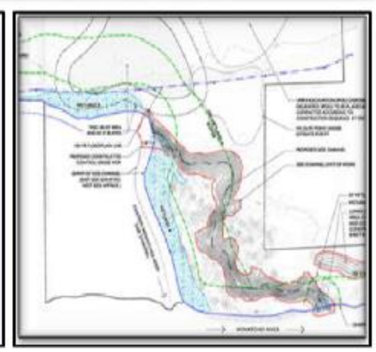
LARGE WOOD NATIONAL MANUAL

ASSESSMENT, PLANNING, DESIGN, AND MAINTENANCE OF LARGE WOOD IN FLUVIAL ECOSYSTEMS:

RESTORING PROCESS, FUNCTION, AND STRUCTURE



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U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

US Army Corps of Engineers®
Engineer Research and Development Center

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ASSESSMENT, PLANNING, DESIGN, AND MAINTENANCE OF LARGE WOOD IN FLUVIAL ECOSYSTEMS:

RESTORING PROCESS, FUNCTION, AND STRUCTURE

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Preface

The historical legacies of anthropogenic removal of large wood from rivers, reduction of wood inputs through land use alterations and channel hardening, the loss of large riparian trees that once formed stable snags, and alterations in wood transport ranging from levees to dams all have contributed to the degradation of riverine ecosystems and decline of native species. Wood was not just debris that rivers carried to the sea; it also altered channel morphology, fluvial processes, the storage of sediment and organic matter, and even the evolution of landscapes. The role of wood in creating aquatic and riparian habitat has led many regulatory agencies and fisheries advocates to recommend the reintroduction of large wood. It makes sense that the methods and manner in which wood gets reintroduced would differ based on hydro-geomorphic conditions and project goals. But the wide range of wood projects and their performance cannot be explained just by differences in site conditions and goals.

This manual is intended to help establish more consistent methods to assess, design, and manage wood projects to restore streams and rivers throughout the United States. Various federal and state agencies are increasingly advocating that more wood be used as a softer, more cost-effective, and ecologically beneficial engineering approach in restoration and mitigation projects to meet environmental mandates and endangered species requirements, while maintaining traditional agency missions. The term *softer* should only imply that wood is a natural part of a stream and, therefore, better fits within the context of restoring natural conditions. But there should not be anything soft about the analysis and design of wood projects: they should be conducted with the same scientific and engineering rigor as any river project. The failure of wood placements in restoration is entirely the fault of the design, not the material. By understanding the geomorphology, hydraulics, and geotechnical aspects of a project and with good engineering, stable wood structures can be designed for various situations and longevities. In many situations it may be desirable to place wood that can move, but designers should understand the fate and function of such programs. In the end, it is stable wood that most directly benefits restoration, and the underlying goal of wood projects should be to restore the function of wood until riparian forests are able to supply the large trees that can sustain those functions. In highly constrained systems where that may not be possible, engineering solutions can still be pursued to restore the function of wood well into the future.

The roles of the U.S. Bureau of Reclamation (Reclamation) and U.S. Army Corps of Engineers (USACE) in protecting native and listed species while meeting water delivery and managing flood risk, navigational, and ecosystem restoration mandates have become increasingly diverse and in demand over the past few decades. Reclamation and the USACE have missions that span the United States. Staff tasked with developing designs for projects, providing technical support, or executing regulatory review must ensure that these projects meet habitat improvement goals—and, in some cases, population improvement metrics—with minimal risks and maximum benefits at reasonable cost. As public stewards, Reclamation and the USACE are also tasked with ensuring due diligence with design of these projects to prevent unanticipated harm to private landowners, infrastructure, or recreationalists on the river. Noting Reclamation's and the USACE's shared missions, mandates, and broad geographic focus, an interagency team of leaders and senior scientists recently recommended a cooperative effort to better understand existing practice; develop collaborative assessment, design, and construction guidelines; and improve standards for wood-based restoration engineering. In the past, the majority of large wood design and implementation has occurred by practitioners. With increased involvement from the federal sector in these types of projects, it is prudent to have a common set of guidelines for the use of wood in restoration efforts that are used by agency staff and serve as a foundation for future planning, design, implementation, and regulatory review. This document is intended to serve as the initial step in the process of agency acceptance of developing standardized practices for the maintenance of existing, and placement of new, wood structures in fluvial ecosystems by providing technical guidance. If appropriate, formal agency acceptance of these guidelines will be determined at a later date.

This document is also meant to serve as a practical resource for planners and to help practitioners in the restoration industry to understand more fully the roles of wood and how it should be reintroduced and managed in fluvial ecosystems using both active (placement) and passive (recruitment and transport) methods. In summary, this effort's goal was to develop a comprehensive publication for the planning, design, placement, maintenance, and assessment of large wood in rivers and streams, with an overarching emphasis on restoring ecosystem forms, processes, and functions, given the current states of science and practice. In fields as fast-changing as restoration ecology, design, and practice, the authors here recognize—and hope—that this material will be improved with additional knowledge and experience. That recognition, however, does not address the current need for technical guidance. We believe the basic elements of this publication will hold true long into the future—particularly the underlying premise that wood is a critical component of fluvial systems that will only become more appreciated with additional research. As such, Reclamation and the USACE hope that this document provides needed technical assistance to restoration practitioners as well as acts as a catalyst to drive further innovations and improved benefits for aquatic ecosystem restoration.

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DISCLAIMER

This document provides information to states, territories, authorized tribes, local governments, watershed organizations, and the public regarding technical tools and sources of material for the planning, design, placement, and maintenance of large wood in rivers. The document may refer to statutory and regulatory provisions that contain legally binding requirements. The document does not substitute for those provisions or regulations, nor is it a regulation itself. Thus, it does not impose binding requirements on federal agencies, states, territories, authorized tribes, local governments, watershed organizations, or the public and might not apply to a particular situation based upon the circumstances. Federal agencies, state, territory, local government, and authorized tribe decision makers retain the discretion to adopt approaches on a case-by-case basis that differ from this guidance. The use of nonmandatory words like *should, could, would, may, might, recommend, encourage, expect*, and *can* in this document means solely that something is suggested or recommended; it does not mean that the suggestion or recommendation is legally required, that it imposes binding requirements, or that following the suggestion or recommendation necessarily creates an expectation of any federal agency approval.

