood might be out of place in a small stream flowing through a natural meadow or in a semiarid grassland setting. Locally derived materials are less prone to introduction of seeds or spores of nonnative and undesirable plant or animal species.

Constructed habitat elements are commonly designed to be relatively nondeformable, using cables, pins, and anchors to ensure that they remain in place during floods such that they continue to provide habitat over long time periods, and to prevent liability associated with debris jams consisting of imported materials. However, these constructed elements may persist for centuries as unwelcome legacies of long past efforts to provide habitat. For example, general consideration should be given to how rigid a habitat element needs to be. Static rigidity may be desired in elements intended to force pool scour at high flows, but in most cases less rigidity is better so that an alluvial stream can adjust and migrate and unintended and detrimental effects on habitat can be prevented. For example, Kail et al. (2007) reported that, based on a review of 50 wood reintroduction projects, unfixed log jams result in more natural channel features than fixed structures and are also significantly more cost effective.

An overarching principle that should be included in the design criteria for all habitat elements is the need to ensure that the degree of complexity is sufficient to meet the relevant project objectives. Complexity is an important attribute of natural habitat at all scales: planform complexity at the reach scale, variability in width and depth at the site scale, bed material variability and patches at cross sections and bends, and lines and edges at micro-habitat scale. Design criteria for the habitat elements in a restoration project should, therefore, specify the nature and degree of complexity at all scales. These criteria must also be reflected in the performance parameters against which success in achieving project objectives will be judged. That means focusing on diversity and variability rather than consistency in monitoring and evaluating the habitat outcomes of a restoration project. In this context, establishing and measuring habitat targets is no more difficult provided that the design criteria properly include and reflect habitat complexity as a project goal.

Example design criteria:

- New habitats will be located where food, cover, and protection from predators are provided, so as not to create an attractive nuisance (attractive to target species, yet without sufficient resources for them).
- Installed and constructed habitat structural elements (log jams, rootwads, log structures, boulders) will not restrict passage of adult (or juvenile in some locations) migratory salmonids, as documented by monitoring of migratory and spawning activity for a period of 2 years following construction.
- Installed and constructed habitat structural elements will not be artificially anchored or fixed in place, but will adjust and evolve with the alluvial channel.
- Constructed off-channel rearing habitat will maintain a hydraulic connection sufficient for passage (may specify depth or other attributes) of all rearing-age native salmonid species from September through May for a period of 5 years following construction.
- Habitat elements will be constructed using only materials native to the site or contributing watershed.

Questions to ask in review:

1. Have habitat limitations been identified as a constraint to recovery or sustainability for any native species? Do habitat objectives specify single species or multispecies habitat? What types of habitat have been identified as limited?
2. What caused or contributed to the lack of habitat? Are these causes being remedied or mitigated? What is the perceived urgency for providing new or additional habitat?
3. Are the stream processes in place to create and sustain habitat through periodic disturbance involving mobilization of bed sediment, local scour, bank erosion, channel migration, large wood entrainment and log jam creation or destruction under a range of flow conditions? If not, will the proposed project restore the necessary stream processes?
4. Is habitat creation an explicit project objective? Are habitat elements to be constructed or will they develop naturally under the action of stream processes in the restored channel?
5. Do the design criteria for habitat elements specify the nature and degree of complexity? Are these criteria reflected in the performance parameters against which success in achieving project objectives will be judged?

Potential risks to resource:

- The primary risk to ecological resources from creating habitats is that they may attract individuals to areas without adequate cover, shade, food, or refuge from predators.
- Secondary risks are from construction and installation. Installation typically requires in-channel work with inevitable disturbance of the streambed, banks, or both, which can cause risks to species on-site and downstream. Construction in dry, dewatered conditions can greatly alleviate these risks, though the construction of flow diversions introduces further risks that must also be evaluated and found acceptable.

Key design references:

- Most references for design of instream habitat describe structural approaches to creating habitat and are suggestive of materials that may be inappropriate, such as angular rock, boulders, cables, and pins. This document emphasizes the importance of establishing processes that create, maintain, and sustain habitat, for which there are no current references. However, the Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004), online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>, provide considerable discussion of habitat design methods, and the Integrated Streambank Protection Guidelines (Cramer et al. 2002), online at <http://wdfw.wa.gov/publications/00046/wdfw00046.pdf>, provide specific discussion of structures.

Structures and Large Wood

Stream projects often include in-channel structural elements constructed from boulders, angular rock, or large wood and may serve the intent of providing grade control, training the channel, stabilizing a bank, or providing habitat. The presence of artificial structures in alluvial streams influences the operation of stream processes and usually introduces constraints on natural rates and patterns of channel adjustment. Therefore, structures should be removed

wherever possible from design plans. Where structures cannot be removed for economic, practical, or social reasons, they should be designed to minimize their impact on stream processes, morphology, and habitat. Where artificial structures remain, they will usually limit the long-term restoration potential of the reach and may jeopardize project objectives.

Where structures are unavoidable or otherwise justified, artificial structures can be designed and constructed to mimic the effects of natural structures. Examples of natural structures that might be mimicked in a restoration design include bedrock outcrops or very coarse material exposed in the bed that provides natural grade control, clay plugs in the banks that limit lateral channel migration, and log jams and beaver dams that act as temporary impoundments that provide sediment sorting and storage functions.

Consideration of the intended function of structural elements with respect to stream processes and habitat value is critical for deciding whether the inclusion of such structures is appropriate in the context of restoring and protecting habitats and ecosystems. Some intended functions are:

1. Create or enhance habitat. Structures may be installed to form flow obstructions and so promote variable or concentrated hydraulics that create pool habitat through local scour, gravel bars in the lee zone, and sorted gravels for habitat value. Such structures include log jams, boulder clusters, drop structures, and riffles.
2. Provide grade control. These are structures created to prevent channel bed incision, cure channel instability due to degradation, or promote recovery of the bed elevation in an incised channel to a former, higher level. Such structures include weirs, sills, armored riffles, and cross-vanes.
3. Store sediment and wood. These structures are used to trap and sort sediment, to increase retention, or to retain wood to create log jams. These include weirs, porous weirs, log jams, grade control structures, and sills.
4. Protect the banks through flow deflection. These are structures intended to prevent erosion or collapse of streambanks by deflecting high velocity flows away from the bank. These include groins, jetties, bendway weirs, barbs, cross-vanes, j-hook vanes, log spiders, and engineered log jams.
5. Protect the bank by armoring. These are structures intended to prevent erosion or collapse of streambanks by increasing erosion resistance and mass stability. Structures include linear revetments and discontinuous hard points constructed from riprap, articulated concrete blocks, bioengineering materials, geofabrics, and rootwads.

The design criteria for the structural elements in a restoration project must first support identification of whether they are essential and, if so, where they should be placed:

- Large wood structures, such as engineered log jams, are generally appropriate in most stream and river systems that have a history of snag removal, splash damming, and riparian forest harvest. They may be inappropriate in historically unforested smaller streams, such as meadow streams or water courses in semiarid regions.
- Large wood may be preferable to rock where structures are considered necessary. Large wood, while ultimately degradable, may take centuries to degrade appreciably in

submerged conditions. Degradation rates vary by species, with cedar species degrading the slowest. Similarly, large wood can be used to build bank stabilization and flow deflection structures, and offers some distinct advantages over rock in that it may provide tangential ecological benefits.

- Grade control structures are best built using rock or large wood. Consideration of when grade control is appropriate is discussed in the Slope subsection of Appendix B.

Design processes for structural elements must include the investigative analyses necessary to ensure that the structures installed will:

- create the desired hydraulic conditions,
- be stable under all design flows including extreme floods,
- not pose any risk to life,
- reduce risks to property or infrastructure to acceptable levels,
- neither destabilize the channel nor constrain its natural processes and adjustments unacceptably, and
- not impede fish passage.

Structures are intended to influence the distributions of velocity and the boundary shear stress, but the way that they interact with the flow varies as a function of discharge. Consequently, hydraulic analyses (Hydraulic Analyses subsection of Appendix A) are necessary to support their detailed design. While guidance exists for designing structures based on the desired performance and function (e.g., Cramer et al. 2002, Saldi-Caromile et al. 2004, NRCS 2007), recommended design standards usually focus on ensuring the stability of the structure and tend to be overly conservative. Thus the use of existing design approaches risks overengineering the stability of the structure rather than designing for appropriate failure.

Design approaches commonly employed tend to be those that can be applied using input data derived from simple at-a-section hydraulic analyses (see the Hydraulic Analyses subsection of Appendix A) and their scope is often limited to the scour and boundary shear stress analyses necessary to ensure that the materials employed are of sufficient size and thickness so as to be immobile at the design flow. In many cases, only rough guidance is provided on the configuration and proportional dimensions.

Ideally, the design of structures employed as part of a restoration project demands one dimensional (1-D) or perhaps two dimensional (2-D) hydrodynamic modeling (see Hydraulic Analyses subsection of Appendix A) so that their performance can be adequately evaluated and channel response predicted over a range of flows. For example, scour—a key design component for structural stability—is greatly influenced by the degree of channel constriction imposed by the structure. Thus where general design guidance may specify design standards based on substrate, depth, and slope only, constriction will affect the resulting scour and can best be estimated with more rigorous analysis of flows (Raudkivi 1990). As such, while many structures are designed with a sufficient factor of safety to ensure they are stable at the maximum design flow (depth of scour and size of materials derived from at-a-section analyses), few are designed on the basis of the detailed investigation necessary to evaluate how they will actually perform

over a range of discharges, or how they will function in the future as the alluvial channel adjusts in response to stream processes and small changes in the flow and sediment regimes. Only through 1-D or 2-D modeling can the structure's interaction with future flows and channel morphologies be evaluated probabilistically to allow assessment of the attendant risks to people, property, infrastructure, habitat, and species.

Specific design considerations for structures placed in stream channels include:

1. Hydraulic effects—the change in flow direction and force over the range of flows and implications for design as well as channel response.
2. Scour depth—the depth to which the bed and substrate may be eroded over the range of anticipated flows, and the structure's impact on local scour around and under it.
3. Drag forces—the loading placed on elements of the structure due to its effect in obstructing flow over the range of discharges. This is particularly important for large wood that projects into the stream.
4. Buoyancy—particularly important for wood that may be submerged as the effect of buoyancy may compromise structural integrity.
5. Materials—composition and size of materials relative to native materials.
6. Height—the height needed for a structure to be functional.
7. Flood effects—the impact on water surface elevations over the range of flows, related inundation frequencies, and effects on shear and scour across the channel from the structure. Structures affect roughness and channel dimension, both of which can elevate water surface elevations for a given flow.
8. Safety—public safety (including recreational users) must not be put at risk.
9. Design life—how long the structure is required to function.
10. Failure mode—what is likely to happen to the structure after it has ceased to be functional.

Example design criteria:

- Installed structures (weirs, log jams, etc.) will be constructed entirely from native, locally derived materials. They will not contain imported rock, cable, anchors, or other artificial elements.
- Structure footings or foundation will be installed to a minimum depth of 1.5 times the calculated depth of scour.
- Structures will remain stable (in place and functional) during all flows up to the 25-year flow for a period of 5 years.
- Grade control structures (where necessary) will not extend above the channel bed and will be stable under all flow conditions and associated scour up to the 100-year flow.

Questions to ask in review:

1. Are structures intended primarily to provide habitat value or primarily to provide stability function? Where structures are intended to provide primarily habitat value, what has caused a deficiency of habitat in the current system, and have these ultimate causes been remedied? Where structures are intended to provide primarily stability functions, have ultimate causes of instability been addressed?
2. How do the design criteria for the structural elements relate to the project objectives, to stream processes and channel morphology, and to benefits for habitat and species?
3. How do the proposed structural elements avoid constraining natural processes and stream functions? What nonstructural alternatives to meeting the relevant project objectives have been considered and are these really unviable?
4. What design flow is specified for functional performance (related to project objectives) and what is the design flow for structural stability (how durable is it)?
5. What is the design life and potential impact of structure when it has been abandoned?
6. From what materials is the structure composed? Will these be relatively benign when the structure is no longer functioning or fails?
7. Are the structure elements designed to function in concert with each other (e.g., bendway weir) or on their own? How do the hydraulic, morphological, and sediment impacts of the structures vary with discharge?

Potential risks to resource:

- Structural components pose inherent risks to stream resources by constraining or concentrating stream processes and natural channel adjustments. While structures may achieve project objectives related to channel stabilization and short-term habitat creation, in doing so they also limit future habitat potential in the project reach. The most immediate risk is that the structure may fail, creating an unplanned and unnatural feature in the channel with unpredictable impacts that are likely to be detrimental to channel stability, habitat, and species. The longer-term risk is that it never fails but becomes dysfunctional as the channel evolves around it with similar outcomes to those of a failed structure.
- Structures are often designed to act independently in obstructing or concentrating flows, affecting the velocity and shear stress distributions, promoting local scour and fill at the bed and protecting the bank line from retreat. However, in nature structures may interact and the failure of one element can lead to destabilization of other elements. Risks to stream resources stem from the domino effect that can occur if one structural element in a restored reach fails or becomes dysfunctional.

Key design references:

- For an overview of general design considerations for instream structures, refer to Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004), online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf>.

- For more specific design guidelines on incorporating large wood in engineered designs for structures, refer to Castro and Sampson (2001).
- For detailed specific design guidelines for a wide variety of structures, refer to NRCS (2007).

Accounting for Global Warming in River Management and Restoration

Recent and projected rates of global warming indicate the need to account for change in climate over the life of the project when planning and designing river restoration schemes. However, accounting for climate change predictions is not a simple task and few examples exist in the design of river restoration projects. The main difficulty is that climate change predictions for flow and erosion regimes are extremely uncertain, and incorporating uncertain predictions into project design is problematic. Therefore, we do not list specific design steps that should be followed to account for climate change in project design. Rather, we provide a brief overview of predicted climate change in the western United States, and offer a few guiding considerations that may lead to more robust project designs for changing climatic conditions.

Most authoritative, scientifically based predictions suggest that current trends toward global warming are likely to continue or accelerate during the remainder of this century, depending on the global rates of greenhouse gas emissions. Global warming affects the global distribution of precipitation and, though different models produce contrasting predictions, a consensus is emerging regarding likely changes in rain and snowfall. Predictions specific to the Pacific Northwest indicate a regional general trend toward continued warming of average annual temperatures and an increase in precipitation, except in summer. The dominant impact on stream systems is likely to be a reduction of regional snowpack (Mote et al. 2003), which may lead to fundamental shifts in the hydrologic regime and lower summer flow conditions. Impacts to precipitation and resulting stream flow vary with location. Reviewers should be familiar with projected trends in their areas and consider proposed projects in the context of those changes.

Global warming is also causing global sea level to rise. Based on sound science, researchers confidently predict that sea level will continue to rise for decades, but considerable uncertainty still exists concerning the rate and global distribution of the rise. This uncertainty arises from unpredictable future greenhouse emissions, model uncertainty, and the possible (unlikely but not impossible) break up of the world's remaining ice sheets in Greenland and Antarctica. Local rates of change in relative sea level (RSL), which is its elevation relative to the adjacent shoreline, are even more uncertain due to the effects of future changes in land elevation associated with subsidence and glacial rebound (isostasy). RSL rise is important to coastal rivers because it can change their base level in ways and at rates that exceed the rivers' ability to naturally adjust.

According to Goudie (2006), during the next few decades, climate change will likely impact:

- Precipitation
 - Annual average and interannual variability

- Seasonality
- Event intensity and duration
- Rain-snow partitioning
- Vegetation and land use
- Evapotranspiration
- Rainfall-runoff relationships
- Base level (RSL and changing lake levels)

These changes are important to channel form, stability, and adjustment because they affect watershed controls and stream processes. Current research reveals that upland, high-energy streams of the types found throughout the western United States are particularly sensitive to changes in the frequency of high intensity, short duration storms that are expected under climate change predictions (Lane et al. 2007, Reid et al. 2008). Thus failure to account for climate change in restoration design in the western United States will threaten sustainability and project success, because restored channels that are unable to respond to changes in watershed controls or stream processes will, through time, become further and further out of adjustment to their future flow and sediment regimes.

Planning a restoration project so that it is able to successfully adjust to the hydrological, sedimentological, and environmental impacts of climate change requires abandonment of some of the design approaches and assumptions routinely used at present. It also has the potential to lead to changes in the design alternative that is selected. This is especially the case because of the large uncertainties associated with climate change and RSL predictions, which render reference reach and deterministic approaches to restoration design inappropriate. For example, accounting for climate change means that:

- practitioners cannot safely rely solely on past records of flow and sediment regimes as the basis for restoration design;
- the future do nothing or baseline condition is no longer static;
- reference reaches may not provide suitable design templates;
- accounting for the loss of stationarity (Milly et al. 2008) in gauging records, which implies previous records of runoff, may not be a good indicator for future conditions;
- no-analog communities and ecological surprises are to be expected (Williams and Jackson 2007);
- the types and timings of future morphological responses to climate changes are not just uncertain, they are unknowable, as they depend on the occurrence and sequence of driving events that cannot be predicted; and
- restored channels must be able to adjust and evolve in response to the actual sequence of future driving events, which can never be predicted deterministically. Channels that are fixed in place or artificially stabilized will become unstable at some point, risking habitat and species, and also potentially threatening life, property, and infrastructure.