This document is not intended to replace any existing planning guidelines previously adopted by federal agencies, such as the Natural Resource Conservation Service's *Stream Restoration Design Handbook* (NEH 654); U.S. Army Corps of Engineers' (USACE's) *Engineer Regulations (ERs) 1105-2-100*, *1165-2-501*, and *1165-2-100*; and U.S. Environmental Protection Agency's *Handbook for Developing Watershed Plans to Restore and Protect our Water* (2008) and *A Quick Guide to Developing Watershed Plans to Restore and Protect Our Waters* (2013). Rather, it addresses how the use of large wood can be considered in concert with these restoration planning processes.

Interested parties are free to raise questions and objections about the appropriateness of applying the guidance provided herein to a specific situation, and Reclamation and USACE will consider whether the recommendations in this guidance are appropriate in that situation. Reclamation and USACE may change or add to this document in the future.

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The idea for preparing this manual came from an interagency meeting of researchers and leaders from the Bureau of Reclamation (Reclamation) and the U.S. Army Corps of Engineers (USACE) Environmental Laboratory, Engineer Research and Development Center, held in Sacramento, California in May 2011. Participants at that meeting identified research and guidance on the roles and utilization of large wood in riverine systems as a first-priority national restoration need. Staff from Reclamation's Sedimentation and River Hydraulics Group and other offices and the USACE Environmental Laboratory then organized a workshop in Seattle in February 2012, where 40 experts from federal, state, and local agencies; tribal governments; academia; and the private sector gathered to refine research and application needs. The lack of current design and application guidance was identified by that group as a critical problem. That group helped with this publication's initial scoping and served in various other roles.

David (DJ) Bandrowski and Jock Conyngham served as agency leads and proponents for Reclamation and USACE, respectively, for the development of this document. Their responsibilities including translating the recommendations from earlier meetings into action; refining the manual's scope; securing funding from multiple sources; developing and executing a support contract; and identifying appropriate authors, co-authors, and peer reviewers. Finally, they each served as Chapter Authors and Lead Technical Editors, and steered the manual through internal agency channels. Reclamation's primary financial support came from the Pacific Northwest Region's Columbia-Snake Recovery Office (CSRO) in Boise, Idaho, in addition to the Research and Development Office, Science and Technology Program at the Denver Technical Service Center. USACE support for the publication came primarily from the Engineering With Nature (EWN) Program, in addition to the Ecosystem Management and Restoration Research Program (EMRRP), both located at the Environmental Laboratory in Vicksburg, Mississippi.

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USER'S GUIDE

As mentioned in the preface, this national publication provides a basic understanding of the role of wood in fluvial aquatic and riparian ecosystems and how it should be maintained, reintroduced, and/or managed. It highlights the best available science, creative engineering, and policies associated with restoring wood in rivers and streams (hereafter *streams* – see Glossary) as well as underscores the significance of wood in fluvial ecosystems. It is also a source of practical information on how to assess the need for wood, use wood in restoration projects, and manage wood that naturally enters streams. To this end, this national publication provides resource managers and restoration practitioners with comprehensive guidelines for the planning, design, placement, and maintenance of large wood in streams with an emphasis on restoring ecosystem process and function. The document is organized into 10 chapters.

Chapter 1. *Large Wood Introduction*

This chapter provides an overview of the importance of wood in fluvial ecosystems as well as a historical perspective on the use of wood in stream channels. As such, it provides a broad overview of the use of wood in restoration projects. Main subjects include:

- ✓ **Ecological Restoration** – introduces the concept of ecological restoration and the key ecosystem divisions across the United States.
- ✓ **Large Wood** – describes the importance of riparian forests and wood recruitment in fluvial ecosystems.
- ✓ **Ecological Functions of Wood** – provides an overview of important biological and physical functions of wood in fluvial ecosystems.
- ✓ **History of Wood Management and Restoration in Streams and Rivers** – provides a summary and overview of the use of large wood in aquatic ecosystem restoration projects.

Chapter 2. *Large Wood and the Fluvial Ecosystem Restoration Process*

This chapter provides a general overview of the ecological restoration-planning and decision-making process and how it applies to the overall planning and implementation of projects that use large wood to restore process and function to fluvial aquatic ecosystems. It describes 12 important components to consider when developing successful restoration projects. Inherent to the restoration process is the recognition that suitable solutions may include a wide range of design elements, from simple changes in resource management practices to major structural alterations, the selection of which depends on the nature of each individual project. To this end, an integrated approach to the planning and decision-making process provides the foundation for selecting and using appropriate tools and procedures for placing wood in streams. Main subjects include:

- ✓ **Ecological Restoration Process** – describes ecological restoration and 12 important considerations in the restoration process.

- ✓ **Restoration Decision Making** – at each step in the ecological restoration-planning process critical decisions need to be made that will influence the outcome of a project. This section discusses considerations for: (1) Planning Team Composition, (2) Scaling the Process, and (3) Integrating Economics into the Restoration Process.

- ✓ **Making Informed Restoration Decisions: A Structured Process** – describes the application of using a structured process as well as decision support tools for making informed restoration decisions.

Chapter 3. *Ecological and Biological Considerations*

Restoration of large wood is often undertaken to achieve biological goals. Hence, the inherent assumption of restoration of large wood is that habitat features in streams associated with wood are positively related to the survival, persistence, and abundance of desired aquatic species and communities and ecological functions. This chapter discusses the ecological and biological considerations associated with large wood in streams. It focuses on stream ecology and the role of wood as a biological habitat, specifically examining the role of wood in salmonid ecosystems and deriving general principles that are applicable to other systems and species. Main subjects include:

- ✓ **Ecological Functions of Large Wood** – highlights the fact that large wood is a key structural element in forested stream ecosystems worldwide. Large wood serves as a food resource for microbes, fungi, and macroinvertebrates, As such, this section discusses the role of large wood in habitat formation, aquatic food webs, and biogeochemical processes.
- ✓ **Hyporheic Zone** – this zone extends streams below the surface flow to include the "sponge" of saturated substrate. This section describes the ecological functions associated with wood and the hyporheic zone.
- ✓ **Regional Differences in Large Wood Ecology** – the biological and physical roles of large wood in streams apply to a wide range of geographies and stream types. This section describes the differences between geographic regions within the United States.
- ✓ **Considering Assessing the Need for Wood Placement** – describes important considerations in determining the need to supplement wood in aquatic ecosystems, including: Fish Population Dynamics and Instream Wood, Linking Habitat to Fish Population Dynamics, Fish Assemblages and Large Wood, Wood as Habitat for Aquatic Invertebrates and Terrestrial Species, and Assessing the Effectiveness of Wood Restoration.
- ✓ **Scale and the River Continuum Concept** – discusses the importance of scale as well as the river continuum process as it relates to the placement of wood in channels.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 4. *Geomorphology and Hydrology Considerations*

This chapter explores how trees and wood influence geomorphology and hydrology through such activities as trapping sediment and organic matter, reducing rates of bank erosion, limiting long-term rates of incision that influence valley formation, and providing habitat resilience to extreme elements. The chapter provides an understanding of how wood can naturally influence a fluvial aquatic system and how it can be used to restore it. The chapter also outlines areas of uncertainties and where further research is necessary. In particular, information and descriptions regarding wood loading and longevity in streams is lacking for many regions of the country including the Southwest, the Sierra Nevada, the Great Plains, the lower Midwest, the South, the Mid-Atlantic, and the Alaskan Interior. A final key points section provides a concise outline of the chapter, summarizing the geomorphic effects of wood in streams, and the factors that influence the morphology and dynamics of a stream. Main subjects include:

- ✓ **Geomorphology** – discusses the process and factors influencing the formation and change of fluvial geomorphology, including the flow of water through a channel network; the movement of sediment and woody debris; the factors controlling channel form, the stability of steam beds and banks, and the rate and magnitude to which channels move; and how large wood and logjams influence flow conditions to alter the channels and floodplains.
- ✓ **Hydrology** – discusses the timing, rate, and mechanism of water movement through watersheds and their role in the geomorphic processes for large woody material design. The section describes how hydrological processes, namely streamflow hydrographs and flood wave dynamics, are affected by riparian vegetation and large wood and explores the implications of this in terms of ecological benefit and altered levels of flood protection.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 5. *Watershed-Scale and Long-Term Considerations*

This chapter addresses issues of large wood supply and recruitment as well as the long-term viability of large wood restoration projects. It discusses effects of climate change, effects of stochastic flooding and storms on pulsed colluvial and alluvial recruitment, planning and infrastructure design for large wood mobilization during peak flows, and the use of large wood in flood response. The chapter also outlines areas of uncertainty and where further research is necessary, such as the transportation dynamics of pulsed wood inputs from stochastic events, the effects of climate change on future peak flow hydrology, and vegetative stress induced by base flow alteration resulting from climate change. A final key points section provides a concise outline of the chapter, summarizing the capacity of a watershed system to produce, supply, recruit, and transport large wood elements as well as the benefits in terms of stability and habitat values resulting from large wood-based projects. Main subjects include:

- ✓ **Corridor and Basin Management Concepts** – explains the reasons for and the effects of the truncation of wood supply to U.S. rivers through forest clearing and development.
- ✓ **Flood Dynamics and Response** – explores how forest dynamics, hillslope dynamics, river-network dynamics, diota, and channel dynamics interact to govern the mechanisms, rates, and quantities of wood recruitment. This section also describes the mechanisms for retention of large wood loads and the role of floods in large wood management.
- ✓ **Large Wood and River Crossing Interaction** – discusses the influence of large wood on channel equilibrium, stability, and instream habitat and how removal of large wood can negatively affect long-term channel bed and bank stability.
- ✓ **Large Wood's Impact on Bridges and Culverts** – discusses the role of wood accumulation near bridges and culverts, leading to scour-inducing turbulence and contributing to bridge failure.
- ✓ **Watershed-Scale Risk to Structures** – discusses the sources of large wood pieces in rivers and forested riverbanks and the risk of large wood blockage on bridges and culverts,
- ✓ **Structure Vulnerability and Design Recommendations** – discusses the vulnerability of bridges and culverts to large wood jams and debris in relation to watershed and channel characteristics and structure geometry.
- ✓ **Floods, Recovery, and Large Wood** – discusses post-flood evaluation of large wood loads within the context of watershed wood budget of source, transport, and retention. The section discusses

wood retention/removal alternatives in terms of the potential of long-term channel destabilization and loss of habitat.

- ✓ **Climate Change** – discusses the pathways by which climate change may alter stream ecosystem structure and function. The section examines how climate change will potentially impact ecological processes related to large wood.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 6. *Engineering Considerations*

This chapter provides an introduction to the engineering design of large wood placements in streams and rivers. Large wood restoration projects require an interdisciplinary design capable of responding to biological, physical, and social factors potentially affecting the security and long-term viability of the structure. It explores hydraulic analysis, landscape architecture, types of structures utilized, and other elements specific to the engineering challenges of large wood restoration projects. The chapter also discusses areas where more information is needed and further research is necessary, for example, the need for a basis to estimate the time required for natural regrowth of forests to sustain instream wood levels. Specific information needs regarding wood piling size, species, and condition are also noted. A final key points section provides a concise outline of the chapter, highlighting the role of wood in assisting the recovery of degraded systems, the role of decay and erosion in large wood projects, and the use and necessity of hydrologic and geomorphic modeling. Main subjects include:

- ✓ **Design Life of Placed Wood** – discusses the decay rates of large wood projects and the goal of replacing natural wood sources and associated processes that will naturally replenish instream large wood and floodplain.
- ✓ **Level of Design Effort** – discusses the appropriate level of effort and analysis for the design of large wood structure projects.
- ✓ **Design Decisions and Data Requirements** – provides a series of data gathering and analysis exercises to guide design decisions. Key design decisions relate to hydrology, reach layout, materials, structure dimensions and details, hydraulics, sediment, vegetation, anchoring, construction, and economics.
- ✓ **Special Considerations or Urban Streams** – provides some key parameters to consider in the design of large wood structures in the urban environment. Considerations include extreme modifications to water, sediment, and wood loading and the potential impacts on public infrastructure and safety.
- ✓ **Integrating Landscape Architecture** – discusses large wood structure in the context of multiuse landscape. The section discusses the interaction between the built and natural environmental in terms of large wood structures.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 7. *Risk Considerations*

This chapter provides an overview of how to assess risk when integrating wood into stream and river restoration projects. It describes risks associated with the use of wood in stream and river restoration projects such as loss or washout of wood placement, unintended geomorphic changes in river corridor conditions, rise in water elevation, and alteration of sediment transport. The chapter also outlines areas of uncertainty where further research is necessary, including the need for region-specific information on the impacts of wood removal (including channel incision resulting from in-stream wood removal) and data on existing wood loading specific to location, size, and mobility of large wood pieces. The need for guidelines pertaining to culvert design, wood-management following storms and floods, and legal liability of wood placement are also noted. Main subjects include:

- ✓ **Defining and Assessing Risk** – discusses quantitative and qualitative approaches to assessing risk, key elements of a risk assessment, and professional liability.
- ✓ **Bridges and Culverts** – discusses the role of describing downstream crossings in risk assessments.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 8. *Regulatory Compliance, Public Involvement, and Implementation*

This chapter addresses the federal, state, and local regulations that control or may influence placement, operation, and long-term operation and maintenance of large wood. It describes the regulatory background, offers potential scenarios under which the regulations may apply, and provides potential best management practices designers and installers should consider.

Public involvement through outreach during a large wood project may occur for several reasons. In general, outreach will be associated with public noticing required by regulations, public outreach to solicit design input and to build project support, and outreach to inform river users about the presence of large wood to help ensure their long-term safety.

The chapter then turns to incorporating large wood structures into a larger aquatic or riparian restoration project. The discussion includes grading in the project reach to accommodate a large wood installation, implications for revegetation and irrigation system placement, erosion control, interpretive and educational opportunities, and landscape aesthetics. Graphic standards for use in construction document preparation are also described. The chapter also discusses areas of uncertainty and where further research is necessary, such as guidance for the use of drones and webcams in monitoring implementation, the development of approaches to inducing (rather than constructing) large wood accumulations, and research into enhanced techniques for rapid revegetation of riparian zones and floodplains. A final key points section provides a concise outline of the chapter, summarizing the issues of contractual arrangements for procuring implementation services, maintaining a daily log as part of implementation project management, and safety considerations. Main subjects include:

- ✓ **Regulatory Compliance and Public Considerations** – describes the types of federal, state, and local regulations that control or may influence the initial placement and long-term operation and maintenance of large wood.
- ✓ **Public Involvement and Input** – discusses the methods of public outreach during a large wood project, including public noticing required by regulations, public outreach to solicit design input and to build public support, and outreach to inform river users about the presence of large wood to help ensure long-term safety.
- ✓ **Examples of Regulatory Compliance Approaches** – provides two example of regulatory compliance approaches for large wood projects.
- ✓ **Construction** – examines legal issues and disputes arising from accidental injuries, cost overruns, project failure, and construction-related risks.

- ✓ **Safety** – discusses potential safety issues, best management practices, personal protective equipment, log handling, and other potential hazards associated with logging, construction, and amphibious operations.
- ✓ **Managing Environmental Impacts** – discusses actions that may be used to minimize impacts on water quality and ecological resources during construction of large wood projects.
- ✓ **Maintenance and Adjustments** – discusses maintenance, adjustment, and adaptive management techniques that may be necessary to maintain large wood project functioning as intended.
- ✓ **Key Findings and Uncertainties** – summarizes and highlights key findings and uncertainties.

Chapter 9. *Assessing Ecological Performance*

This chapter discusses evaluation approaches to the ecological performance of large wood restoration projects that address the uncertainty and associated risks that remain an inevitable part these projects. The chapter identifies carefully designed evaluations and/or experiments, performance indicators, and research designs, which would assist managers in making informed decisions regarding large wood restoration projects. Main subjects include:

- ✓ **Incorporating Best Science Practices** – discusses the use of best science practices in restoration projects, including using conceptual models and following scientific principles and guidelines.
- ✓ **Measurable Outcomes and Performance Indicators** – discusses the selection of appropriate measurable outcomes and performance indicators pertaining to water quality, periphyton, aquatic macroinvertebrates, and fish and aquatic vertebrate assemblage.
- ✓ **Monitoring** – discusses varieties of monitoring activities from ecosystem restoration projects, including compliance monitoring, effectiveness monitoring, and long-term status and trend monitoring.
- ✓ **Research and Experimentation** – discusses the role of research and experimentation in natural resources management actions.
- ✓ **Making Decisions and Choices** – explores the role of adaptive management in restoration projects.

Chapter 10. *Large Wood Bibliography*

This chapter provides a bibliography of relevant scientific publications on the use of wood in stream and river channels.