Under these circumstances, a scenario-based approach is required to identify a range of possible futures that may occur, then design a restoration project that is robust; that is, it can meet its goals regardless of which of the possible scenarios actually occurs.

Generally, accounting for climate change in planning and designing a restoration project will require that:

- hydrological and sediment projections are based on calculations or modeling rather than past records;
- baseline, do-nothing, or without-project futures account for possible changes in the project reach due to climate and environmental changes;
- the number of degrees of freedom kept open to the river is maximized, so that its response to climate change is able to mimic that of a natural fluvial system by accommodating change through mutual adjustment of multiple parameters of channel form; and
- allow for additional space for morphological adjustments in order to lower the risk of adverse impacts on habitats, species, people, and property along the watercourse.

Accounting for global warming in river management and restoration projects poses serious challenges to conventional planning and design approaches. However, following four broad, guiding principles will result in river restoration actions that either withstand or adjust to changes in flow and sediment regimes caused by climate change.

1. Remove as many artificial constraints as possible to allow the river to respond to climate change through mutual adjustments to all dimensions of channel form. This principle steers planners and designers toward approaches that free the channel to respond to climate change impacts in ways that mimic the adjustments displayed by natural, alluvial rivers. Experience shows that habitat will be most sustainable under these circumstances.
2. Provide additional space for morphological adjustment to lower risks to habitats, people, and property along the watercourse. Adjustments to the dimensions, cross-sectional form, and planform pattern driven by climate change inevitably involve changes in rates and distributions of scour, deposition, and especially lateral channel shifting that cannot be predicted in advance. If property and infrastructure are set back from the river, risks to life, property damage, and disruption to infrastructure are avoided. This means mapping historical and potential channel migration to identify a CMZ within which the river will be allowed to shift and adjust as necessary to accommodate climate change (Figure B-2). The CMZ should include the:
 - historical migration zone identified from historical maps and air photos,
 - erosion hazard zone associated with currently retreating banks, and
 - avulsion hazard zone associated with slough and abandoned channels in the floodplain.

Areas that are unlikely to be occupied by the channel as they are formed in exposed bedrock or have become disconnected migration areas due to construction of structural

defenses may be excluded from the CMZ. Refer to the Stream Corridor Management Strategies subsection of Appendix C for further discussion of CMZs.

3. Redesign remaining artificial constraints within the channel (culverts, bridges, weirs, grade controls, bank protection) allowing for future changes in flow and sediment regimes. This reminds project proponents and stakeholders that any infrastructure that remains within the channel and CMZ must convey different discharges of water and sediment and are, in the future, likely to be exposed to hydraulic and erosive forces more extreme than those experienced recently (Figure B-3). Recognizing this, it is essential that artificial constraints be modified or redesigned accordingly in order to avoid structural failure leading to risk to life or property or project failure.
4. Explicitly incorporate monitoring and postproject appraisal to support adaptive management of climate change impacts as they occur. This principle highlights the fact that the best way to ensure continued project benefits is to put in place the monitoring protocols needed to support postproject appraisal and adaptive management (see subsection 4.8, Monitoring and Management). This way, the impacts of climate change can be identified as they emerge and dealt with if they threaten people, property, or the continued success of the project.

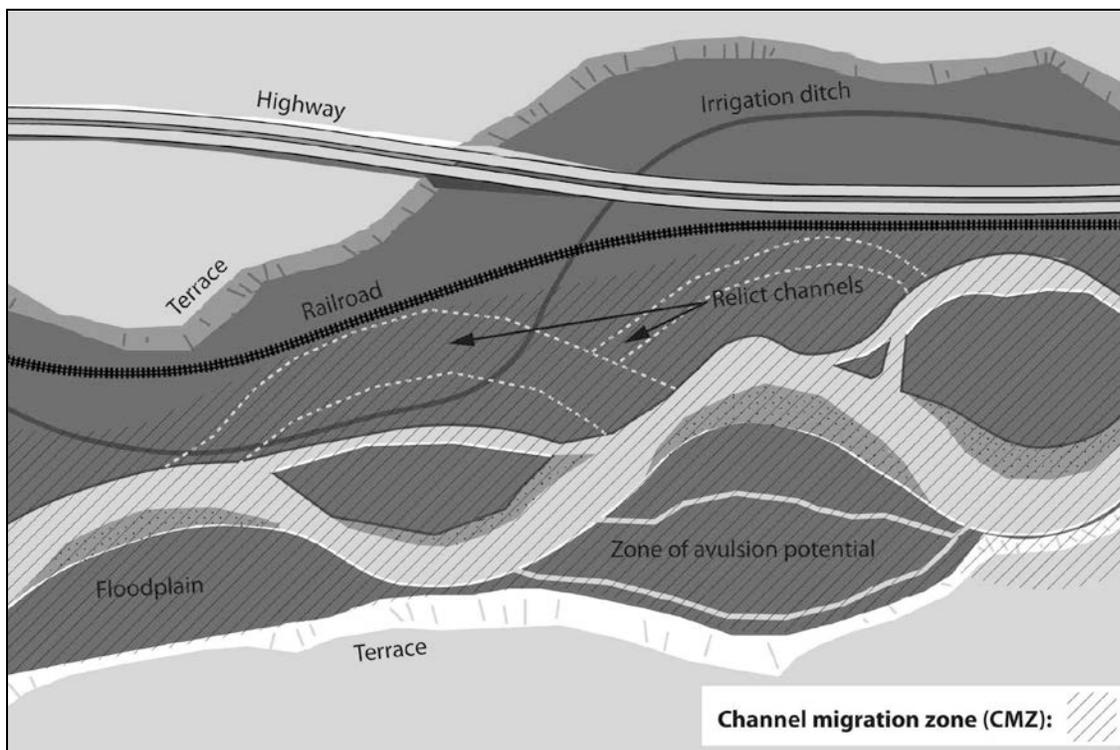


Figure B-2. Schematic delineates a zone set aside for channel migration, within which development and land use is restricted. (Drawn from color photo in DTM and AGI 2008, Custer County Conservation District, Montana.)



Figure B-3. Traditional culvert and new bridge span crossings.

Design Documentation and Review

The documentation reporting the design principles, investigations, elements, criteria, and details provides the basis for design review; design documentation provides the details that a reviewer needs to assess and evaluate the adequacy of the restoration design as a whole. The documentation should anticipate and articulate answers to most of the questions a reviewer is likely to pose during review.¹⁶ A comprehensive checklist of this information is provided as an additional resource at www.restorationreview.com. Questions to address include why a design analysis was performed, how it was performed, who performed the analysis, and when in the process it occurred. The documentation components suggested below use the example of design of typical channel cross section geometry to illustrate appropriate content. Channel cross section geometry is one component of the design. Other related components will be floodplain area, selection of bed material and substrate, design of the streambanks, vegetation design, and constructed habitat elements that may be incorporated in the channel. Many of these components may be designed iteratively, as they influence and are influenced by the details of cross-sectional design. Ideally, documentation will be developed for each of the design analyses and project elements presented previously. Comprehensive documentation will include the components listed below for each analysis and project element.

Project objective—Each element of the restoration project must be designed to support one or more of the project objectives, which in concert support the overall project goal. For example, a project objective may be to restore the channel to a condition that will achieve sediment transport continuity through the reach over a range of selected design flows while providing a desired range of instream and riparian habitats. A related objective may be to ensure no net increase in area inundated during a 100-year flood, to meet Federal Emergency Management Agency flood prone area requirements.

¹⁶ For design practitioners in the private sector, design documentation is typically a requirement of their errors and omissions insurance. Without a documented design process and foundation, insurance coverage may be void. This establishes considerable liability not only for the design practitioner, but also for the project owner, as there may effectively be no recourse for failure in the absence of viable insurance coverage.

Design criteria—These criteria are specific, measurable attributes of project elements developed to clarify the intent of each project element and demonstrate how it will help the project meet its objectives (Miller and Skidmore 2003). Design criteria articulate the specific values that design components are supposed to achieve. For example, design criteria for the channel cross section will specify the selected flows with which a cross section will be designed and the intended condition for the sediment balance in the project reach, as well as the range of typical cross-sectional shapes used at riffles, pools, and runs. Additional design criteria may include maintaining the existing limits to inundation under the 100-year flood and providing specified habitat under low flows. Each discrete project element warrants at least one design criterion.

Data source and data limitations—Data inputs to the design process are almost never ideal. As such, the design team should document data sources and quality and clearly acknowledge data limitations or gaps. Designing the cross-sectional elements will require survey, hydrologic, and sediment data inputs. Information on the survey data will include who collected it, when it was collected, a description of what survey points were collected and their spatial frequency, how data were processed, and the format and resolution of the output (e.g., cross sections only or a digital elevation model and topographic surface). Because of the importance of hydrologic and sediment data and analyses, these will typically be documented separately and in considerable detail. However, the design documentation may only briefly summarize and refer to these more detailed investigative analyses.

Assumptions applied and necessary to conduct analyses—Most design analyses and associated models require inputs for which data or derived values are unavailable and unobtainable within the resources available to the team preparing the restoration project proposal. Hence assumptions will be necessary to conduct the required analyses. For example, cross section design will typically require the input of a roughness value, yet roughness for as-built conditions can only be estimated and for future conditions it cannot be known. Consequently, roughness inputs will typically be an educated guess or an assumption. Similarly, assumptions must be made where data limitations or gaps affect analysis. For example, in alluvial systems, designers may assume that the size distributions derived from sampling of bed and bank materials are also representative of the sediment supply from upstream.

Design method applied and justification—The design process requires selection of appropriate methods, models, and tools. Selection is made using the experience and professional judgment of the design team to ensure that the methods, models, and tools applied are appropriate. Documentation will include justification for these selections and often relates to assumptions and data previously described. In this example, a design team must choose between at-a-section, 1-D, and 2-D models. Specific conditions may warrant use of an hydraulic model, as opposed to an at-a-section approach. Conversely, data limitations may suggest that application of a 2-D model will require too many assumptions or require sensitivity testing of model parameters. In some cases, a 1-D model would be appropriate for investigative and design analyses if there is too much uncertainty in 2-D model results. The documentation will offer justification for the selection of a model.

Results and outcome—Each project element will ultimately be defined through its design details. The design process may shed light, however, on uncertainties associated with the

outcome of the design process. Description of uncertainties associated with design outcomes may be the most important element of design documentation, as it serves as the basis for evaluating the risks associated with proposed designs. Design details do not illustrate these uncertainties; in fact, viewed alone they will likely paint a picture of certainty. As such, only full documentation of the analyses that lie behind the details will provide the correct perspective on uncertainty, risk management, and the confidence that the design team has in the proposed design.

Design documentation presented for each project element within the outline framework suggested above will support internal design review, demonstrating that the design team has been thoughtful in its process, and providing the basis from which to justify its approach and methods. When the proposal is submitted for permitting, it will allow the services staff (e.g., National Marine Fisheries Service, U.S. Fish and Wildlife Service) reviewing it to drill down into the intricacies of the design process to the degree required, given the type and scale of the proposed restoration and the risks that might be posed to ecosystems and managed species. Where the type of restoration is of low impact, the scale is limited, and the risks to species are small, provision of full documentation allows services staff to conduct their review rapidly and efficiently, focusing only on those elements of design that are of greatest interest or concern.

Appendix C: Management Alternatives

Sustainable Project Planning

A sustainable project is one for which goals and objectives are not only achieved, but are sustained indefinitely with minimal interventions. Sustainable projects, then, must ensure that stream processes and channel responses that sustain ecosystem requirements are in place. Project designers may confuse concepts of channel stability and sustainability. Projects often present a reconstruction or stabilization scheme with intentions to create a channel form that will be stable at the time of construction and withstand certain flows. But without consideration of how the constructed channel form may adjust and evolve over time, the stable channel conceived cannot be considered to provide a sustainable outcome.

Sustainability requires that solutions be process based. The construction of physical habitat features, or even entire channel reaches, in and of itself may not be sustainable because, while the constructed elements may exhibit a stable geomorphic form at the time of completion, they do not necessarily fulfill a sustaining geomorphic function (Soar et al. 2001). For example, rock structures or cables and ballast rock with wood are often used to ensure that constructed features will not fail under anticipated flows, yet by doing so, natural processes and channel adjustments are constrained, thereby putting limits on project sustainability. Process-based design focuses on the stream processes (flow resistance, sediment transport, bank erosion/accretion) and boundary conditions (bed and bank materials, valley slope, riparian vegetation) that create and maintain desired features. Generally, installation of any permanent, rigid features (e.g., rock toe in bank treatments, bendway weirs, rootwad reinforced meander bends, and submerged large wood¹⁷) may be inconsistent with a sustainability objective.

This is not to say that installation of these features is inappropriate. They may indeed be necessary to provide immediate protection to severely impacted systems or to stabilize actively degrading channels, but many projects that lengthen the channel and reduce slope (decrease stream power locally) also unnecessarily incorporate new vertical grade stabilization. Further, constructed features may be necessary to jump-start the recovery of natural processes. While log jams cabled to a bank for permanence may not perform a geomorphic function at the reach scale, they may provide local bank protection, much-needed cover, and facilitate maintenance of pool habitat through scour. But ultimately their value is localized and temporary. Streams are dynamic and will eventually abandon or undermine the structure, and if processes are not in place to create a new log jam, that is, an active and dynamic channel with ample sources for large wood recruitment, then the feature is not sustainable (Naiman et al. 2002).

¹⁷ The decay rate of large wood and rootwads in stream systems is a function primarily of species and inundation (Naiman et al. 2002). Wood buried in alluvium may persist for centuries to millennia (Nanson et al. 1995, Abbe and Montgomery 1996); wood consistently submerged may persist for many decades to centuries; wood that is intermittently submerged, however, may decay more rapidly (Bilby et al. 1999).

While sustainability can be presumed to be an objective of most restoration projects, the reality is that many rivers may require decades of adaptive management interventions and maintenance to achieve sustainability. A good example is a stream channel that was historically damaged by splash dam practices and whose riparian corridor has also been logged. Restoration of form and process in the most expedient fashion in this system would require importing large wood, building log jams, and restoring the riparian forest system. Some of these log jams may (and should in a dynamic sustainable system) be abandoned or washed downstream due to the operation of natural stream processes and dynamics of channel adjustment. However, until the riparian forest has reestablished, sufficient large wood may not be present to replenish the system. In such cases, repeated large wood imports or installations may be necessary to continue achieving the objectives for a specific frequency of log jams in the channel. Thus project goals and objectives, including sustainability objectives, need a time frame qualification. The most expedient route to maintaining benefits of log jams during the period of riparian recovery may require regular interventions. Alternatively, achieving sustainability may require many decades as the riparian forest matures. In this case, monitoring may serve the primary purpose of ensuring that channel stability is not compromised during the recovery phase.

Ideally, a project designed and implemented to be sustainable will not need further management actions. However, regardless of how projects are developed and how much consideration is given to creating or fostering a dynamic, deformable¹⁸ channel system, the future cannot be known. Consequently, accommodating this and other elements of uncertainty in project development is critical to achieving sustainability.

Mosquito Lake Road provides an alternatives analysis case study. It is a two-lane county road in the north fork of the Nooksack River drainage that travels through primarily U.S. Forest Service lands in northwestern Washington. The north fork is relatively pristine and characterized by log jams, riffle-pool morphology, occasional forested islands, and a morphologically active channel that changes course through a mosaic of floodplain forests. The river was actively eroding the valley margin, creating a near-vertical retreating bank greater than 10 m in height, and at some points coming within meters of a road right-of-way.

A bank stabilization project to protect the road was proposed. However, because of the height of the bank and the high ecological value of the river (which supports listed Chinook salmon [*Oncorhynchus tshawytscha*]), a feasibility study was commissioned to:

- develop conceptual bank stabilization measures and estimate costs,
- evaluate the feasibility of constructing the stabilization measures during narrow construction windows and using predominantly large wood structures, and
- evaluate the probable impact to salmonids and identify mitigation measures.

Preliminary findings indicated exceptional geotechnical engineering challenges, problematic yet unavoidable construction practices in regard to salmon, and significant costs. However, a review of construction logistics showed that a U.S. Forest Service dirt road would provide a detour during construction or in the event of road failure. The feasibility study soon

¹⁸ Deformable channels and streambanks are those designed with boundary conditions that allow for channel adjustment and evolution through boundary deformation.

became an analysis of two alternatives: a well developed but problematic and expensive bank stabilization scheme or a road relocation scheme (which presented its own social and institutional challenges). A cost comparison of alternatives indicated similar costs for the alternatives, though easement concerns presented significant hurdles for a road relocation alternative. Ultimately, the road was relocated away from the river, with the project completed shortly before the old road fell into the river. The river was allowed to evolve naturally, and the road is now safe from future erosion risk.

Stream Corridor Management Strategies

For any identified problem, there is generally a suite of alternative solutions that range from no action to passive and active solutions, from instream to upland treatments, from protection of existing resources to mitigation of damaged resources, and from species-specific to ecologically general approaches. Passive approaches may include simply resting stressed resources, removing constraints and stressors such as dams, fencing riparian corridors, or removing artificial structures such as passage barriers. Active approaches may range from reconstruction of channelized streams to stabilization of degrading stream channels (see The Stream Restoration Spectrum—Restoration to Stabilization subsection below). On the spectrum between passive and active approaches are strategies for “prompted recovery” that jump-start self-adjustment (Brookes and Sear 1996, Newson et al. 2002) without intrusive or expensive channel reconstruction. While these approaches will not create a finished stream as quickly as more active approaches, allowing the stream to recover through natural processes may foster greater resilience and sustainability.