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GLOSSARY

Adaptive capacity	An asset or resource's ability to adjust and cope with existing climate variability or future climate impacts.
Adaptive management	An approach to management that addresses changing site and project conditions, as well as taking into account new knowledge; a management approach that incorporates monitoring of project outcomes and uses the monitoring results to make revisions and refinements to ongoing management and operations actions.
Adfluvial fish	Species that hatch in rivers or streams, migrate to lakes as juveniles to grow, and return to rivers or streams to spawn.
Aggradation	Long-term sediment deposition that occurs on the bed of a channel; the opposite is degradation or bed erosion.
Alignment	*Planform* of a *channel*.
Allowable shear stress design method	A threshold channel design technique whereby channel dimensions are selected so that the average applied grain bed shear stress is less than the allowable shear stress for the boundary material.
Allowable velocity	The greatest mean velocity that will not cause a channel boundary to erode.
Allowable velocity design method	A threshold channel design technique whereby channel dimensions are selected so that the applied velocity during design conditions is less than the limiting velocity of the channel boundary.
Alluvial channel	Streams and channels that have bed and banks formed of material transported by the stream under present flow conditions. There is an exchange of material between the inflowing sediment load and the bed and banks of an alluvial channel.
Alluvial channel design	A design approach whereby a channel configuration is selected so that it is in balance with the inflowing sediment and water discharges.
Alluvium	Loose, unconsolidated (not cemented together into a solid rock) soil or sediments, which has been eroded, reshaped by water in some form, and redeposited in a non-marine setting; typically made up of a variety of materials, including fine particles of silt and clay and larger particles of sand and gravel. When this loose alluvial material is deposited or cemented into a lithological unit, or lithified, it is called an *alluvial deposit*.
Amphidromous fish	Species that move between fresh and salt water during some part of their life cycle, but not for breeding.
Anabranching channel	A stream or river that has two or more channels at bankfull or effective discharge flow. Unlike braided channels, anabranching channels are separated by vegetated islands. While a braided channel becomes a single wide channel at bankfull flow, anabranching channels still retain multiple channels. Generally this term is synonymous with *anastomosing*.

Anadromous fish	Species that incubate and hatch in freshwater, migrate to saltwater as juveniles to grow, and return to freshwater as adults to spawn.
Analogy design method	A design approach that is based on the premise that conditions in a reference reach with similar characteristics and watershed conditions can be copied or adapted to the project reach.
Analytical design method	The use of bed resistance and sediment transport equations to calculate channel design variables.
Anastomosed channels	See *Anabranching*.
Annual duration gage analysis	The analysis of the recorded peak flow values that have occurred for each year in the duration of interest; typically used for the estimate of flows with return intervals in excess of 2 years.
Annual flood	The highest peak discharge that can be expected to occur on average in a given year.
Anoxic	Depleted of dissolved oxygen.
Anthropogenic constraints	Constraints on a stream or river that are caused by human (i.e., *anthropogenic*) activities or constructed projects.
Areal sediment sampling	See *Surface sediment sampling*.
Arid	An area that generally has insufficient rainfall to support conventional agriculture without supplemental irrigation.
Armor layer	A streambed containing at least some sediment that is too large to be transported by the hydraulic flow conditions; finer particles are selectively removed leaving a layer of coarser materials.
Armor layer (sampling)	Technique used to sample the upper layer of coarse surface layer material.
Articulating concrete block (ACB)	A matrix of interconnected concrete block units installed to provide an erosion-resistant revetment for streams and rivers.
Asymptote	In a curve, an asymptote is a line such that the distance between the curve and the line approaches zero as they tend to infinity.
Attenuation	The subsidence or flattening of a floodwave as it moves down the channel.
Avulsions	The rapid abandonment of, and formation of a new, river channel; occur when bank erosion and longitudinal adjustment occur at a large scale; typically characterized by rapid changes in channel planform.
Band-aid solution	Treatment techniques used to address small, local issues.
Bank zone	The area above the toe zone, located between the average water level and the *bankfull discharge* elevation.
Bankfull	The water level, or stage, at which a stream, river, or lake is at the top of its banks and any further rise would result in water moving into the flood plain.
Bankfull depth	The distance from the deepest part of the channel to the bankfull elevation line, typically measured across a straight section (riffle) of a channel.

Bankfull discharge	Used as a surrogate for *channel-forming discharge*, defined, in part, by the visual identification of morphological bankfull indices, such as abrupt changes in bank angle or the presence of perennial plants.
Bankfull indices	Field indicators of bankfull discharge.
Bankfull width	The width of channel at bankfull elevation.
Bankline migration	The adjustment of planform in natural meandering channels.
Bar apex jam	Wood structure composed of 10–30 logs placed in the middle of the channel to initiate bar formation or placed on the upstream end of an existing bar or island.
Barb	A type of flow deflection structure (see *Stream barb*).
Base flood	The flood having a 1% chance of being equaled or exceeded in any given year.
Base flow	See *Low flow*.
Batter pile	An inclined pile that can provide downward resistance to buoyancy when used with another (“A” frame) or with a vertical pile.
Bed control structure	A type of grade control structure that is designed to provide a hard point in the streambed that is capable of resisting the erosive forces of the stream.
Bed zone	The bottom of the channel.
Bedding layer	See *Filter layer*.
Bedform scour	Vertical channel bed movement that results from the troughs between crests of the bedforms.
Bedrock	A solid rock on the face of or beneath the Earth’s surface.
Bend scour	Bed erosion along the outside of a river or streambed.
Bendway weirs	A flow-changing bank stabilization technique used to protect and stabilize stream and river banks. Flows are directed over the *weir* perpendicular to the angle of the weir.
Benthic zone	The ecological region at the lowest level of a body of water such as an ocean or a lake, including the sediment surface and some sub-surface layers. Organisms living in this zone are called *benthos*.
Biofilm	Bacteria, fungi, and often algae that grow on submerged woody surfaces.
Biogeomorphology	The study of interactions between organisms and the development of landforms, and are thus fields of study within *geomorphology* and *ichnology*. Organisms affect geomorphic processes in a variety of ways. For example, trees can reduce landslide potential where their roots penetrate to underlying rock, and plants and their litter inhibit soil erosion.
Biota	The plants and animals of a region.