Regardless of whether an active or passive approach is applied, a range of commonly practiced stream corridor management strategies may be viable alternatives to active channel restoration or stabilization or may be used as supplementary strategies in concert with more active schemes. One of the guiding principles presented earlier states: invest wisely and protect the investment. Stream corridor management strategies described below can serve to enhance or protect investments in management actions.

Channel Migration Zone

The active river area encompasses the land adjacent to the stream channel with which the channel interacts both occasionally and frequently. In headwater streams that are not alluvial in character, the active river area includes those areas that contribute sediment directly to the channel. As a channel transitions downstream into an alluvial system, it encompasses the active floodplain, which represents the historic range of channel migration as well as the historic limit of the associated riparian community.

In a naturally meandering stream, bends grow through lateral extension and point bar accretion, migrating downstream at the same time. The floodplain is constructed and reworked over time through a combination of channel migration, bar and overbank deposition, and vertical adjustment. A dynamic fluvial system therefore requires a channel migration zone (CMZ) within which to create, maintain, and sustain adequate levels of habitat (Rapp and Abbe 2003, Brummer et al. 2006). In alluvial floodplain river systems, the CMZ and active river area are equivalent concepts. However, in steeper and straighter nonalluvial systems where boundary characteristics

constrain lateral channel movement, the active river area may be better characterized by the valley bottom width and evidence of channel migration may be lacking.

Delineating the active river area presents an effective means of examining habitat potential and providing adequate space for these processes. Protecting the active river area from development or stabilization is a crucial element of stream corridor management. Protecting riparian space prevents future conflict and need for ongoing expensive river management schemes. In relatively undisturbed systems, establishment and protection of an active river area may be the most important and enduring benefit to the stream ecosystem. In developed valleys, a CMZ may be established within the valley bottom and range of historic meandering, within which actions may be necessary to restore a dynamic channel, floodplain, and riparian complex (e.g., riprap removal, levee setbacks, riparian revegetation). Rapp and Abbe (2003) provide a comprehensive framework for delineating CMZs that offers a basis for determining how much room a stream channel needs to maintain dynamic processes.

A maximum CMZ delineation would include the historical limit of channel migration, where a given meander belt width has migrated across a broader valley. A minimum CMZ width delineation would include only the maximum stream meander belt width. While this may be sufficient to allow for dynamic stream processes in the current context, it may not be sufficient to manage responses to future climate or land use changes or other disturbances. Furthermore, the minimum CMZ is unlikely to sufficiently accommodate the full range of overbank flood processes. As such, levee systems in a minimum CMZ scenario may need to be set back to allow increased space for flooding.

Stream Buffers

The creation or restoration of riparian corridors or buffer zones is another project option that has relevance to alluvial and nonalluvial systems. In a comprehensive literature review of more than 130 riparian corridor width studies, Knutson and Naef (1997) cited a wide range of buffer widths that provide a variety of ecosystem services and value, including shading and associated water temperature control, recruitment of small and large wood, filtration of upland sediments and pollutants, erosion control, microclimate influences, wildlife and fish habitat, organic litter supply, and nutrient supply.

Despite the strong correlation among CMZs, floodplain width, and extent of functional riparian area, recommendations for riparian areas typically consider only the perpendicular distance of influence of key riparian functions. As such, use of a CMZ delineation as a management tool is preferable to riparian buffers, as buffers will typically underestimate the CMZ and be inadequate to allow all processes associated with channel migration to operate naturally. While a riparian buffer zone will provide for shading, filtering, organic inputs, and large wood recruitment, it may not be sufficient to accommodate nutrient and energy fluxes through the floodplain and within the floodplain hyporheic zone. Further, where active channel shifting involves avulsions or rapid rates of migration, a riparian buffer may be quickly abandoned by the active channel unless it extends across the active river area. In the absence of CMZs, however, riparian buffers are a strong and viable management tool to protect most short-term functions associated with channel-floodplain-riparian dynamics.

Conservation Easements

The protection or creation of CMZs and sufficient riparian corridor widths offer targets for conservation and restoration, but the regulatory or legal framework necessary to implement them typically exists only as local level land use ordinances. Currently, the best option for protecting the CMZ and riparian corridor may be acquisition or conservation easements (Lucchetti et al. 2005). Conservation easements provide a vehicle for private landowners to maintain ownership, with voluntary agreement that cedes the development rights associated with a property to another entity or organization, generally a land trust or state agency (e.g., Land Trust Alliance, The Nature Conservancy, Northern California Regional Land Trust, or other local land trusts). Conservation easements can also be issued under the Conservation Reserve Program (CRP, <http://www.nrcs.usda.gov/programs/crp/>), a federal program aimed at conservation of wetlands that pays landowners to participate. CRP easements, however, are typically only for 10-year to 15-year terms. Easements can be written specifically to allow or restrict any type of development, land use, or management action within the easement, making it a valuable tool with which to permanently protect CMZs and riparian areas of the floodplain. This is significant as many restoration projects sited on private property are currently implemented with no guarantees that future management of the riparian zone or streambank will be consistent with the project's long-term habitat management objectives.

Canyon Creek—Alternatives Analysis Case Study

Canyon Creek for most of its length is a steep and confined mountain stream in the northern Cascades of Washington, tributary to the north fork of the Nooksack River. The confluence of Canyon Creek and the north fork is characterized by alluvial fan morphology, where the steep stream exits a canyon and enters the north fork river valley. Property on the alluvial fan is privately owned and subdivided. In the 1990s it was being subdivided and developed up to the active channel margins. While flooding of properties was not considered a great threat, the chance of significant channel shift, as is characteristic of geomorphic processes on alluvial fans, would result in loss of property and structures, as well as threats to human safety. Previous management of the stream channel to protect property during the 1980s included relocation following erosion events and installation of a buried rock wall to prevent further channel shifts. These installed structures failed in subsequent high flow events. In response, a rock-reinforced dike was installed to train the river from the mouth of the canyon downstream to below the at-risk properties. While this dike protected the properties in subsequent high flow events, it sustained damage and was in need of repair. In 1999 Whatcom County Public Works commissioned a conceptual alternatives analysis for addressing protection of property from flooding and erosion (Inter-Fluve 1999, Jakob and Weatherly 2008).

Four alternatives were evaluated to compare costs of initial actions and predicted project maintenance costs and probable outcomes:

1. No action. A no action alternative was included as a comparative tool to evaluate costs, benefits, and risks of other alternatives relative to minimal or no further protection.
2. Purchase property. The property purchase alternative was included to evaluate the cost of “buying the problem,” in effect converting the property to public ownership and allowing

the stream channel to evolve naturally with no or greatly reduced liabilities, and no long-term cost of maintenance.

3. Install channel dike. Installing a channel dike to contain high flows and associated sediment, the traditional approach at this site, was considered with the understanding that engineered approaches had not yet been effective and so would require far greater stabilization measures than previously, and likely perpetual maintenance expenses.
4. Install sediment basin. As an alternative to containment and in an effort to include all possible solutions, trapping of sediment at the canyon mouth was evaluated as an alternative to minimize channel erosion and avulsion related to excess sediment (the inherent sediment regime in alluvial fans). Sediment basins require regular and perpetual management to remove trapped sediments.

Table C-1 presents a summary and comparison of alternatives, and demonstrates that the property purchase option is economically viable. This option provides the greatest certainty in protection of property and threats by reducing potential for further development of the alluvial fan, and allows for natural, dynamic, and arguably uncontrollable dynamic channel processes. Purchasing properties was selected as the preferred alternative. Whatcom County along with a local land trust have since secured ownership or easements for virtually all of the properties along the channel and removed preexisting levees, thereby allowing the channel to be left largely unprotected and free to adjust and evolve naturally (Cooper 2008).

Flow Management

The natural flow regime (Poff et al. 1997) has been described as a master variable in determining abundance, distribution, and life history evolution of aquatic and riparian species and is a fundamental component of healthy and naturally functioning freshwater ecosystems (Resh et al. 1988, Power et al. 1995, Doyle et al. 2005). Subsection 3.3.2, Flow Regime, details the natural flow regime and the consequences of artificial alterations. Water needs in developed watersheds inevitably require that stream flow is managed through diversions and impoundments. Species extirpations, declining fisheries, groundwater depletion, impaired water quality, habitat loss, and increased flood risk can result from water extraction, diversion, and alterations to the daily, monthly, seasonal, and interannual distributions of flow. The integrity of freshwater ecological systems depends largely on their naturally dynamic behavior, which is adapted to and maintained by the natural flow regime.

Water rights and instream flow rules vary significantly between states and it is beyond the scope of this document to summarize them here. However, a number of strategies are increasingly employed to move adversely impacted stream systems back toward a natural flow regime by improving seasonal and interannual variation of high and low flows. These strategies include:

- Instream water rights. In most western states there are provisions within the beneficial use doctrine for instream water use, allowing water rights holders to keep water instream for ecological use rather than requiring diversion to traditional out-of-stream beneficial uses, namely irrigation and stock watering. Instream water rights may be purchased, leased, or acquired through easements.

Table C-1. Canyon Creek, Washington, alternatives analysis matrix. Four alternatives were evaluated to alleviate flooding of a subdivision on an alluvial fan: 1) no action, 2) property purchase, 3) channel dike, and 4) sediment basin. Evaluation of each alternative included a summary of project components, level of risk flood damage, maintenance requirements, project cost and maintenance cost, and summary of benefits and considerations. Risk to resource was not included in the evaluation.

	No action	Property purchase	Channel dike	Sediment basin
Project components	Repair and maintain existing structure as needed	Acquisition of streamside properties and resort for short-term protection Acquisition of all properties within alluvial fan for long-term protection	Improve upstream tie-in to existing dike Extend downstream beyond resort and raise dike crest Improve rock-toe armoring Install groins in rock toe Repair and maintain dike as needed	Excavate and construct sediment basin at mouth of canyon Install fish passage structures at all grade controls Install grade control structures Repair and maintain existing dike Extend dike downstream beyond resort and raise dike crest Repair and maintain dike, basin, and passage structures as needed Dredge basin regularly, as dictated by deposition
Remaining level of risk	Short term: same as current level of risk Long-term: increased risk with time due to aggradation and further development	No risk to purchased properties Long-term: risk to highway	Short-term: reduced risk Long-term: Increased risk with time due to aggradation and further development	Short-term: reduced risk Long-term: reduced risk, although increase in number of properties at risk
Maintenance requirements	Repair and maintain existing dike	None for county	Repair and maintain existing dike and extended dike in perpetuity	Dredging of basin and maintenance of existing and extended dike in perpetuity
Project cost estimate	Implementation cost: \$50,000	Riverside properties: \$1.2 million All properties: \$2 million	Implementation cost: \$600,000	Implementation cost: \$1 million to \$2 million

Table C-1 continued. Canyon Creek, Washington, alternatives analysis matrix. Four alternatives were evaluated to alleviate flooding of a subdivision on an alluvial fan: 1) no action, 2) property purchase, 3) channel dike, and 4) sediment basin. Evaluation of each alternative included a summary of project components, level of risk flood damage, maintenance requirements, project cost and maintenance cost, and summary of benefits and considerations. Risk to resource was not included in the evaluation.

	No action	Property purchase	Channel dike	Sediment basin
Maintenance cost	\$1,000s to \$10,000s (unpredictable)	None to county; potential high costs to Department of Transportation for highway	Similar to the no action alternative (unpredictable)	Highest of all alternatives (unpredictable)
Benefits and considerations	Short-term reduction of damages Highway protection may be required Encourages further development Maintenance in perpetuity May not be permitable	Short- and long-term elimination of damages Highway protection may be required Reduces/eliminates further development Owner willingness to sell No permits required	Short-term reduction of damages Highway protection may be required Encourages further development Maintenance in perpetuity Habitat impacts likely	Short- and long-term reduction of damages Highway protected Encourages further development Maintenance in perpetuity Habitat degradation likely

- Dam release management. Significant advances have been made in using water releases from dams (Postel and Richter 2003) to provide ecological benefits without significantly compromising flow management economics. For many Federal Energy Regulatory Commission regulated dams, relicensing offers opportunities to regulate dam operations to provide for greater variability in flows. A common strategy is the release of spring pulses—high flows released from impoundments to mimic the frequency, duration, and magnitude of channel-forming flows. Additionally, there is often opportunity to greatly improve critical low flows using dam releases and to moderate the rapid rates of change in flow often associated with negative ecological effects.
- Irrigation efficiencies. Improved efficiency can be achieved at the point of diversion through upgrades, metering, and consolidation, along the delivery system by lining ditches or converting to a pipe, and at the point of use by upgrading irrigation systems. Ideally, increased efficiency will allow more water to remain instream, although this assumes that the water is not overallocated. While irrigation efficiencies show great promise, water rights law and status quo management pose significant management and legal challenges to widespread adoption.

The Stream Restoration Spectrum—Restoration to Stabilization

The preceding subsections describe strategies that can be employed as alternatives to or complementary conservation strategies for proposed channel restoration projects. This subsection draws distinctions between the more common types of active channel projects in terms of their relative positions along the restoration spectrum.

Restoration is a commonly stated component of many or perhaps most stream project proposals, or is implied as many stream management projects are funded under state or federal restoration programs. To restore in the purest sense is to return to a previous condition. For many disturbed systems, restoration in this sense would require a significant period of implementation and recovery, far more than most projects commit to. Yet most projects proposed as restoration are not actually intended to restore to historic conditions. Given altered watershed controls and climate change, restoring to a historic condition is probably not advisable in most situations, as those conditions may no longer represent equilibrium conditions in the context of altered sediment or hydrologic regimes.

River restoration is currently applied as a catchall phrase describing a wide spectrum of actions affecting streams including relocation, reconfiguration, rehabilitation, stabilization, habitat enhancement, habitat creation, and even flow management (Wohl 2004). Restoration in this context is generally interpreted to mean restoring the physical features, channel forms, or stream processes in a degraded river, and may not involve attempts to return the system to a previous state (Cairns 1990). Hence restoration projects cannot be assumed to be inherently beneficial to ecological processes.

The restoration spectrum (Figure C-1) illustrates a range of actions commonly taken to improve stream or ecosystem conditions. The actions in the spectrum should be considered in relation to the extent to which they allow for or constrain the interaction between stream processes and channel boundary conditions that drive dynamic channel adjustments, foster or

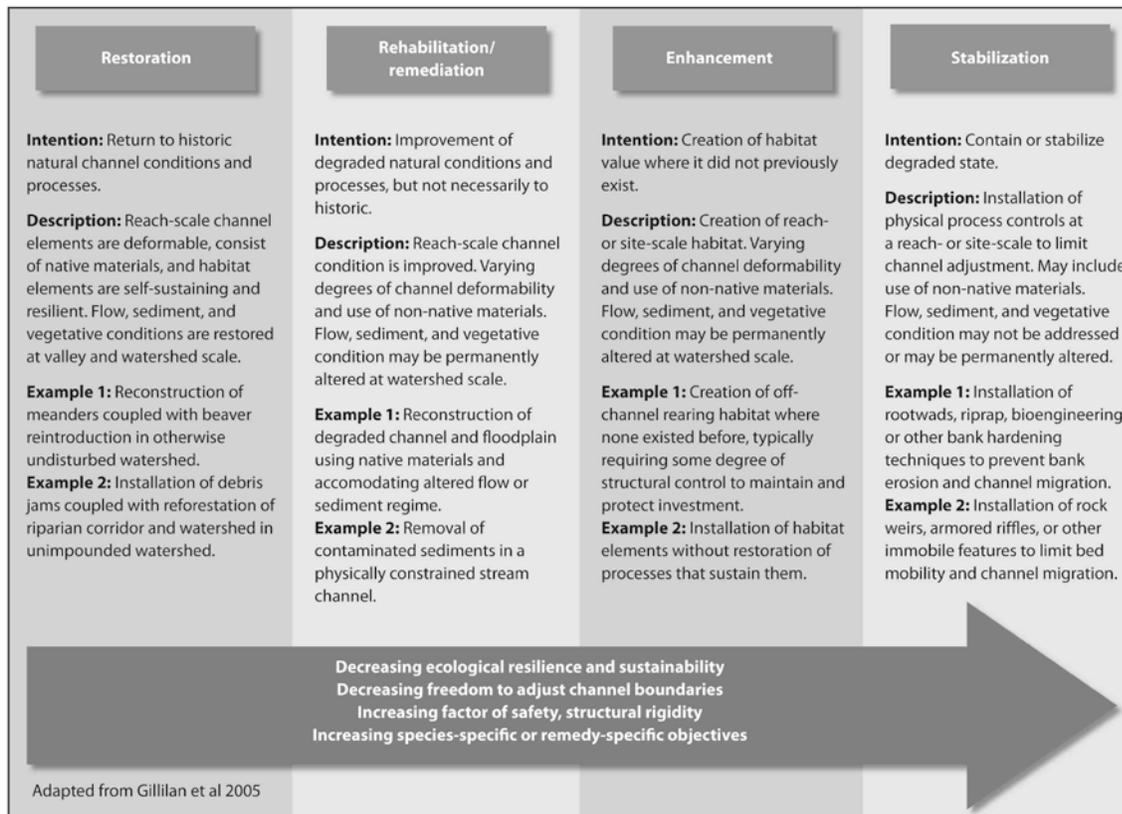


Figure C-1. The channel restoration-stabilization spectrum. Projects commonly referred to as restoration projects in fact span a spectrum of project goals and effective outcomes from restoration of natural process to stabilization and constraint of natural process. In between these endpoints are rehabilitation and enhancements, both of which may be limited in the extent to which they restore process. (Adapted courtesy of S. Gillilan, Gillilan Associates Inc.)

constrain ecological resilience and sustainability, and benefit multiple native species. Also, each action in this spectrum should be considered in relation to the goals and objectives of the proposed project and according to its categorization. The simple act of appropriately categorizing an action is a big step toward understanding its ultimate affect on the stream ecosystem and the risks associated with these impacts (see the Uncertainty and Risk subsection below).

Stabilization refers to actions taken to limit channel adjustments, either vertically or laterally. Many proposed nonrestoration projects, and some projects under a restoration banner, explicitly state their intention to stabilize the channel in their goals and objectives, with the aim of limiting future active channel adjustments or evolutionary trends. Restoration or enhancement projects may also include stabilization measures, though they may not be explicitly described as such. Constructed riffles, weirs designed to promote pool development, and reconstructed banks incorporating rootwads, large wood, or rock revetments are features common in channel restoration project proposals that are intended to provide some measure of constraint on the channel.

Stabilization measures often reflect efforts to account for uncertainties and reduce the risk of failure of specific project elements. These can, however, jeopardize other project goals and objectives that relate to sustainability, because they constrain important stream processes and limit opportunities for channel deformation responding to variations in hydrology or sediment load or riparian vegetation growth. As such, investigating the necessity and extent of stabilization measures becomes central to evaluating proposals.

Adjustments occur in even stable alluvial channels and are essential to maintaining long-term dynamic stability, as well as the associated aquatic and riparian habitats. Therefore, stabilizing what were naturally adjustable elements of the channel (bed elevation and channel banks) involves considerable ecological risk. However, significant risk to property and infrastructure may be involved if vulnerable sites are not stabilized. Where stream dynamics have been anthropogenically affected, interim stabilization measures may be warranted while a more comprehensive approach to addressing impacts is developed. Similarly, temporary bank stabilization measures may be necessary to allow time for riparian plantings and volunteer plants to become established and provide natural, vegetative bank protection. However, experience has shown that most “temporary” stabilization measures are not later removed.

Two general conditions¹⁹ often warrant some degree of stabilization to prevent vertical or lateral stream adjustments:

- protection of public infrastructure (e.g., highways, railroads, and associated bridges) where opportunities for relocation out of a CMZ or away from the channel are impossible, and
- prevention or reduction of active or anticipated channel or bank instability that can be attributed to anthropogenic impacts.

In the first general condition, a strong case can often be made for relocation of infrastructure rather than stabilizing a stream, especially as ongoing repair and maintenance will be necessary. A cost-benefit analysis may be the most practical approach to evaluating alternatives in this case. The costs of stabilization alternatives should consider whole life costs including maintenance and repair costs and should also take into account the long-term probabilities that stabilization at one location may trigger new patterns of channel migration and so generate additional locations where the channel is likely to threaten infrastructure. Additionally, the relative risk and associated costs of failure of stabilization components installed to protect infrastructure need to be factored in, particularly where loss of infrastructure will result in significant environmental degradation, risk to life, or substantial economic cost as in the case of failures of bridges, gas lines, or power lines. However, cost-benefit analyses should be limited to comparing costs of alternatives. Because acceptable means to derive the value of ecological resources have not been established, the value of land at risk in a cost-benefit analysis cannot be considered.

¹⁹ Stabilization is often justified by or fundamentally directed toward protection of property. This listing limits property to infrastructure that serves a public value, thus distinguishing it from property that benefits individuals or private entities. Similarly, stabilization is often promoted to reduce sediment impacts. This listing distinguishes sediment inputs that are part of a natural dynamic system from those generated as a result of anthropogenic impacts that exacerbate sediment input.

In the second scenario, grade control or bank stabilization may be employed to control bed degradation or excessive bank erosion resulting from anthropogenic impacts. Grade control in reaches with actively migrating headcuts can be an effective interim measure to halt the continued degradation and destabilization of the channel upstream until the underlying causes of channel instability can be addressed. The common occurrence, however, is that the application of this interim measure becomes a permanent solution. Grade control structures in incising streams where ultimate causes are not addressed can trigger other stream responses, such as channel widening, lateral migration, and further degradation downstream due to sediment starvation. Additionally, channel-spanning structures can become fish passage barriers or be abandoned as the stream flows around them. Reach-scale and watershed-scale assessments can help determine whether headcuts and incision are responses to natural causes of channel evolution or caused by anthropogenic disturbances. Attempting to halt the natural evolution of the channel will fix the channel in a state of lower ecological value and usually be a futile exercise. However, grade control structures have been used with some success to stabilize channels destabilized by channelization in lower gradient river systems.

Uncertainty and Risk

Uncertainties and risks are inherent to any project involving an intervention in the river system or a change in its management. It is important to acknowledge, understand, and address uncertainty and risk—not only at each stage of project development, but also in the project review process. In the past the only easily usable, predictive models available for rivers were deterministic and the methods and techniques for handling uncertainty and risk were difficult for nonspecialists to access and apply. These constraints no longer exist because guidance and tools are readily obtainable for probabilistic modeling, estimating uncertainty, and evaluating risk (e.g., Pappenberger and Beven 2006). Consequently, all project proposals should deal with the challenges of accounting for uncertainty and managing risk. In the United Kingdom, the Flood Risk Management Research Consortium has provided a Web site (<http://www.floodrisknet.org.uk/methods/>) with in-depth discussion, definitions, and analytical tools for assessing risk and incorporating risk assessment in project planning and design.

Uncertainty

Uncertainty may be defined in a number of ways, the most general being a lack of sureness about something. However, such a definition is of little practical use when attempting to analyze uncertainty as part of a project proposal. In this context, the overall uncertainty must be quantified in association with each of the predicted outcomes of the project, which results from uncertainty in the input parameters plus uncertainties implicit to the:

- science underpinning the analyses used in designing the project,
- models used to represent the river, its habitat, and its ecosystem, and
- different possible future behaviors of the river under existing and with-project assumptions.

Classically, uncertainty is divided into natural variability, which refers to the randomness observed in nature, and knowledge uncertainty, which refers to our limited understanding of a

physical system and our ability to measure and model it (Hall 2003). Thus while knowledge uncertainty can be reduced, natural variability is inherent to natural systems and is, therefore, irreducible. Moreover, natural variability is a property of the river, whereas knowledge uncertainty is a property of the people performing the analysis.

Beechie et al. 2003 provide a comprehensive discussion of uncertainty in the context of predicting habitat capacity for ecosystem recovery planning and further break down uncertainty as being associated with a range of five known uncertainties, each of which may have either a known or unknown probability distribution:

- natural variation,
- measurement error,
- inaccurate parameterization,
- incomplete representation of nature in modeling, and
- limits on the predictive capacity of models and tools.

The first of these represents uncertainty due to natural variability, while the others are variations on knowledge uncertainty. While these distinctions are interesting as a theoretical concept, in most cases it is impossible to distinguish clearly between these sources of uncertainty. For instance, when knowledge is gained from imperfect observations, measurement error and knowledge uncertainty are blurred and will change over time as more reliable methods of observation become available. As an example, an imperfect understanding of the watershed controls that determine flow, sediment, and vegetation regimes and which vary widely in time and space might initially be classed as natural variation. However, when the imperfect representation of those controls is translated into a mathematical model, this appears to shift some of the uncertainty into modeling uncertainty.

Given the complexity of natural systems and the models that represent them, the relationship between uncertainty in model input and output may be highly nonlinear. Uncertainty may also be magnified by the assumptions embedded in an analysis or assessment, such as the application of generalized channel evolution models to particular problem reaches with unique and imperfectly known boundary conditions and constraints. However, uncertainty in the outcome may be reduced as experience is gained and deeper insights into the operation of physical and biological processes are developed for the particular river being investigated. In the case of highly complex models, it is impossible to track uncertainty between input and output variables, which makes the model unable to be parameterized. Under these circumstances, simpler, reduced complexity models must be used if uncertainty is to be addressed explicitly.

The uncertainty discussed above has known consequences, and is thus characterized as the things “we know we do not know.” However, a deeper level of uncertainty also exists, where the source of the uncertainty is unrecognized. This is ignorance and has been described as the things that “we do not know we do not know.” Every effort should be made to reduce ignorance concerning the outcomes of a project; however, like natural variability, ignorance is to a degree unavoidable, given that our understanding of nature will never be complete.

Based on the preceding discussion, consideration of the theoretical breakdown of uncertainty may seem of limited value, but it in fact provides the basis for identifying the five key steps in any uncertainty analysis:

1. Define the sources of uncertainty in the input data, analyses, and models. The various sources of natural variability and knowledge uncertainty must be identified, and where possible quantified using an appropriate methodological approach.
2. Estimate the uncertainties in the outputs of the analyses and models. The effects of all the various uncertainties must be propagated through the analysis and modeling processes to assess uncertainty in the outcomes.
3. Condition the uncertainty estimates as further analytical and modeled outcomes become available. Uncertainty estimation requires a definition of the performance of the analysis or model (e.g., how well does the analysis or model predict an outcome or variable compared to the observed outcome of the measured value of a variable, which is itself subject to natural variability). Improved understanding of the performance of analyses or models gained during the project should lead to reduced uncertainty, through refinement or rejection of unreliable analytical procedures or models.
4. Establish the potential consequences of the uncertainties. Qualitatively or quantitatively explore the significance of the uncertainties in terms of the range of possible outcomes or of unforeseen outcomes (especially adverse ones); that could be associated with the project due to natural variability and uncertainties in data, analyses, or models.
5. Communicate the uncertainties to stakeholders. The uncertainties in inputs and outcomes must be accurately relayed to project stakeholders so that all interested parties can discuss whether the risks associated with those uncertainties are tolerable (see next subsection for a discussion of risk). Where uncertainty generates unacceptable risks, these risks must be reduced by reducing either the probability of undesirable outcomes or their consequences for people, species, or property.

When developing a design for a stream management action, a further source of uncertainty exists, called indeterminacy. This occurs because a project is intended to produce outcomes not only on completion, but throughout its design life and typically beyond. Indeterminacy is significant because the future is not only uncertain, it is unknowable. This is the case regardless of how much the science underpinning the project is improved or how well the analytical and modeling procedures are performed, because the future performance of a restoration project will be affected by events (droughts, normal flows, floods, watershed fires, landslides, changes in land use or river management policy, further engineering interventions, etc.) that have not yet occurred. For example, the magnitude, duration, timing, and sequencing of floods will affect the future evolution of the channel, riparian corridor, and floodplain, but these aspects of future flows cannot be predicted deterministically. This problem can be partially resolved through the use of stochastic approaches that generate multiple possible future time series of flows, resulting in a scheme whose outcomes are acceptable regardless of exceptionally low or high flow events. This type of scheme is thus resilient to disturbance and, therefore, much more certain in its outcomes. However, while stochastic approaches improve confidence in predictions concerning the impacts and outcomes of the project, the uncertainty concerning the future performance of a project cannot be avoided.

Also, stochastic approaches cannot account for the type of nonstationarity in catchment hydrology associated with, for example, climate change, and no parallel method to the stochastic treatment of flow series exists to account for future changes in stakeholder behavior, such as changes in catchment land use, the environmental values held by society, or socioeconomic development that may have significant impacts on future project performance.

When dealing with uncertainty, assessment using appropriate tools and methods is necessary. Uncertainty should be reduced to an acceptable level while recognizing that it cannot be eliminated entirely. To address an indeterminate future, scenario modeling to develop visions of potential futures can be helpful (Limbrick et al. 2000). If scenarios are selected to cover the range of likely futures and the project performs in a satisfactory manner in them all, then its outcomes are not only resilient but also robust. Hence the project proponents may have greater confidence in the viability of the scheme as the design is to an extent future proof. Scenario modeling can be accomplished for many elements of project design, but may be most readily conducted within the realm of hydraulic models that can evaluate forces under any defined range of flow conditions (refer to the Hydraulic Analyses subsection of Appendix A).

Initially, the basis for planning project actions is provided by problem identification and the setting of goals and objectives, coupled with conceptual models of the future physical and biological states expected under existing conditions and with-project conditions. In the early stages of project development, the proponents of the project will understandably be uncertain to some extent concerning the nature of the problem, details of the future impacts of the problem if no further actions are taken, and the potential outcomes of various project options for dealing with the problem.

Uncertainties often stem from:

- incomplete knowledge of the operation of the fluvial system in the project reach;
- incorrect identification or inexact characterization of the causes and symptoms of the problems;
- shortcomings in the conceptual models describing the geomorphic, engineering, and biological forms and functions of the project reach;
- biased or inconsistent ideas and opinions held by technical specialists concerning the efficacy of alternative project approaches and designs; and
- conflicting agendas amongst the stakeholders with respect to the aims and objectives of the planned project.

In the early stages of project planning, uncertainties should be identified, considered, and described qualitatively to provide the basis for subsequent quantitative analysis, moderation, and management during the project design and implementation stages. When considering alternatives, selecting the preferred scheme, and designing the project, uncertainty is unavoidable; it should be accounted for and, ideally, embraced (Wheaton et al. 2008). During these phases, 1) tracking the uncertainties identified during the planning stage should continue and 2) uncertainties associated with the analytical and modeling work being performed to

support selection of the preferred alternative and detailed design of the project should be identified. In this respect, knowledge uncertainty and natural variability are important.

Uncertainty estimation requires some understanding of how well the analysis or model predicts an output parameter compared to the observed value, which is itself subject to natural variability. As analytical activities and model runs progress, the improved understanding of the performance of analyses or models so gained should lead to reduced uncertainty, through refinement or rejection of unreliable analytical procedures or models. There are numerous methods of uncertainty analysis, such as Kalman Filtering, nonlinear propagation step method, nonlinear regression, Bayesian dynamic methods, Generalized Likelihood Uncertainty Estimation Method (Beven and Binley 1992), or Monte Carlo simulations. Selection of an approach that is appropriate to the case in point is crucial to success and should be undertaken with advice from a person with training and experience in uncertainty and risk analysis.

Once the uncertainties have been conditioned and analyzed, it is necessary to explore, either qualitatively or quantitatively, the significance of the uncertainties in terms of the probability and consequences of uncertainties leading to failure of the project or an unacceptable outcome, such as a take of a listed species. At this point, the results should be communicated to the stakeholders so a decision can be made whether the risks associated with those uncertainties are acceptable, tolerable, or unacceptable. Where uncertainty generates unacceptable risks, it will be necessary to:

1. allocate additional resources to reduce the uncertainty (and so reduce the probability of project failure or an unacceptable outcome occurring) by collecting more data or improving the modeling,
2. conduct a pilot study and reduce uncertainties through learning by doing, or
3. modify the design of the project so that the consequences of failure or an undesirable outcome are acceptable or at least tolerable.

The first course of action is more obvious, but additional data collection and modeling may be prohibited by cost or practical considerations. However, the development of more accessible models has recently improved assessment of dam removal projects (Cui et al. 2006) by facilitating the examination of the spectrum of probable sediment loads and natural variability in hydrology (i.e., dam removal during drought or flood, or quick and complete removal, versus step wise and progressive removal). This approach decouples uncertainty and risk by examining a wide spectrum of uncertain hydrologic or sediment scenarios to assess the risks associated with each, thus creating a risk envelope for alternative selection and decision making. The second course of action is becoming more popular but relies on stakeholder acceptance and cooperation. The third course of action has many advantages (Wheaton et al. 2008) and in Europe designing for failure is gaining credence as a way of delivering river projects that are resilient and robust—that is, ensured of continued project benefits.

Practical examples of the types of project modification that might be invoked during the alternatives selection and design phases to deal with high and irreducible levels of uncertainty and risk include:

- removing as many artificial constraints as possible to allow the stream channel to absorb unexpected developments through mutual adjustments to all dimensions of channel form;
- providing additional space for hydrological and morphological adjustments to absorb unexpected developments within the riparian corridor without damaging or destroying valuable habitats, species, ecosystems, people, or property;
- redesigning any remaining constraints (bridges, culverts, bank protection works, etc.) in the project reach with additional capacity to allow for unpredicted changes in the flow or sediment regimes due to, for example, climate or land use changes; and
- including postproject monitoring and appraisal in the project specification to support adaptive management of unforeseeable developments if and when they occur.

Risk

Risk may be broadly defined as the combination of the chance of a particular event (probability) with the impact that the event would cause (consequence) if it occurred. Helm (1996) warned that the simple product of probability and consequence will never be sufficient to describe risk fully, but concluded that it provides an adequate basis for comparison and decision-making. Hence for most project related purposes, risk may be defined as:

$$\text{Risk} = (\text{Probability of an outcome occurring}) \times (\text{Consequences should it occur}) \quad (9)$$

Probability is usually expressed nondimensionally on a scale between 0 (impossible) and 1 (absolutely certain to occur). Thus the units of risk will usually reflect the units of consequence. Commonly, the consequences are economic losses (in dollars), but if the risk is social or environmental other units may be used, demonstrating the flexibility of the risk concept. For example, risks to people are often expressed in units of quality-adjusted life years, reflecting the long-term impacts of a particular event on a person, such as having their home flooded.