Blockage coefficient	Typically expressed as percentage of effective flow area (for design discharge) obstructed by a structure such as wood or logjam. Can be expressed in terms of width (structure width/channel width) or area (structure x-sectional area/channel cross-sectional area), with structure measured orthogonal to flow.
Braided streams	Wide shallow channels with multiple unvegetated bars. At low flows they have multiple channel threads, but at a bankfull or effective discharge the bars are submerged and flows coalesce to form a single channel. Braided channels form in areas with high sediment supplies and relatively steep gradients, such as downstream of alpine glaciers. The multiple channels of braided streams tend to be shallow and wide as opposed to the narrow and deep channels of an *anabranching* or *anastomosing* channel.
Branch packing	A soil bioengineering technique used to fill localized slumps and gullies; involves the use of alternating layers of live cuttings and soil.
Bridge pier scour	Erosion of a streambed around the piers of bridges.
Brush layering	A soil bioengineering technique that provides protection against surface erosion and shallow-seated slope failure; involves the use of alternating layers of live cuttings and soil.
Brush mattress	A streambank soil bioengineering technique that includes a layer of live cuttings placed flat against the sloped face of the bank.
Brush revetments	A soil bioengineering technique used to stabilize streambanks. Brush and tree revetments are nonsprouting shrubs or trees installed along the toe of the streambank to provide bank erosion protection and to capture sediments.
Brush spur	A long, box-like structure of brush that extends from within the bank into the streambed; functions very similarly to stone stream barbs.
Brush trench	A soil bioengineering technique that inserts a row of live cuttings into a trench along the top of an eroding streambank, parallel to a stream. The live cuttings form a fence that filters runoff and reduces the likelihood of drilling.
Brush wattle fence	See *Wattle*.
Bulk sediment sampling	See *Volumetric sediment sampling*.
Burst swimming speed	The highest swimming speed of a fish; generally lasts less than 20 seconds and ends in extreme fatigue.
Cable	Steel aircraft cable or wire rope used to secure large wood.
Catadromous fish	Species that hatch in saltwater, migrate to freshwater as juveniles to grow, and return to saltwater to spawn.
Catchment	See *Drainage area*.
Celerity	The speed that a floodwave moves down the channel.

Channel	Convergent topography where water is conveyed either all year (perennial) or seasonally (ephemeral). The principal part of all streams and rivers. Channel features include bars and bedforms. Unconfined channels include floodplains as opposed to confined channels which do not. Channels can be alluvial or bedrock. Channel types are defined by morphologic characteristics, bed and bank materials, and influence of vegetation. See *Classification*.
Channel alignment design	Techniques used to establish a stable channel planform.
Channel classification	See *Classification*.
Channel evolution	Systematic changes of a stream channel to a perturbation.
Channel evolution model (CEM)	A model that illustrates the stages through which a stream progresses when subjected to destabilizing influences.
Channel evolution model classification	A classification system that provides a predictable sequence of change in a disturbed channel system.
Channel-forming discharge	Concept based on the idea that for a given alluvial stream, there exists a single or range of discharge that, given enough time, would produce the width, depth, and slope equivalent to those produced by the natural flow in the stream. This discharge, therefore, dominates channel form and process.
Channel incision	The process of downcutting into a stream channel, leading to a decrease in the channel bed elevation. Incision is often caused by a decrease in sediment supply and/or an increase in sediment transport capacity. A decrease in base level can cause headcutting that migrates upstream and produces incision upstream and initiating aggradation downstream.
Channel morphology	The shapes of river channels and how they change over time. The morphology of a river channel is a function of a number of processes and environmental conditions, including the composition and erodibility of the bed and banks (e.g., sand, clay, bedrock); vegetation and the rate of plant growth; the availability of sediment; the size and composition of the sediment moving through the channel; the rate of sediment transport through the channel and the rate of deposition on the floodplain, banks, bars, and bed; and regional aggradation or degradation due to subsidence or uplift.
Channel slope	The average slope of the longitudinal thalweg profile.
Channel stage classification	A stream classification system based on the channel evolution model.
Channel stages	See *Channel evolution model*.
Channel storage	Water that is temporarily stored in a natural or constructed channel while en route to an outlet.
Channelization	The alteration of an existing river or stream for a specific physical, biologic, or aesthetic purpose, generally involving the removal of meander bends to straighten the flow path and increase bed slope to increase channel conveyance.

Check dam	A small dam constructed to slow stream velocity and/or prevent degradation.
Classification	The categorization of a stream reach into a specific class based on factors and measurements such as dominant mode of sediment transport, entrenchment ratio, and sinuosity. Streams can also be classified by their biota, habitat conditions, baseflow levels, and direct measures of water quality.
Clear water scour	Occurs when there is insignificant transport of bed-material sediment from the upstream into the contracted section.
Climate change	A change in the statistical distribution of weather patterns when that change lasts for an extended period of time (i.e., decades to millions of years). Climate change may refer to a change in average weather conditions, or in the time variation of weather around longer-term average conditions (i.e., more or fewer extreme weather events). Climate change is caused by factors such as biotic processes, variations in solar radiation received by Earth, plate tectonics, and volcanic eruptions. Certain human activities have also been identified as significant causes of recent climate change, often referred to as "global warming"
Coefficient of determination	Usually expressed as R2, this commonly used measure of the goodness of fit is a dimensionless ratio of the explained variation in the dependent variable over the total variation of the dependent variable.
Coir fascine	A soil bioengineering technique used to stabilize streambanks. A manufactured product consisting of coconut husk fibers bound together in a cylindrical bundle held by natural or synthetic netting.
Compaction	The process of densifying soil so that air is expelled and the pore space is reduced.
Compliance Monitoring	An activity often required by permits that focuses on and reports on whether restoration activities are being implemented as designed.
Conditional Letter of Map Amendment (CLOMA)	Provides Federal Emergency Management Agency's comment on whether a proposed project would be excluded from the Special Flood Hazard Area.
Conditional Letter of Map Revision (CLOMR)	Provides for a review of whether a proposed project within a Special Flood Hazard Area meets the minimum flood plain management criteria of the National Flood Insurance Program.
Confidence limits	Provides a measure of the uncertainty or spread in an estimate. In hydrologic gage analysis, confidence limits are a measure of the uncertainty of the discharge at a selected exceedance probability.
Confluence	The point where two streams or rivers merge. If they are of approximate equal size, this point may be called a fork.
Conservation management unit (CMU)	An area having similar land use and treatment needs and management plan.
Constraints	Limitations on the physical or biologic behavior and characteristics of a stream.