In the context of project review, several known risks must be considered, including:

- risk to listed species (take),
- risk to project owners (cost, liability),
- risk to ecosystem (environmental degradation),
- social risk (perception associated with project failing to meet objectives), and
- institutional risk (creating or perpetuating risk averse management).

Clearly, since a series of risks must be managed, a multicriteria analysis to provide the basis for selecting the optimum solution is required, with the optimum solution generally having the lowest overall risk, although some risks, such as take of an endangered species may simply rule out a particular project option, design approach, or construction procedure.

To reduce risk, a decrease in the consequences of an outcome as well as its probability can be highly effective. Thus if erosion is a risk, and the probability of its occurrence cannot be reduced without jeopardizing important ecological functions, erosion risk can still be reduced by

managing down the consequences. This might involve relocating key infrastructure out of the channel migration zone, increasing the space allowed for channel shifting by setting back levees, or changing land use from one that is erosion vulnerable (housing) to one that is erosion tolerant (restored wetland, nature reserves, or parklands).

There is a strong case for learning by doing with regard to risk assessments associated with river corridor restoration. As Petroski (1992) pointed out, “No one wants to make mistakes, but we cannot learn enough from successes to go beyond the state of the art.” Hence a much wider use of pilot and demonstration schemes is warranted. These should be employed in places where the consequences of failure are small and the project’s proponents, stakeholders, regulators, and beneficiaries can all agree to testing the envelope, safe in the knowledge that the lessons learned will more than justify the costs of any adaptive or restorative actions that might be necessary to correct undesirable trends or outcomes.

Accommodating Uncertainty and Managing Future Risks

Some uncertainty is inherent and irreducible and, therefore, needs to be accepted. The law of diminishing returns dictates that as uncertainties are reduced to a very low level, the cost of any further reductions increases steeply. With respect to managing uncertainty, three simple rules pertain:

- Uncertainty and knowledge—uncertainty decreases as knowledge of the system increases.
- Uncertainty and project cost—project costs rise in a nonlinear manner with reduced uncertainty.
- Uncertainty and learning—the amount of new understanding generated by a project decreases as the uncertainties associated with its outcomes decrease.

In deciding whether further reductions in uncertainty merit the expenditure of time and resources necessary to achieve them, project proponents and reviewers must consider the level of risk stemming from the uncertainty. Risk and uncertainty are not the same thing: uncertainties may be large, but many of them pose little risk to the outcomes of the project. Attempts to further reduce uncertainty (through, for example, additional data collection or higher resolution modeling) should only proceed if the risk associated with the current level of uncertainty is serious enough to justify the additional investment. In this context, the level of uncertainty that is tolerable must be identified. A tolerable level of uncertainty lies between that which is acceptable and that which is unacceptable. These levels may be defined using a scheme modified from that proposed by Brookes and Dangerfield (2008):

- Acceptable. The risks associated with existing uncertainties are insignificant.
- Tolerable. The risks associated with existing uncertainties are significant but can be withstood; efforts to further reduce uncertainties would be disproportionate to the risk reductions achieved.
- Unacceptable. Risks associated with existing uncertainties cannot be tolerated and further effort must be made to reduce them at least to a tolerable level and ideally to an acceptable level.

Where the level of risk is unacceptable, uncertainties can be feasibly reduced using one or a combination of:

- better characterization of natural variability by gathering and incorporating more and better data and information;
- increasing the use of structural components in the design, which will reduce the probability of structural failure, but will almost certainly increase ecological risks, reduce resiliency and sustainability, and may increase risk of regulatory constraints;
- altering objectives to encompass uncertainty by accommodating uncertain elements as a goal of the project rather than a constraint (for example, giving more space for channel migration or flooding);
- incorporating learning by doing into project goals, thus recognizing uncertainty and using the project to learn about and accommodate it; or
- learning lessons from past experience, such as drawing on the records and performance (good or bad) of existing projects to reduce the risk of being found to have failed to apply best practice or to have created unforeseen take.

A particular problem with managing uncertainty and risk in stream channel projects lies in the wide range of disciplines and sciences involved in project development. A good way of handling the plethora of possible risks and uncertainties is to create an uncertainty/risk matrix to capture the sources, levels, and types of uncertainty and associated risks, and to show how these relate to the goals of the restoration project and assessment of take. Once validated, the matrix provides a framework for deciding what actions and additional investments are necessary to manage risk down to tolerable or even acceptable levels. In this context, the resources delivered within this project include a qualitative risk matrix that may be used to screen project proposals when allocating the depth of review they require on the basis of the risk to resource associated with the project and the stream within which implementation is being planned.

A risk management–based approach makes it essential to develop quantifiable objectives, produce design criteria that can be explicitly connected to these quantifiable objectives, and invoke postproject monitoring and appraisal to measure success against these clearly established objectives and criteria. It further promotes the case for adaptive management. Such an approach relieves the project proponents and designers of the onerous responsibility to foresee and guard against every possible adverse outcome at the project planning and design stage. Monitoring, appraisal, and adaptive management make it possible to identify and evaluate unexpected developments before they become problems and take the steps necessary to control or prevent undesirable developments.

Finally, a risk management–based approach to dealing with uncertainty would also promote a cooperative system of learning, aimed at identifying and reducing the most important (riskiest) uncertainties, and so develop the cognitive and science bases for restoration design. The result, through time, would be to reduce the liabilities associated with restoration projects by promoting practices that acknowledge uncertainty and accommodate it into the design, thus reducing the risk that the project will produce damaging outcomes.

Appendix D: Annotated Bibliography

Guidance Documents Grouped by Agency

Federal Agencies

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- The “big blue book,” good general guidance, cursory information on various reach-scale techniques, heavy on structural approaches. This is an extensive manual covering stream corridor theory and analysis, hydrology and hydraulics, geomorphic processes, chemical characteristics, biology, stability, disturbance, restoration planning, project design and implementation, and adaptive management of restoration projects. It is widely used in the United States to support restoration education and illustrate the different phases of project planning. It stresses that careful planning, based on comprehensive and reliable information, is critical to the design of successful projects. However, coverage of hydraulics and engineering aspects of restoration design has been described by some practitioners as thin. Relevance: high.
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Guidance on gravel mining from streams and floodplains in the context of salmon recovery. Relevance: moderate.

NRCS (Natural Resources Conservation Service). 2007. Stream restoration design. Part 654, National Engineering Handbook. (Available free by request from NRCS, 14th and Independence Ave. SW, Washington, DC 20250.)

This NRCS document on CD-ROM offers guidance on project design. It presents engineering and ecological assessment and design tools applicable to a wide range of stream restoration work. It covers natural stream restoration approaches and structural projects. The focus of this handbook is on how to perform restoration in practice. It is a useful reference document with more than 1,700 pages. Each chapter contains pros and cons of various methods and techniques and includes example problems and calculations. Relevance: high.

Resier, D. W., and T. C. Bjornn. 1979. Habitat requirements of anadromous salmonids. Gen. tech. rep. PNW-96. U.S. Dept. Agriculture, Washington, DC.

Early document on this important topic that has some utility in illustrating that there is a long history of federal studies and concerns about habitat and salmonids. Relevance: low.

Richardson, E. V., D. B. Simons, and P. F. Lagasse. 2001. River engineering for highway encroachments: Highways in the river environment. FHWA NHI 01-004. U.S. Dept. Transportation, Federal Highway Administration, National Highway Institute, Washington, DC. Online at <http://www.engr.colostate.edu/~bbledsoe/CIVE413/> [accessed 2 September 2010].

Considers all aspects of the environmental problems caused by highway encroachments, such as bridges and culverts. It considers their effect on open-channel flow, fluvial geomorphology, sediment transport, river mechanics, design, and maintenance. Relevance: moderate.

Soar, P. J., and C. R. Thorne. 2001. Channel restoration design for meandering river. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Comprehensive channel design manual based on collaborative doctoral research by the first author who was sponsored by the U.S. Army Corps of Engineers. Provides the basis for corps courses on channel design and restoration, but more of a stable channel design manual for meandering rivers than a restoration manual. Relevance: moderate.

Sotir, R. B., and J. C. Fischenich. 2001. Live and inert fascine streambank erosion control. EMRRP-SR-31. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Sotir, R. B., and J. C. Fischenich. 2003. Vegetated reinforced soil slope streambank erosion control. EMRRP-SR-30. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Sotir, R. B., and J. C. Fischenich. 2007. Live stake and joint planting for streambank erosion control. EMRRP-SR-35. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

- Sylte, T. L., and J. C. Fischenich. 2000. Rootwad composites for streambank erosion control and fish habitat enhancement. EMRRP-SR-21. U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Sylte, T. L., and J. C. Fischenich. 2002. Techniques for measuring substrate embeddedness. EMRRP-SR-36. U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Transportation Research Board. 2005. Environmentally sensitive channel and bank protection. Online at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_544.pdf [accessed 2 September 2010]. Guidelines for bank protection, with a decision support tool. Relevance: high.
- U.S. Bureau of Reclamation. No date. River spanning rock structures research (undated). Online at <http://www.usbr.gov/pmts/sediment/kb/SpanStructs/index.html> [accessed 2 September 2010]. Reports on research program for restoration of river systems using river spanning rock structures. Notes that interactions between restoration structures and a river network are not always understood, so differences between expected and actual performance may result in unintended consequences including damage to morphology, ecological impairment, failure to meet objectives, or the loss of the structure. Design guidelines are intended to improve the understanding of physical mechanisms in order to better meet project objectives and reduce maintenance requirements. Scope includes design and performance parameters for a wide array of structures including weirs, roughened channels, boulder clusters, rock ramps, and check dams. End product will consist of design guidelines and tools for achieving specific hydraulic and ecologic performance objectives in a sustainable manner. Relevance: moderate.
- USACE (U.S. Army Corps of Engineers). No date. Ecosystem Management and Restoration Research Program (2000–present). Online at <http://el.erdc.usace.army.mil/emrrp/> [accessed 17 May 2011]. This program has produced a large number of useful and relevant technical notes that can be downloaded in pdf format. The titles and links to those notes that are of moderate or high relevance to this science document are provided in this bibliography, but users may wish to visit the EMRRP website to investigate it for recent additions not listed here. Relevance: moderate to high.
- USACE (U.S. Army Corps of Engineers). 1994. Channel stability assessment for flood control projects. U.S. Army Corps of Engineers, Washington, DC. Online at <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA402439&Location=U2&doc=GetTRDoc.pdf> [accessed 3 September 2010]. Guidance document that addresses instability in flood control channels associated with maladjustment to discharge and sediment regimes. Practices dealt with focus on cleaning out or enlarging the channel to improve flood conveyance rather than redesigning it to mimic a more natural form. Despite this, the stability evaluation and design chapters offer useful input to stable channel design, with reference to hydraulic engineering design and geomorphic principles. Some of the nomographs (e.g., linking mean flow velocity to bed material grain size) might be useful for establishing outline design of a stable channel. Relevance: low.
- USFWS (U.S. Fish and Wildlife Service) and MWC (Montana Water Center). 2002. The wild fish habitat initiative. Online at <http://wildfish.montana.edu/> [accessed 3 September 2010]. This cooperative effort between USFWS and MWC, Montana State University-Bozeman, began in 2002. Research is carried out by water center staff and MSU biologists in collaboration with private landowners and private and public agency biologists. The initiative is a critical national effort to restore important fish and wildlife habitat that provides financial and technical assistance to private landowners seeking to restore habitat on their lands. Habitat degradation can exacerbate wild fish population loss to predators, exotic competitors, and diseases such as

whirling disease (*Myxobolus cerebralis*), and it is a principal reason for the listing of wild fish as threatened or endangered under the U.S. Endangered Species Act. In recent years, many techniques of fish habitat enhancement have been implemented, but their long-term efficacy is not well understood because little or no evaluation and monitoring have been conducted. This initiative seeks to augment the success of the Partners Program and other fish habitat restoration programs by conducting targeted research related to native fish habitat restoration techniques, and by implementing a technology transfer program to provide technical information to landowners and project managers. The Web site provides background on common problems and their solutions in a variety of restoration contexts. Relevance: high.

USFWS (U.S. Fish and Wildlife Service), NMFS (National Marine Fisheries Service), USACE (U.S. Army Corps of Engineers), and EPA (Environmental Protection Agency). 2006. Sediment removal from active stream channels in Oregon: Considerations for federal agencies for the evaluation of sediment removal actions from Oregon streams. Online at <http://www.fws.gov/oregonfwo/ExternalAffairs/Topics/Documents/GravelMining-SedimentRemovalFromActiveStreamChannels.pdf> [accessed 3 September 2010].

Considerations of instream mining impacts on aquatic habitat and recommendations for minimization of impacts. Relevance: moderate.

Watson, C. C., D. S. Biedenbarn, and F. Scott. 1999. Channel rehabilitation: Processes, design, and implementation. U.S. Army Corps of Engineers. Online at <http://chl.erdc.usace.army.mil/Media/2/9/0/ChannelRehabilitation.pdf> [accessed 3 September 2010] and <http://chl.wes.army.mil/library/publications/ChannelRehabilitation.pdf> [accessed 3 September 2010].

Covers the planning process, theory of geomorphology, description of channel modification activities, and fundamentals of engineering design for stream channel rehabilitation. Although an interdisciplinary approach is advocated, the document mainly deals with the engineering aspects of stream projects. Determination of effective discharge is explained in an appendix that could be useful during the initial assessment and design phases of a restoration project. Relevance: high.

State Agencies

CNRA (California Natural Resources Agency) and CDFG (California Department of Fish and Game). 1998. California salmonid stream habitat restoration manual. California Natural Resources Agency, Sacramento. Online at <http://www.mkwc.org/publications/fisheries/CDFG%20California%20Salmonid%20Stream%20Habitat%20Restoration%20Manual.pdf> [accessed 3 September 2010].

A how-to manual of habitat restoration with a focus on structural enhancements; founded on natural channel design using Rosgen methods. Relevance: moderate.

Doll, B. A., G. Grabow, K. Hall, J. Halley, W. Harman, G. Jennings, and D. Wise. 2003. Stream restoration: A natural channel design handbook. North Carolina State Univ., Raleigh. Online at http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html [accessed 3 September 2010].

A manual created by the state of North Carolina promoting the methods and techniques associated with the natural stream channel design approach. Draws on the Rosgen method in terms of variables measured and classification system used and includes a section on options for restoring incised channels. A useful section on regionalizing the natural stream channel design approach is presented in the form of hydraulic geometry relationships, gauge data, reference conditions, and sample projects. Regionalization is recommended in other states where the method is likely to be applied. Relevance: moderate.

EPA (Environmental Protection Agency) 2001. Generic quality assurance project plan for stream morphology data collection. Environmental Protection Agency, Washington, DC. Online at <http://www.epa.gov/quality/qs-docs/r5-final.pdf> [accessed 3 September 2010].

A generic quality assurance project plan (QAPP) for grant projects funded through the New Hampshire Department of Environmental Services using EPA Clean Water Act Section 319 funds that involve stream morphology data collection. The document offers a template for the steps in typical stream restoration projects, including problem identification, project tasks, minimum standards, documentation, useful existing data, field measurement methods, and reporting. Relevance: moderate.

Gflosi, G., S. Downie, M. Bird, R. Coey, and B. Collins. 2002. California salmonid stream habitat restoration manual. California Dept. Fish and Game, Sacramento. Online at <http://www.mkwc.org/publications/fisheries/CDFG%20California%20Salmonid%20Stream%20Habitat%20Restoration%20Manual.pdf> [accessed 3 September 2010].

Covers assessment, habitat restoration, and other pertinent information with a focus on recovery of salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*). Watershed and habitat assessment are covered, with a comprehensive system for naming 24 habitat types and schematics describing each. This convention seems to be a useful way to classify habitat with regard to its fisheries potential. A study indicated that a 10% random sample still generates accurate estimates of what is present in a reach. The manual's project implementation section has a good library of instream habitat enhancement methods. The section on fish passage at stream crossings presents a useful way to identify good and bad fish passage sites and label questionable sites for further hydraulic analysis using FishXing. Data tables supply helpful inputs on fish behavior. The section on upslope assessment and restoration is under revision. The final section discusses the importance of riparian habitats and their restoration. A library of plantings for California is presented. The appendices offer useful supplemental information and a completed habitat assessment report that can be used as a guide to using the protocols discussed in the manual. Relevance: high.

ISU (Iowa State University). 2004. Restoring Iowa streams. Iowa State Univ., Univ. Extension Service, Ames. Online at <http://www.extension.iastate.edu/Publications/PM1351J.pdf> [accessed 2 September 2010].

Very brief, very general. Relevance: moderate.

Kelly, F. 2001. Restoration of urban streams. New Jersey Dept. Environmental Protection, Div. Watershed Management, Trenton. Online at <http://www.state.nj.us/dep/watershedmgt/DOCS/Restoration%20of%20Urban%20Streams.pdf> [accessed 3 September 2010].

A qualitative overview of urban stream restoration issues. Table 3 is useful as it presents Natural Resources Conservation Service cost estimates (per unit length or area) of common stream rehabilitation practices used in urban stream restoration programs. Relevance: moderate.

MDE (Maryland Dept. Environment). 2000. Maryland waterway construction guidelines. Maryland Dept. Environment, Baltimore. Online at http://www.mde.state.md.us/Programs/WaterPrograms/Wetlands_Waterways/documents_information/guide.asp [accessed 3 September 2010].

This technical guidance document presents design details for popular traditional and bioengineering practices employed in the alteration and restoration of streams. A brief introduction presents the fundamentals of estimating design velocity (Manning's equation) and shear stress (DuBoys equation), although little design process information is given. For each practice, a description, effective uses and limitations, material specifications, installations guidelines, and detailed sketch are presented. Relevance: low.

Miller, D., P. Skidmore, and D. White. 2001. Channel design. White paper for Washington Dept. Fish and Wildlife, Washington Dept. Ecology, and Washington Dept. Transportation. Inter-Fluve Inc., Bozeman, MT.

Issues addressed include design and ecological considerations for new channels, habitat restoration and mitigation, channel relocation and realignment, channel modification for habitat and stability, placement of large woody debris (including removal and relocation), placement of boulders (including smaller rocks and substrate), off-channel ponds (rearing and other), off-channel channels (new floodplains, high flow bypass), gradient control structures, habitat enhancement activities, and structures. Relevance: high.

NCDENR (North Carolina Dept. Environment and Natural Resources). 2001. Internal technical guidelines for stream restoration. NCDENR, Raleigh. Online at <http://h2o.enr.state.nc.us/ncwetlands/streamgd.doc> [accessed 3 September 2010].

This document guides North Carolina Department of Environment and Natural Resources staff on stream restoration. The guide is largely qualitative, but contains several very useful components for design and review of projects. A flowchart of potential federal and state permits (p. 5) guides the project team and reviewer through the permitting process. A stream work check list (p. 29) for project designers helps increase the probability of a proposal addressing all of the needs of the regulatory community and producing a successful project. Relevance: moderate.

NHDES (New Hampshire Dept. Environmental Services). 2003. Guidelines to the regulatory requirements for dam removal projects in New Hampshire. DES-WD-03-35. New Hampshire Dept. Environmental Services, Water Division, Dam Bureau, River Restoration Program, Concord.

Guide to the relatively new and rapidly expanding practice of dam removal or decommissioning to restore rivers and river habitats. Relevance: moderate.

NHDES (New Hampshire Dept. Environmental Services) and NHDOT (New Hampshire Dept. Transportation). 2007. Guidelines for naturalized river channel design and bank stabilization. New Hampshire Dept. Environmental Services, Concord. Online at <http://des.nh.gov/organization/commissioner/pip/publications/wd/documents/r-wd-06-37.pdf> [accessed 3 September 2010].

The continually growing knowledge in applied local rehabilitation and enhancement and full system restoration has led to an expanded set of available design procedures and tools. To address the challenge of selecting appropriate design methods for each unique project, a classification system is presented that is based on project goals, scope, physical site constraints, ecological risks, and likely level of societal acceptance. Classification of a project as routine, moderate, or comprehensive informs the planning process, guides selection of design methods, supports project implementation, and increases the chances for meeting goals and objectives. Relevance: high.

OPSW (Oregon Plan for Salmon and Watersheds). 1999. Oregon aquatic habitat: Restoration and enhancement guide. Oregon Watershed Enhancement Board, Salem. Online at <http://wildfish.montana.edu/manuals/habguide99-complete.pdf> [accessed 3 September 2010].

A guide to restoration and enhancement in Oregon that provides a qualitative account of each activity that may be used to improve stream condition. Each practice is described in terms of regulatory requirements, guidance and considerations, and agencies offering technical assistance. The permitting component in the practical descriptions and particularly in the section on state and federal agencies could be useful in planning restoration activities. Relevance: moderate.

Saldi-Caromile, K., K. Bates, P. Skidmore, J. Barenti, and D. Pineo. 2004. Stream habitat restoration guidelines: Final draft. Washington Dept. Fish and Wildlife, Washington Dept. Ecology, and

U.S. Fish and Wildlife Service, Olympia, WA. Online at <http://wdfw.wa.gov/publications/00043/wdfw00043.pdf> [accessed 15 September 2011].

Comprehensive discussion of planning, assessment, and techniques with design guidance and detailed technical appendices. Overview of stream processes with clear discussion of the dynamic nature of streams, including disturbance regimes and recovery cycles. Treatment is process-focused and can provide a sound foundation for restoration planning. Assessment chapter covers the relevant scales from watershed to site. Chapter on developing a restoration strategy links river processes to enhancement, rehabilitation, and restoration planning. The account differentiates between each of these terms and presents recommended goals and objectives for each. Emphasis is placed on the advantages of passive restoration and the desirability of restoring process as well as form. The channel modification subsection deals with analog (reference reach), empirical (universal data sets), and analytical (engineering geomorphic design) approaches and recommends that a combination of these offers a safer design. The account of project implementation covers identifying stakeholders, project constraints, goals and objectives, design criteria to meet goals, necessary data, and risk. The importance of postproject monitoring is stressed. Popular rehabilitation practices are reviewed with examples. Theoretical aspects of understanding aquatic ecosystems are presented in appendices. Relevance: high.

Schiff, R., J. G. MacBroom, and J. Armstrong Bonin. 2006. River restoration and fluvial geomorphology white paper. R-WD-06-27. New Hampshire Dept. Environmental Services, Concord. Online at <http://www.nhacd.org/GeomorphologyWhitePaper.pdf> [accessed 3 September 2010].

Overview of concepts and approaches to restoration and description of problems within a geomorphic context. Relevance: high.

SMCWPPP (San Mateo Countywide Pollution Prevention Program). 2000. Erosion and sediment controls for riparian areas. San Mateo, CA.

This pamphlet (draft) offers in a single sheet information on erosion and sediment controls for riparian areas to be used in San Mateo County, California. The goal is to inform streamside land owners of best management practices. The pamphlet could be useful as a template for producing brief guidance to citizens and links to regulatory agencies that perform and guide stream restoration in other areas. Relevance: moderate.

VDCR (Virginia Dept. Conservation and Recreation), VDEQ (Virginia Dept. Environmental Quality), and NOAA (National Oceanic and Atmospheric Administration). 2004. The Virginia stream restoration and stabilization best management practices guide. VDCR, Division of Soil and Water Conservation, Richmond, VA. Online at http://www.dcr.virginia.gov/soil_&_water/documents/streamguide.pdf [accessed 3 September 2010].

This guide was developed to provide a technical resource for government, private, and nonprofit organizations involved in permitting, designing, or constructing stream channel and bank stabilization and restoration projects by combining information found scattered in numerous documents into a single publication. It assumes readers have a basic understanding of stream functions and values, as well as basic design and engineering concepts. Topics include permitting issues and processes, planning and design principles and guidelines, costs, and individual best management practices. Relevance: moderate.

VTANR (Vermont Agency of Natural Resources). 2004. Vermont stream geomorphic assessment protocol handbooks: Remote sensing and field surveys techniques for conducting watershed and reach level assessments. Vermont Agency of Natural Resources, Waterbury. Online at http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm [accessed 3 September 2010].

These handbooks support the comprehensive physical assessment of streams in three phases. Phase 1 is a watershed-scale information gathering protocol based on using maps and windshield surveys. Phase 2 consists of a reach-scale rapid field assessment where key variables are

measured along selected reaches to develop a more detailed understanding of stream geomorphology. Phase 3 is a site-scale, field-based component wherein detailed data are collected. Although these protocols are not designed specifically for restoration design and implementation, they could be used for this purpose and should enhance the chances of achieving successful outcomes. Relevance: moderate.

Nongovernment Organizations

Brown, K. 2000. Urban stream restoration practices: An initial assessment. Center for Watershed Protection, Ellicott City, MD. Online at http://www.civil.uwaterloo.ca/cive770/papers/Restoration_methods/urban_stream_restoration.pdf [accessed 3 September 2010].

Examines 24 different types of stream restoration practices that vary from “hard” structural approaches to “soft” bioengineering approaches and includes details of more than 450 individual installations. Each practice was evaluated in the field according to four simple visual criteria: structural integrity, function, habitat enhancement, and vegetative stability. Relevance: moderate.

CMU (Carnegie Mellon University). 2003. Three rivers second nature stream restoration and daylighting program. Carnegie Mellon University, Pittsburgh, PA. Online at <http://www.cmu.edu/studio/projects/past.html> [accessed 10 September 2010].

This project addressed the meaning, form, and function of public space and nature in Allegheny County, Pennsylvania, and focused on the Allegheny, Monongahela, and Ohio rivers, as well as streams and subwatersheds. The 5-year project revisited questions of nature and postindustrial public space that were first addressed on the Nine Mile Run Greenway Project. The focus of the work was research to benefit the public realm, applied as strategic knowledge with accompanying outreach programs intended to enable creative public advocacy and change. The project conducted integrative analysis and instrumental planning based on rigorous field studies beginning in 2000, with a focus on partnerships to accomplish interdisciplinary analysis, spatial mapping, and concept design within and among specific communities. Relevance: moderate.

CWP (Center for Watershed Protection). 2004. Urban subwatershed restoration manual series. Center for Watershed Protection, Ellicott City, MD. Online at http://www.cwp.org/documents/cat_view/68-urban-subwatershed-restoration-manual-series.html [accessed 3 September 2010].

Under an EPA grant, the nonprofit center developed an 11-manual series on practical techniques to restore urban watersheds. The manuals cover the seven major practices used to restore urban watersheds: stormwater retrofits, stream repair, riparian management, discharge prevention, pollution source controls, watershed forestry, and municipal operations. In addition, the series outlines new methods for desktop and field assessment and stakeholder management to develop effective small watershed restoration plans and presents an integrated framework for urban watershed restoration. Although these manuals focus on urban stream restoration, the principals and practices set forth in each may also pertain to other land use settings. The content of these manuals has been used to develop many community-based restoration plans and projects. Relevance: high.

KST (Keystone Stream Team). 2002. Guidelines for natural stream channel design for Pennsylvania waterways. Keystone Stream Team, Canaan Valley Institute, and Alliance for the Chesapeake Bay, Williamsport, PA. Online at http://www.keystonestreamteam.org/kst_documents.htm#NSCDGuidelines [accessed 3 September 2010].

This document offers an overview of the natural channel design approach, including technical information on project planning, design, and implementation. The fundamental philosophy employed is to work with, not against, a stream’s natural form and function. The Rosgen method is recommended, with a reference reach used as a template for restoration, although empirical and

analytical approaches are also addressed. The concept of bankfull discharge is presented and its importance to restoration design is discussed. Use of an interdisciplinary team is suggested to cover all aspects of the stream. Projects must be addressed on a case-by-case basis. Key aspects include community, data, design, permitting, consultants, construction, and monitoring. Presents a nice overview of working with stakeholders to achieve a common view of what is to take place and acceptance among partners and regulators. Covers permitting at the state and federal levels, and Pennsylvania's phased project approach to spreading permitting time and costs throughout the course of the project is described. Presents thorough sections on how to hire a qualified consultant and how to proceed with construction. Finally, gives a brief mention of monitoring. Relevance: moderate.

NCED (National Center for Earth-surface Dynamics). No date. River restoration Web site (2002–present). National Science Foundation, Science and Technology Center, University of Minnesota, St. Cloud. Online at <http://www.nced.umn.edu/content/partnership-river-restoration-and-science-upper-midwest-prrsum> [accessed 3 September 2010].

NCED began in 2002. Its goal is for its Web site to encourage and facilitate urgently needed communication and cooperation among civil engineers, ecologists, project managers, geomorphologists, trainers, hydrologists, agency personnel, biologists, and social scientists. The Web site provides a place for all stakeholders in the stream restoration field to share advances in science, innovation in practice, and opportunities for education and training. The principal investigators are at Fond du Lac Tribal and Community College, Johns Hopkins University, Science Museum of Minnesota, University of California, University of Colorado, University of Illinois, Louisiana State University, University of Texas, and University of Minnesota. NCED's aim is integrative research and its delivery to students, the public, and practitioners. The stream restoration Web site is a resource that blends community-wide and NCED efforts in stream restoration. Resources on the Web site include research, education and training, partners, restoration in action, resources, and St. Anthony Falls Laboratories. Users can also subscribe to an NCED newsletter, view its calendar, and join the Stream Restoration Network. Relevance: high.

Pinkham, R. 2000. Daylighting: New life for buried streams. Rocky Mountain Institute, Snowmass, CO. Document dealing specifically with culvert removal. Relevance: moderate.

Smith, M. P., R. Schiff, A. Olivero, and J. G. MacBroom. 2008. The active river area: A conservation framework for protecting rivers and streams. (Available from The Nature Conservancy, 5th floor, 11 Avenue De Lafayette, Boston, MA 02111.) Online at http://www.nature.org/initiatives/freshwater/files/active_river_area.pdf [accessed 3 September 2010].

The active river area provides a systematic means for conceptualizing and protecting the river as a dynamic system with a broad range of conditions that are typical of natural river systems. The active river area is spatially explicit and can be readily identified—narrow in some areas, wider in others—and captures the living, dynamic processes, and places that define these systems. The active river area includes a number of distinct components that provide specificity to guide actions for protection, restoration, and management. Relevance: high.

Foreign Agencies

Australia

Australia Water and Rivers Commission. 2002. River Restoration. Department of Water, Perth. Regional document covering Southwest Australia. More of a planning document than a restoration guide. Relevance: low.

Koehn, J. D., G. J. Brierley, B. L. Cant, and A. M. Lucas. 2001. River restoration framework. The National Rivers Consortium: Land and Water Australia, Canberra.

Provides a step-by-step process through which the complex task of river restoration can be undertaken. Aimed at catchment managers and community groups as well as scientists and other stakeholders. Highlights the core requirements and elements of river restoration with the aim of promoting a process that incorporates the variety of biophysical, societal, economic, and political structures that affect and are affected by river restoration. The framework employs three key principles: 1) management procedures must be flexible and adaptable, 2) there must be much greater integration and communication of knowledge between disciplines (within the sciences and across to the social sciences), and 3) the community must have ownership of the project (where ownership constitutes control over decision making processes and commitment to follow throughout the restoration process). Relevance: moderate.

Land and Water Australia. 2006. Design guidelines for the reintroduction of wood into Australian streams. PX061171. Griffith University, Australian Rivers Institute, Nathan, Queensland. Online at <http://freedom.dicea.unifi.it/massimo.rinaldi/RiqFluv%20IAT/Brooks%20guidelines%20LWD.pdf> [accessed 3 September 2010].

Andrew P. Brooks, Griffith University, Southport, Queensland; with contributions by Tim Abbe, Herrera Environmental Consultants, Seattle, Washington; Tim Cohen, University of Wollongong, Wollongong, New South Wales; Nick Marsh, Queensland Environmental Protection Authority, Brisbane; Sarah Mika and Andrew Boulton, University of New England, Armidale, New South Wales; Tony Broderick, New South Wales Northern Rivers Catchment Management Authority, Grafton; and Dan Borg and Ian Rutherford, University of Melbourne. Begins with the premise that in many respects wood in rivers is akin to coral reefs in oceans, as it provides substrate for invertebrates and biofilms, provides complex habitat that supports a wide range of aquatic species, and performs a critical geomorphic role. The main purpose is to help design wood reintroduction that will last long enough to enable natural wood recruitment to take over. The authors have incorporated up-to-date knowledge and experience on wood reintroduction, with a view to improve the likelihood of implementing successful wood-based stream rehabilitation strategies. Relevance: high.

MDBA (Murray-Darling Basin Authority). 2002. Guidelines and protocols for the management of native fish habitat. Project R2120. Murray Darling Basin Commission, Malvern, Victoria, Australia. Online at http://www.mdbc.gov.au/__data/page/65/execsum_habitat_restoration_protocols.pdf [accessed 2 September 2010].

Includes a flowchart for planning and conducting restoration. Relevance: moderate.

Rutherford, I. D., K. Jerie, and N. Marsh. 2000. A rehabilitation manual for Australian streams (2 vol.). Monash University, Cooperative Research Centre for Catchment Hydrology, Clayton, Victoria, Australia. Vol. 1 online at http://www.engr.colostate.edu/~bbledsoe/CIVE413/Rehabilitation_Manual_for_Australian_Streams_vol1.pdf. Vol. 2 online at <http://nlwra.gov.au/files/products/river-landscapes/pr000325/pr000325.pdf> [both accessed 3 September 2010].

Comprehensive and detailed guidance to assist local and regional professional managers in rehabilitating, preserving, and returning the natural physical and biological diversity of Australian streams. Emphasis is on the physical condition of stream reaches and channel stability. Covers common stream problems, project planning, and intervention tools. Vol. 1 covers basic rehabilitation concepts and includes a 12-step program for planning a rehabilitation project or procedure. Vol. 2 presents tools that can be used for rehabilitation. Relevance: moderate.

Canada

OMNR (Ontario Ministry of Natural Resources), 2001. Adaptive management of stream corridors in Ontario and natural hazards technical manual. Ontario Ministry of Natural Resources, Peterborough.