Constructed channel	A ditch or reconstructed natural channel.
Construction inspector	The person responsible for the day-to-day quality control inspection required to ensure that prescribed work is installed according to the design, industry standards, and contract requirements.
Contour fascine	See *Fascine*.
Contract types	The many methods used to direct and pay for the installation of stream restoration or stabilization. The contract types vary primarily by administrative burden, construction oversight, and incentive for the contractor to control cost.
Contracting officer (CO)	The person responsible for administering the contract, including ensuring that the proper type of contract is being used and funds are spent according to regulations.
Contracting officer's representative (COR)	The person responsible to the state engineer and the contracting officer to see that the work is carried out as designed and in accordance with the contract requirements.
Contraction scour	Erosion of a streambed that occurs when the flow cross section is reduced by natural features, such as stone outcrops, ice jams, or debris accumulations, or by constructed features such as bridge abutments.
Conveyance	A measure of the flow-carrying capacity of a cross section.
Cost reimbursement contract	A contract type whereby the contractor is paid for identified costs that are defined as reimbursable. See *Contract types*.
Crib wall	A soil bioengineering technique used to stabilize streambanks. A crib is a hollow, box-like structure of interlocking logs or timbers. The structure is filled with rock, soil, and live cuttings or rooted plants.
Crimping and seeding	A soil bioengineering surface roughening treatment that secures straw to the surface. This is a temporary surface treatment that protects and promotes the establishment of permanent grasses and vegetation.
Critical shear stress	The shear stress at the initiation of particle motion.
Critical uncertainties	Key questions that shape how an ecological system is actively managed (see *Adaptive management*).
Cross-section area	See *Flow area*.
Cross vane structure	A structure that provides grade control and a *pool* for fish habitat.
Crumb test	A common field test for dispersive clays.
Darting speed	See *Burst swimming speed*.
Dead stout stakes	Diagonally cut 2- by 4-inch lumber used to secure soil bioengineering practices.

Debris	Fragments of solid matter, typically rock or organic material found moving down a river. Commonly has a negative connotation synonymous with "refuse" or "garbage" that concerns some people when using it to describe natural materials found in rivers; therefore, "debris" is increasingly being replaced by "material" when referring to wood (see *Large woody debris* and *Large woody material*).
Deflector	A structure that forms a physical barrier to protect the bank and forces the flow to change direction either by direct impact or deflection.
Deforestation	The removal of a forest or stand of trees where the land is thereafter converted to a non-forest use. Examples of deforestation include conversion of forestland to farms, ranches, or urban use.
Degradation	Long-term sediment removal occurring through increased erosion from the channel bed.
Deposition	The geomorphic process in which sediments, soil, and rocks are added to a landform or land mass. Wind, ice, and water, as well as sediment flowing via gravity, transport previously eroded sediment, which is deposited, building up layers of sediment.
Depth	The distance between the channel bottom and the water surface.
Design flow	Stream restoration design should consider a variety of flow conditions. These flows should be considered from both an ecological and physical perspective.
Design layout	The physical location of design elements in a stream restoration project; the most common methods used to locate features on a drawing include referencing to a baseline or centerline, creating a grid, or using a global positioning system (GPS).
Design storm	A prescribed precipitation distribution and associated recurrence interval.
Dimensionless shear stress	The ratio of the critical shear stress and the product of the grain diameter and the submerged specific weight of the particle—also referred to as the Shields parameter.
Direct use	When humans directly use the end product of an ecosystem service, such as consuming fish and animals, harvesting timber, or using other forest products.
Discharge	The rate of flow, often expressed in cubic feet per second, or ft^3/s.
Displacement	Submerged volume of an object (large wood).
Disturbances	Changes to the physical or ecologic condition that are outside of the normal range of natural variations. Disturbances can be natural or anthropogenic.
Ditch	A long, relatively narrow, constructed channel.
Dominant channel processes	The forces at work in the watershed that cause and limit channel change.
Dominant discharge	See *Channel-forming discharge*.

Dormant post planting	A soil bioengineering technique involving the use of large dormant stems, branches, or trunks of live woody plant material that are planted for bank erosion control and creation of riparian vegetation.
Downwelling	The process of accumulation and sinking of higher density material beneath lower density material.
Drag	The fluid force component acting on a sediment particle, which is parallel to the mean flow.
Drainage area	The area from which surface rainfall runoff is contributed to a specific point.
Drained soil conditions	This is not a description of the water level in the soils, but rather a description of the pore pressure condition in the soil when it is loaded. A drained condition implies that either no significant pore pressures are generated from the applied load or that the load is applied so slowly that the pressure dissipates during the slowly applied loading. See *Undrained soil conditions*.
Duration	The length of time that water flows at a given discharge or a given depth.
Ecological evaluation	Classifying and/or assessing the relative worth, in non-monetary terms, of different ecological resources.
Ecological stress	The physical, chemical, and biological constraints on the productivity of species as well as alteration of ecosystem function.
Ecoregion	An ecologically and geographically defined area that covers a relatively large area of land or water, and contains characteristic, geographically distinct assemblages of natural communities and species. The biodiversity of flora, fauna, and *ecosystems* that characterize an ecoregion tends to be distinct from that of other ecoregions.
Ecosystem	A community of living organisms (plants, animals, and microbes) in conjunction with the nonliving components of their environment (things like air, water, and mineral soil), interacting as a system.
Effective discharge	The mean of the arithmetic discharge increment that transports the largest fraction of the annual sediment load over a period of years; often used as a surrogate for channel-forming discharge.
Effectiveness monitoring	Activity that assesses ecosystem-, natural community–, and covered species–scale responses to the implementation of conservation measures and monitors progress made toward achieving biological goals and objectives.
Embankment bench	A technique used to stabilize steep banks with little or no disturbance at the top of the slope and minimal disturbance to the streambed. A gravel bench is constructed along the toe and protected with riprap.
Endangered Species Act (ESA)	A 1973 act of Congress instructing federal agencies to carry out programs to conserve endangered and threatened species and to conserve the ecosystems on which these species depend.