CD-ROM created by OMNR as a collaborative effort involving regulators, practitioners, and academics. An interdisciplinary guide to stream management that is rooted in geomorphology, engineering, and ecology, it offers important information on restoration design, including adaptive management. The document is based on protecting what is healthy and rehabilitating what is not. A nice comparison of the differences between natural systems and nonnatural designs is presented. In the first version of this document, OMNR stated goals of natural channels to be physically stable, biologically self-sustaining, and overall self-regulating. This document does a good job of distinguishing between the management options of restoration, rehabilitation, enhancement, and protection, which are often confused. A clear picture of the physical jurisdiction of regulatory agencies and needed permits clearly illustrates the potential permitting process in stream restoration. The section on the effects of land use on streams offers nice overviews of potential impacts associated with European settlement and present day watershed activities. An informative review of stream processes, forms, and function is presented with several data tables for easy reference. The planning and design process is well laid out, although it might be preferable to formulate the monitoring plan early in the design phase (i.e., after the initial assessment) so it is in place prior to project implementation. An extensive bibliography of articles published before 1999 is presented. Relevance: moderate.

Slaney, P. A., and D. Zaldokas (eds.). 1997. Fish habitat rehabilitation procedures. British Columbia Ministry of Environment, Victoria. Online at http://www.env.gov.bc.ca/wld/documents/wrp/wrtc_9.pdf [accessed 3 September 2010].

Recent reviews of the status of anadromous salmonid stocks of the western United States and British Columbia indicate that in less than a century, wild stocks have gone from a pristine state to one of numerous extinctions, threatened status, or uncertain status. The causes of the declines are described as due to various impacts dominated by overharvesting of weaker stocks, problems associated with hatcheries, hydroelectric developments, and habitat loss. It concludes that for many stocks to survive and prosper in the next century, a major shift is needed to restore habitats and ecosystem function, rather than rely on artificial production. A watershed focus is required and the River Continuation Concept (Vannote et al. 1980, modified by Triska et al. 1982) is suggested as a useful ecological template for a holistic approach. The guide recognizes that fluvial geomorphic processes, within a drainage from its headwater gullies to the stream mouth, largely regulate biological processes involving energy input, nutrient spiraling, organic matter transport, storage, and use by aquatic biota, including invertebrates and fish. Hence, downstream communities functions are contingent on upstream contributions of materials. Relevance: moderate.

United Kingdom

River Restoration Centre (UK). 1995 (updated 2002). Manual of river restoration techniques. Cranfield University, River Restoration Centre, Cranfield, Bedfordshire, UK. Online at http://www.engr.colostate.edu/~bbledsoe/CIVE413/Manual_of_River_Restoration_Techniques.htm [accessed 3 September 2010].

Cookbook manual of practical techniques presented as case studies. Deals almost exclusively with small streams. Lacks guidance on planning a restoration project and selecting between alternative restoration design approaches. Relevance: low.

Guidance Books and Chapters

Beechie, T. J., G. R. Pess, M. M. Pollock, M. H. Ruckelshaus, and P. Roni. 2009. Restoring rivers in the twenty-first century: Science challenges in a management context. *In* R. J. Beamish and B. S. Rothschild (eds.), *The future of fisheries science in North America*, Chapter 33, p. 697–717. Springer, New York.

Legal mandates force consideration of at least some level of river restoration in many developed nations (e.g., Clean Water Act and Endangered Species Act in the United States, Water Framework Directive in the European Union), but a lack of specifics in legislation compels decision makers to ask three persistent management questions. First, how much river restoration do we need? Second, how do we best achieve cost-effective river restoration? Third, how do we know we have restored enough? Moreover, the broader management context is permeated with tremendous inertia to continue development of rivers for societal and economic gain, continual application of small and fragmented restoration actions, and skepticism that river restoration can succeed in the face of climate change and steady population growth. It is in this context that the authors identify key science challenges for river restoration in the twenty-first century. They suggest that a fundamental shift toward restoring watershed and river processes (process-based restoration) is needed if scientists are to develop the tools needed to provide relevant policy answers. The basic conceptual framework of process-based restoration requires an understanding of how habitat is formed and changes, how habitat changes alter biota, and how human actions alter river habitats and the landscape processes that create river habitats. Restoration actions must then directly address human actions that caused habitat degradation, thereby addressing the root causes of biological impacts. Understanding this framework will allow scientists to better address key science challenges for advancing river restoration, including development of ecosystem models to predict the kinds and quantity of restoration that is needed, an expanded suite of process-based restoration techniques for large river ecosystems, and comprehensive but cost effective suites of metrics for monitoring river health. Relevance: high.

Brierley, G. J., and K. A. Fryirs. 2005. *Geomorphology and river management: Applications of the river styles framework*. Blackwell Publishing, Malden, MA. Online reviews at <http://www.riverstyles.com/georiv.php> [accessed 3 September 2010].

This book outlines a generic set of procedures, termed the River Styles Framework, which provides a set of tools for interpreting river character, behavior, condition, and recovery potential. Applications of the framework generate a coherent package of geomorphic information, providing a physical template for river rehabilitation activities. This book is a learning tool with which to approach geomorphic applications to river management. It describes essential geomorphological principles underlying river behavior and evolution, and demonstrates how the River Styles Framework can turn geomorphic theory into practice to develop workable strategies for restoration and management. Examples are provided based on real case studies and the authors' extensive experience applicable to river systems worldwide. The key is synthesis of fluvial geomorphology, ecology, and management. The book is intended for environmental scientists, geologists, and ecologists interested in river management. It is clearly written and the quality of the photographs and figures is good. Relevance: moderate.

Brookes, A., and F. D. Shields. 1999. *River channel restoration: Guiding principles for sustainable projects*. Wiley & Sons, London.

An edited collection of chapters by various authors on topics in restoration. A wealth of relevant information. No guidelines but useful as a reference book. Out of print but can be obtained from university and agency libraries. Relevance: moderate.

Darby, S. E., and D. A. Sear (eds.). 2008. River restoration: Managing the uncertainty in restoring physical habitat. Wiley & Sons, London, UK. Online excerpts at <http://www.wiley.com/WileyCDA/WileyTitle/productCd-047086706X.html> [accessed 3 September 2010].

Provides a systematic overview of issues involved in minimizing and coping with uncertainty in river restoration projects. A series of thematic sections are used to theoretically define uncertainty, then introduce the various sources of uncertainty in restoration projects and how these show up at different points in the life cycle (design, construction, and postconstruction phases) of restoration projects. The book presents a rational analysis of uncertainty with practical guidance in managing the different sources of uncertainty. It concludes that uncertainty should not be ignored or feared, but embraced. The importance of postproject monitoring, appraisal, and adaptive management as an antidote to uncertainty is stressed. Case studies come from Europe, North America, and Australasia. Relevance: high.

Davy, A. J., and J. Perry (eds.). 2001. Handbook of ecological restoration, Vol. 1: Principles and restoration, and Vol. 2: Restoration in practice. Cambridge University Press, Cambridge, UK.

The two volumes of this handbook provide a comprehensive account of ecological restoration of habitats and species. Ecological restoration aims to achieve complete structural, functional, and self-maintaining biological integrity following disturbance. In practice, any theoretical model is modified by a number of economic, social, and ecological constraints. Consequently, material that might be considered as rehabilitation, enhancement, reconstruction, or re-creation is also included. The underlying principles of restoration ecology are defined in relation to manipulations and management of the biological, geophysical, and chemical framework. The accompanying volume, Restoration in practice, provides details of restoration practice in a range of biomes within terrestrial and aquatic ecosystems. The handbook is a valuable resource to those concerned with the restoration, rehabilitation, enhancement, or creation of habitats in aquatic or terrestrial systems. It was written by an international team of expert scientists and practitioners, ensuring worldwide applicability. Relevance: high.

Hayes, D. F. 1998. Engineering approaches to ecosystem restoration. Proceedings of the 1998 Wetlands Engineering and River Restoration Conference. American Society of Civil Engineers, Reston, VA.

The papers in this proceedings volume provide valuable insights to successful approaches for river restoration, wetland restoration, watershed management, and the use of constructed wetlands for water and wastewater treatment. They describe successful and unsuccessful case studies from Florida to Alaska. Potential solutions to a wide variety of ecosystem concerns in urban, suburban, and coastal environments are presented. The proceedings also contain summaries of discussion sessions on hot-button topics related to restoration such as whether watershed management is achievable, whether ecologists and engineers have differing views on restoration, and many others. Relevance: low.

Hayes, D. F. 2001. Designing successful stream and wetland restoration projects. Proceedings of the 2001 Wetlands Engineering and River Restoration Conference. American Society of Civil Engineers, Environmental and Water Resources Institute, Reston, VA.

Nearly 200 papers provide information on the design of successful stream, riparian, and wetland restoration projects along with insightful approaches to watershed management. Case studies detail successes and failures of various design approaches on local and watershed scales. This collection provides a valuable resource for professional engineers and scientists struggling with design, implementation, and monitoring of restoration projects. The interdisciplinary background and practical information presented make these proceedings particularly useful to the practitioner. Topics include stream and channel restoration, wetlands, design, watersheds, hydraulics, and unique habitat restoration approaches. Relevance: moderate.

Kondolf, M., and H. Piégay (eds.). 2003. *Tools in fluvial geomorphology*. Wiley & Sons, London. Online excerpt at <http://www.wiley.com/WileyCDA/WileyTitle/productCd-047149142X.html> [accessed 3 September 2010].

This volume provides an integrated approach to the interdisciplinary nature of the subject and offers guidance on the tools available to answer questions on river management on very different scales. The coverage extends from general concepts to specific techniques. Topics include evolution of methods, guiding concepts, a framework for deciding when to apply specific tools, advantages and limitation of the tools, sources of data, equipment and supplies needed, and a summary table. The aim is to highlight the applications, advantages, and limitations of various tools using case studies. Relevance: moderate.

Montgomery, D. R., and S. M. Bolton. 2003. Hydrogeomorphic variability and river restoration. *In* R. C. Wissmar and P. Bisson (eds.), *Strategies for restoring river ecosystems: Sources of variability and uncertainty in natural and managed systems*, p. 39–80. American Fisheries Society, Bethesda, MD.

Fisheries and natural resource managers and policymakers need more efficient procedures for identifying sources of variability in ecosystems (natural and managed) and assessing uncertainties of managing and making decisions for developing and implementing river restoration strategies. This book integrates perspectives on variability of physical and biological functions and concepts of uncertainty in natural and managed systems into strategies for renewing and conserving river ecosystems. The book explores approaches to understanding and communicating the processes contributing to the variability of different types of river systems, and to assessing major sources of uncertainty in natural and managed river ecosystems. Relevance: moderate.

Montgomery, D. R., S. Bolton, D. B. Booth, and L. Wall (eds.). 2003. *Restoration of Puget Sound rivers*. University of Washington Press, Seattle.

The listing of Pacific salmon under the Endangered Species Act has led to substantial interest in the scientific basis for river restoration in the Pacific Northwest. This volume addresses the need for a solid understanding of fluvial processes and aquatic ecology in order to predict river and salmonid response to restoration projects. Practitioners are still learning about the processes that create habitat and river structure, how those processes influence aquatic ecosystems, and how to gauge the response of river systems to land-use changes and restoration efforts. River systems are still responding to historic changes and degraded habitat may not be restored successfully if natural conditions are not well understood, particularly if massive changes in watershed hydrology or other processes are the root cause. The book's 18 chapters were written by regional experts who attended a symposium of the Society for Ecological Restoration. They examine geological and geomorphological controls on river and stream characteristics and dynamics; biological aspects of river systems in the region; and the application of fluvial geomorphology, civil engineering, riparian ecology, and aquatic ecology in efforts to restore Puget Sound rivers. This volume is of interest to geomorphologists, aquatic biologists, civil engineers, planners, and those interested in the interface of science and policy in addressing river restoration. Relevance: high.

Mount, J. F. 1995. *California rivers and streams: The conflict between fluvial processes and land use*. University of California Press, Berkeley. Online excerpt at <http://www.ucpress.edu/books/pages/6664.php> [accessed 3 September 2010].

A comprehensive book on Californian rivers that has been described as the best general primer currently available. Although not a textbook, it is suitable for introductory courses because of its scope and readability. The book is divided into two parts. Part 1, how rivers work, includes nine chapters: introduction to the rivers of California, water in motion, a river at work, the shape of a river, origins of river discharge, sediment supply, river network and profile, climate and the rivers of California, and tectonics and geology of California's rivers. Part 2, learning the

lessons, includes eight chapters: rivers of California, mining and the rivers of California, logging California's watersheds, food production and the rivers of California, a primer on flood frequency, the urbanization of California's rivers, the damming of California's rivers, and the future. Relevance: moderate.

NRC (National Research Council). 1992. Restoration of aquatic ecosystems: Science, technology, and public policy. National Academies Press, Washington, DC. Online at http://www.nap.edu/catalog.php?record_id=1807#reviews [accessed 3 September 2010].

Examines the prospects for repairing damage that society has done to the nation's aquatic resources: lakes, rivers and streams, and wetlands. Outlines a national strategy for aquatic restoration, with practical recommendations, and features case studies of aquatic restoration activities around the country. Relevance: moderate.

Ostfeld, A., J. Ostfeld, and M. Tyson. 2005. River basin restoration and management. IWA Publishing, London.

This book is the result of two workshops held at the 4th International Water Association World Water Congress: the first on restoration of degraded river basins and the second on river basin management using machine learning. The first workshop set out to share experience in the institutional, policy, and public participation elements of restoration programs, the "soft" issues surrounding restoration of a degraded river basin, and the development of the river basin plan. Resulting papers include case studies from a variety of river basins in Israel, South Africa, United Kingdom, Australia, and central Europe. The second workshop highlighted and compared the two different approaches to watershed management: physically based modeling relying on the system physics versus data driven modeling based on exploring the system data behavior. It was motivated by the recent rapid advance in information processing systems. Relevance: low.

Petts, G., and P. Calow. 1996. River restoration. Blackwell Science Ltd., London.

Now dated and out of print but available secondhand. Good to gain impression of the roots of restoration thinking and how this has evolved in the last decade. Relevance: low.

Postal, S., and B. D. Richter. 2003. Rivers for life: Managing water for people and nature. Island Press, Washington, DC. Online reviews at http://islandpress.org/bookstore/details7a6f.html?prod_id=512 [accessed 3 September 2010].

Presents a concise yet comprehensive global perspective on the challenges of managing water for people and nature. Covers the relevant science, policy, and management issues. Intended for professionals concerned with water policy, planning and management, river conservation, and biodiversity. Questions river protection focused on water quality and maintaining a minimum flow, arguing that the ecological health of a river system depends not on a minimum amount of water at any one time but on the naturally variable quantity and timing of flows throughout the year. The authors explain why restoring and preserving more natural river flows are key to sustaining river biodiversity and health, and describe innovative policies, scientific approaches, and management reforms for achieving those goals. Case studies come from the United States, Australia, and South Africa. Relevance: moderate.

Ralph, S. C., and G. C. Poole. 2003. Putting monitoring first: Designing accountable ecosystem restoration and management plans. In D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall (eds.), Restoration of Puget Sound rivers. University of Washington Press, Seattle. Online at http://www.krisweb.com/biblio/gen_uofw_ralphetal_ip.pdf [accessed 3 September 2010].

The authors state that recovery of Puget Sound rivers and their native fish depends on carefully documenting the ultimate effectiveness of restoration actions, yet as currently designed and implemented, monitoring programs are predestined to fail in this task. Consequently, attempts to implement iterative, adaptive restoration or management actions will also fail unless

managers and researchers alter their current conceptual models about the relationship between monitoring and management/restoration, design and implement monitoring programs before planning restoration/management actions, recognize the need for hierarchical monitoring programs and learn how to implement them, and eliminate myths about monitoring. For monitoring programs to provide reliable and timely information required by iterative and adaptive approaches to ecosystem restoration and management, they must serve as a scientifically rigorous framework for empirical management of natural resources. To accomplish this, managers and researchers must work together first to design hierarchically structured monitoring experiments, then to plan on-the-ground management and restoration actions that serve as experimental manipulations in the context of the monitoring experiment. Unlike current approaches, this empirical approach has the potential to generate rigorous new scientific information about the efficacy of implemented actions and therefore could support adaptive, iterative improvement in management and restoration plans. Relevance: high.

Riley, A. L. 1998. Restoring streams in cities: A guide for planners, policymakers, and citizens. Island Press, Washington, DC.

Includes detailed information on all relevant components of urban stream restoration projects. It seeks to aid those involved with stream management in their community and describes options for the treatment of urban streams. Chapters provide information for making intelligent choices, asking necessary questions, and hiring the right professionals to perform restoration projects. Topics include the history of urban stream management and restoration, information on federal programs, technical assistance, and funding opportunities, as well as in-depth guidance on performing projects (collecting watershed and stream channel data, installing revegetation projects, and protecting buildings from overbank stream flows). The book can be used by community stakeholders and professionals alike. Relevance: moderate.

Rosgen, D., and L. Silvey. 1996. Applied river morphology. Wildland Hydrology, Fort Collins, CO.

Provides a detailed explanation of the Rosgen Classification System and how it can be used in restoration designs. Chapter titles include: new challenges, fundamental principles of river systems, stream classification, geomorphic characterization, morphological description, assessment of stream condition and departures from its potential, field data verification, and applications. Techniques covered include fundamental principles of river behavior, hierarchical stream inventory, and classification of natural rivers. Field techniques and forms are provided for stream classification reference reach, bank erosion prediction, fish habitat structure evaluation, sediment relations, hydraulics, and channel stability evaluation. Relevance: moderate.

Rosgen, D., and L. Silvey. 1998. Field guide for stream classification. Wildland Hydrology, Fort Collins, CO.

A waterproof book that is designed to fit into field vest or belt pouch. The contents are extrapolated from Applied river morphology, 1996. Relevance: moderate.

Rosgen, D., L. Silvey, and D. Frantila. 2008. River stability field guide and river stability forms and worksheets. Wildland Hydrology, Fort Collins, CO.

This field guide includes the river assessment techniques related to the Rosgen method for assessing reach condition for river restoration planning and design. Supplements the WARSSS (Watershed Assessment of River Stability and Sediment Supply) approach, providing detailed field procedures and examples. The aim is to assist practitioners in performing four levels of assessment to evaluate streambank erosion, lateral stability, and vertical stability using morphologic, hydraulic, and sediment variables. Includes a CD-ROM of electronic worksheets and forms. Presents validation methods to improve prediction models and improve understanding of river processes and responses. Relevance: moderate.

Schumm, S. A. 1977. *The fluvial system*. Wiley & Sons, New York.

Out of print, this book can be obtained from university and agency libraries or secondhand. It provides much of the geomorphological science and reasoning that underpins our understanding of sediment dynamics and morphological responses to perturbation in alluvial river systems. Required reading in many university courses on river mechanics, channel forms, and stream processes; valuable background reading for practitioners. Relevance: low.

Thorne, C. R., R. D. Hey, and M. D. Newson (eds.). 1998. *Applied fluvial geomorphology for river engineering and management*. Wiley & Sons, London.

Provides river engineers and managers, who may lack specialist training, with an understanding of the natural channel forms and fluvial processes. That is a prerequisite for developing environmentally sensitive design and management procedures to preserve riverine environments and restore degraded ones. The book incorporates material on methods and techniques of data collection, analysis, and interpretation, and makes extensive use of case studies. The aim is to demystify applied fluvial geomorphology by demonstrating that, while there is still an element of judgment, major contributions to geomorphic understanding usually come from the careful assemblage and objective analysis of all available data and information. Relevance: moderate.

Wissmar, R., and P. Bisson. 2003. *Strategies for restoring river ecosystems: Sources of variability and uncertainty in natural and managed systems*. American Fisheries Society, Bethesda, MD.

This book integrates perspectives on variability of physical and biological functions and concepts of uncertainty in natural and managed systems into strategies for renewing and conserving river ecosystems. It explores approaches to understanding and communicating the processes contributing to the variability of different types of river systems, and to assessing major sources of uncertainty in natural and managed river ecosystems. Relevance: moderate.

Bank Protection and Riprap Documents

Bank Protection

Allen, H. H., and J. R. Leech. 1997. *Bioengineering for streambank erosion control*. TR EL-97-8. U.S. Army Corps of Engineers, Washington, DC. Online at http://www.engr.colostate.edu/~bbledsoe/CIVE413/Bioengineering_for_Streambank_Erosion_Control_report1.pdf [accessed 7 September 2010].

Information on bioengineering applications. Includes planning and design guidelines for use of bioengineering treatments on eroding streambanks and successful case studies from the United States and Europe. Relevance: moderate.

Bentrup, G., and J. C. Hoag. 1998. *The practical streambank bioengineering guide*. U.S. Dept. Agriculture, Natural Resources Conservation Service, Plant Materials Center, Aberdeen, ID. Online at http://www.engr.colostate.edu/~bbledsoe/CIVE413/Practical_Streambank_Bioengineering_Guide.pdf [accessed 7 September 2010].

Guide to bioengineered stream stabilization techniques for arid and semiarid streams in the great basin and intermountain west. Intended for the use by conservationists who provide technical assistance to private landowners for restoration work. Relevance: moderate.

Buer, K., D. Forwalter, M. Kissel, and W. Stohler. 1989. *The middle Sacramento River: Human impacts on physical and ecological processes along a meandering river*. Gen. tech. rep. PSW-110. U.S. Forest Service, Sacramento, CA. Online at http://www.fs.fed.us/psw/publications/documents/psw_gtr110/psw_gtr110_a_buer.pdf [accessed 2 September 2010].

This early study focused on changes in bank erosion, bank composition, river length, depth, width, and sinuosity. Its floodplain deposition studies produced one of the first indications that bank protection significantly reduces a source of salmon spawning gravel from freshly eroded banks with knock-on effects on preferred spawning areas such as point bar riffles, chute cutoffs, multiple channel areas, and areas near islands. It also argues that bank protection increases the tendency of the confined river to deepen and narrow, further reducing spawning habitat. Wildlife populations have declined markedly due to loss of riparian habitat and suppression of the natural successional processes that maintain the density and diversity of habitat within the riverine environment. Flood control is believed to have interrupted the natural equilibrium between erosion and deposition, resulting in reduction in bank erosion rates and overbank sediment deposition. Solutions to these problems require a comprehensive river management program that reinstates natural processes of meandering and bank erosion. Relevance: moderate.

Cramer, M., K. Bates, D. E. Miller, K. Boyd, L. Fotherby, P. Skidmore, and T. Hoitsma. 2002. Integrated streambank protection guidelines. Washington State Aquatic Habitat Guidelines Program, Olympia. Online at <http://wdfw.wa.gov/publications/00046/wdfw00046.pdf> [accessed 15 September 2011].

Guidelines that, while scientific in approach, can be understood and used by volunteers, planners, designers, and managers of aquatic restoration projects and facilities. Each guideline is based on current best science and technical practice surveyed in topical, state-of-the-knowledge white papers or a thorough literature search. Their content includes background science and literature, policy issues, site and vicinity environmental-assessment processes, project design processes and standards, and case studies. Relevance: high.

Eubanks, C. E., and D. Meadows. 2002. A soil bioengineering guide for streambank and lakeshore stabilization. U.S. Forest Service, Technology and Development Program, San Dimas, CA. Online at <http://www.fs.fed.us/publications/soil-bio-guide/> [accessed 2 September 2010].

A comprehensive guide on planning and implementing soil bioengineering that includes detailed specifications on application techniques. Watershed/stream interaction is emphasized to help understand how reach-scale projects might best be designed and what effects might occur. The connection between upland and stream—the riparian ecosystem—is addressed in depth to frame the importance and challenges of streambank stabilization. Use of an interdisciplinary team is advocated to increase the odds of reaching the desired future condition, which must be clearly identified at project outset. Useful design specifications are presented, along with an example of monitoring forms. A recommended monitoring timeline is presented that should be performed for all projects to increase the chances of meeting project goals. Well-documented case studies offer sound project guidance. The guide concludes with an instructive listing of bioengineering techniques, each of which includes purpose, application, construction guidelines, inert materials list, installation directions, and photographic examples. Plant lists and blank field forms are in the appendices. Relevance: moderate.

GASWCC (Georgia Soil and Water Conservation Commission). 2000. Guidelines for streambank restoration. Georgia Soil and Water Conservation Commission, Atlanta, and Robbin B. Sotir Associates, Athens, GA.

This booklet is intended to help owners of streamside property prevent and, if necessary, correct simple streambank erosion problems. It describes the interactions of stream flows, streambanks, sediment, and streamside vegetation. Understanding this information helps a property owner appreciate the need for bank protection and assist in selecting the most appropriate natural methods for correcting bank erosion problems. Covered are streambank stabilization techniques that utilize live plant materials, structural measures, or a combination of both. The techniques described in this manual are intended for small stream systems with uncomplicated erosion problems. Relevance: low.

NRCS (Natural Resources Conservation Service). 1996. Chapter 16 of the Engineering field handbook: Streambank and shoreline protection. U.S. Dept. Agriculture, Portland, OR. Online at <http://wildfish.montana.edu/manuals/EFH-Ch16.pdf> [accessed 2 September 2010].

This document covers structure, soil bioengineering, and vegetation of streambanks. It offers restoration planning and design guidance in addition to detailed specifications of a variety of streambank protection techniques. Dimensions and installation recommendations are presented for many popular soft and hard bank stabilization methods. Appendix A contains the Isbash methodology to determining riprap size and Appendix B has a regional plant list for revegetating streambanks. Relevance: moderate.

Peters, R. J., B. R. Missildine, and D. L. Low. 1998. Seasonal fish densities near river banks stabilized with various stabilization methods. First year report of the Flood Technical Assistance Project. U.S. Fish and Wildlife Service, Lacey, WA. Online at <http://www.fws.gov/westwafwo/fisheries/Publications/FP125.pdf> [accessed 7 September 2010].

This study determined the type of bank protection used at 667 sites of rivers in Washington state and investigated the impacts of bank protection on fish densities. Riprap (414 sites) was the most common method. Large woody debris (LWD) (13) was the least popular method of bank protection. However, LWD sites showed increases in fish density during spring and summer sampling surveys, while densities at riprap sites were lower for all sampling seasons. From a fisheries standpoint, LWD is recommended as the preferred method of bank protection. If riprap is used, it must create more complex covers than those customarily associated with rock revetments. Relevance: moderate.

U.S. Bureau of Reclamation. No date. Bank stabilization design guidelines research. U.S. Bureau of Reclamation, Denver, CO. Online at <http://www.usbr.gov/pmts/sediment/kb/BankStab/index.html> [accessed 2 September 2010].

A project intended to improve the understanding of physical mechanisms in order to better meet project objectives and reduce maintenance requirements. Research products include design and performance parameters for a wide array of structures including deflector features (spur fields, barbs, dikes, bendway weirs, groins, hard points) and longitudinal features (stone toe, revetments, soil cement), as well as bioengineering description and design guidelines and resources for instream rock structures. Takes a multifaceted approach to developing a fuller understanding of rivers and bank stabilization. Relevance: moderate.

USFWS (U.S. Fish and Wildlife Service). 2001. Policy on streambank stabilization projects. U.S. Fish and Wildlife Service, Region 6, Denver, CO. Online at <http://www.fws.gov/mountain-prairie/pfw/PDFFiles/bankersos10threv.pdf> [accessed 2 September 2010].

USFWS guidance document endorsing concepts of naturally stable channels when reviewing or designing bank stabilization projects. The document advocates the Rosgen Classification System to promote consistent reporting of stream types and condition. The emphasis here is the Mountain-Prairie Region of USFWS. The importance of riparian habitat is discussed, as well as allowing continual tree recruitment of riparian species. A suggestion is made that hard materials are not used on streambanks unless they are rapidly eroding (i.e., several lateral feet every year). Guidance for this document was also obtained from Stream corridor restoration: Principals, processes, and practices. Relevance: low.

Walter, J., D. Hughes, N. J. Moore, F. Inoue, and G. Muhlberg. 2005. Streambank revegetation and protection: A guide for Alaska. Alaska Dept. Fish and Game, Juneau.

A variety of soil bioengineering techniques have been developed to protect and restore damaged streambanks for the benefit of fish. Selection of an appropriate technique depends largely on existing site conditions that dictate how, when, and to what extent a given technique is applied. Important factors to consider are stream hydrology, bank stability, icing conditions,

soils, surrounding vegetation, and the causative agent or agents responsible for the observed damage. It is necessary to have a clear idea of how the restored streambank will function once work on the site is complete. Design features must anticipate postrestoration use of the site (e.g., recreational use, boat tie-downs, erosion control, etc.) and incorporate design elements that provide for fish habitat while preventing additional damage. The techniques described may be used either singularly or in combination to achieve desired results. Relevance: moderate.

Riprap

Beamer, E., and R. Henderson. 1998. Juvenile salmonid use of natural and hydromodified streambank habitat in the mainstem Skagit River, northwest Washington. Report prepared for U.S. Army Corps of Engineers, Seattle, WA. Skagit System Cooperative, La Conner, WA. Online at http://www.skagitcoop.org/documents/EB217_Beamer_and_Henderson_1998.pdf [accessed 7 September 2010].

Examines juvenile salmonid use and habitat changes associated with bank protection in the mainstem Skagit River. Natural and modified banks were paired by location over an 80-mile river length. Bank habitat was defined as either natural or hydromodified based on the presence of riprap or other human induced bank modification and distinguished from mid-channel units (e.g., riffle, glide, and pool) by differences in water current velocity. Natural banks had a higher percentage of their area in wood, cobble, boulder, aquatic plants, undercut bank, and no cover types when compared to hydromodified banks. Wood cover in hydromodified banks increases with time after modification. Riprap, rubble, and wood cover were not correlated with water surface velocity. However, the bank gradient and stream discharge were correlated. For juvenile Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) in bank habitat, fish abundance has a significant positive correlation with the amount of wood cover. Wood cover in hydromodified banks explained 82% of the variation in Chinook salmon abundance. For juvenile coho salmon at the end of summer rearing, wood cover in both bank types explained 62% of the variation in fish abundance. There is evidence of preference for riprap (but not rubble) and some specific types of wood cover by rainbow trout (*O. mykiss*), suggesting that they may not be adversely impacted at the site level by bank modification provided rocks are large. Fish abundance is greater in rootwad cover than single logs for all species and life stages, except subyearling chum salmon (*O. keta*). Subyearling chum salmon prefer aquatic plants and cobble, two cover types more common in natural banks. The findings also suggest that the use of natural cover types along with bank protection may mitigate some site (but not reach) level impacts of bank protection. These results can inform use of rock in restoration projects. Relevance: moderate.

Fischenich, J. C. 2002. The effects of riprap on riverine and riparian ecosystems. ERDC/EL TR-WRAP-02-XX. U.S. Army Engineer Research and Development Center, Vicksburg, MS. Online at <http://el.ercd.usace.army.mil/wrap/pdf/trel03-4.pdf> [accessed 2 September 2010].

Evaluates the environmental impacts associated with riprap applications for streambank stabilization. Riprap has mixed effects on aquatic organisms, with the majority of coldwater applications leading to negative impacts and most warm water applications being beneficial. The discrepancy is likely a function of many factors (e.g., existing habitat and riprap specifications), thus potential impacts on biological communities must be addressed on a site-by-site basis. The effects of riprap on stream function also vary. Riprap alters stream morphologic evolution by reducing or eliminating lateral stream migration and prevents riparian plant succession. Riprap has limited impacts on the hydrologic balance, with the exception of the chance for increased local water surface elevations due to near-bank velocity reduction and backwatering. Sediment dynamics tend to be altered by riprap application where local scour and deposition are frequently encountered and persist for various lengths of time after installation. Riprap can improve habitat

by offering underwater interstitial voids for macroinvertebrates and juvenile fish; however, in many instances the loss of bank and riparian vegetation reduces cover and terrestrial food inputs. Water quality impacts of riprap are presumed to be minor. Some construction specifications are given for stone size, revetment dimensions, deflectors, incorporation of vegetation, grade control, and sound installation procedures. Relevance: high.

- Li, H., C. Schreck, and R. Tubb. 1984. Comparison of habitats near spur dikes, continuous revetments, and natural banks for larval, juvenile, and adult fishes of the Willamette River. Final technical completion report, project G864-05. Oregon State Univ., Water Resources Research Institute, Corvallis. Online at http://ir.library.oregonstate.edu/jspui/bitstream/1957/582/1/WRRI-95_ocr.pdf [accessed 2 September 2010].

This older study established early on that natural banks, because they are diverse in structure, afford the best habitat for resident fishes of the mid-Willamette River. The numbers of fish species and densities of larval and juvenile fishes at spur dikes are intermediate between natural banks and discontinuous revetments. The number of adult fish species were similar to those found at the continuous revetments. The one important difference was that juvenile Chinook salmon use this area during early spring and were observed to feed in slack water between spur dikes during a hatch of mayflies. Juvenile Chinook salmon were not captured from continuous revetments. Woody debris accumulated between spur dikes. The authors hypothesize that as the debris accumulates and as the riparian vegetation develops, habitat for adult fishes will improve, especially during winter. Because habitat needs changed during growth and physical gradients such as temperature and velocities became less severe as time passed, relationships between habitat variables and juvenile fish density changed between major sampling periods. Two factors were consistent: juvenile fish avoided velocities greater than 11 cm/sec and were found at depths no greater than 30 cm. Relevance: low.

- Lister, D. B., B. J. Beniston, R. Kellerhals, and M. J. Miles. 1995. Rock size affects juvenile salmonid use of streambank riprap. *In* C. R. Thorne, S. R. Abt, S. T. Maynard, K. Pilarczyk, and F. Barends (eds.), *River, coastal, and shoreline protection: Erosion control using riprap and armourstone*, p. 621–632. Wiley & Sons, New York.

This chapter investigates how salmonids use riprap at various stages in their lives and shows that if they are of sufficient size, rock can provide some useful habitats. However, the chapter is not available on the Web and the book is expensive and not widely available in U.S. libraries. Relevance: low.

- Schmetterling, D. A., C. G. Clancy, and T. M. Brandt. 2001. Effects of riprap bank reinforcement on stream salmonids in the western U.S. *Fisheries* 26(7):6–13.

A literature review shows the effects of riprap on salmonid habitat and populations. Riprap may provide habitat for juvenile salmonids and bolster densities on reaches of streams that have been severely degraded. However, it does not provide the intricate habitat requirements for multiple age-classes or species that are provided by natural vegetated banks. Streambanks with riprap have fewer undercut banks, less low-overhead cover, and are less likely than natural streambanks to contribute large woody debris to the stream. Although permitting of individual projects may attenuate localized negative effects to banks, it may not effectively curtail cumulative effects to a watershed. Use of riprap on banks goes against current practices and philosophies of stream renaturalization and impedes future restoration work. Relevance: high.

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