Energy	A property of a body or physical system that enables it to move against a force. It is the amount of work required to move a mass through a distance.
Engineer	The person responsible for the technical requirements of project installation; represents the owner. An engineer is trained in or follows as a profession a branch of engineering, licensed in the state of the proposed project.
Engineered logjams (ELJs)	General term referring to a human designed and constructed structure of inter-locking logs intended to emulate natural logjams using scientific and engineering data to determine appropriate placement, materials, architecture, and size to ensure the stability and function that will achieve project goals. There is no single type of ELJ, and structures can vary significantly in shape, architecture, size, and function.
Engineered wood placement (EWP)	Structures ranging from a single log to hundreds of logs, woody debris, and other materials that are intended to provide restoration function such as grade control, flow deflection, and stress-partitioning; create *pools*; provide cover and hydraulic refugia for fish; collect floating debris and sediment; create islands and side channels; or improve floodplain connectivity by raising water elevations. EWP includes ELJs.
Entrenchment	The extent of vertical containment of a channel relative to its adjacent floodplain.
Entrenchment ratio	The flood-prone width divided by the bankfull width.
Ephemeral stream	A stream or reach of a stream that flows only in direct response to precipitation, and whose channel is above the water table at all times. The term may be arbitrarily restricted to a stream that does not flow continuously during periods of as much as a month.
Equilibrium bed slope	The slope at which the sediment transport capacity of the reach is in balance with the sediment transported into it. Also referred to as *equilibrium slope*.
Equipment rental contracts	A contract type used in instances where a fixed-price construction contract would be impractical because of the nature of the work and when it would not be feasible to prepare detailed drawings and specifications. It requires substantial construction oversight. See *Contract types*.
Erosion	The wearing away of soil by gravity, running water, wind, or ice.
Erosion control blankets (ECB)	A temporary protective blanket laid on top of bare soil vulnerable to erosion; commonly made of mulch, wood fiber, or synthetics.
Erosion control fabric	See *Erosion control blankets*.
Erosion stop wattle fence	See *Wattle*.
Eutrophication	An increase in the rate of supply of organic matter.

Excavated bench	A technique used to stabilize steep banks with little or no disturbance at the top of the slope and minimal disturbance to the streambed; involves shaping the upper half or more of the high bank to allow the formation of a bench to stabilize the toe of the slope.
Extremal hypothesis	A hypothesis that assumes a channel will adjust its geometry so that the time rate of energy expenditure is minimized.
Existence value	The value people place on knowing an environmental amenity exists, even if they have no plans to personally use it.
Facet	A distinct morphological segment of a longitudinal profile; *riffle*, *pool*, *run*, or *glide* (tail-out).
Fascine	A soil bioengineering technique used to provide stabilization to the toe of streambanks. A long bundle of live cuttings bound together into a rope or sausage-like bundles.
Federal Acquisition Regulations (FAR)	Regulations that govern federal contracts.
Filter layer	A layer that prevents finer grained particles from being lost through the interstitial spaces of the riprap material, while allowing seepage from the banks to pass. This layer typically consists of a geosynthetic layer or sand, gravel, or quarry spalls.
First-order stream	An unbranched tributary.
Fish screen	Screen that is designed to prevent fish from swimming or being drawn into an aqueduct, cooling water intake, dam or other diversion on a river, lake, or waterway where water is taken for human use. They are intended to supply debris-free water without harming aquatic life.
Fixed-price contract	In most cases, considered to be the preferable type of construction contract. However, it requires an accurate cost estimate and construction details. See *Contract types*.
Flood	A general term given to a relatively high flow measured in height or discharge quantity.
Flood insurance rate map (FIRM)	The official map of a community on which the Federal Emergency Management Agency has delineated both the special hazard areas and the risk premium zones applicable to the community.
Floodplain	An area of land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge often absent in incised channels.
Floodplain maps	Maps developed by the National Flood Insurance Program to reduce damages and loss of life caused by floods. The basis for flood management, regulation, and insurance requirements by identifying areas subject to flooding are provided.
Flood-prone width	The width of the active floodplain at the floodplain elevation (twice the maximum bankfull depth); composed of the active channel (bankfull width) and left and right flood plain (flood-prone) widths.

Floodway	The channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation by more than a designated height.
Flow area	The area of the cross section between ground and water surface.
Flow-changing devices	A broad category of structures that can be used to divert flows away from eroding banks.
Flow depth	See *Depth*.
Flow duration	The percentage of time that a flow level is equaled or exceeded in a stream or river, typically represented with a flow-duration curve.
Flow-frequency analysis	A consistent, statistical method for denoting the probability of occurrence of flow magnitudes at a specific point in a stream system.
Fluvial	Term referring to the channel drainage network of a watershed and the processes and conditions influencing the flow of water, sediment; and organic material; includes channels of all sizes from where they initiate to where they end. The term is used to refer to all topics related to flowing water and is a major discipline in the earth sciences, physical geography, and water resource engineering.
Fluvial fish	Species that live in the flowing waters of rivers or streams but migrate between rivers and tributaries for breeding, feeding, or sheltering.
Fluvial geomorphology	The study of the origin and evolution of landforms shaped by river processes.
Food chain	A succession of organisms in an ecological community that constitutes a continuation of food energy from one organism to another as each consumes a lower member and in turn is preyed upon by a higher member.
Food web	A combination of food chains that integrate to form a network; the entirety of interrelated food chains in an ecological community.
Force account agreements	Used when the sponsor performs the work using its own equipment and personnel.
Formal contract	Under the Federal Acquisition Regulations as of 2005, formal contracts must be used for projects with a value greater than $100,000.
Friction factor (f)	The roughness coefficient in the Darcy-Weisbach velocity equation.
Froude number	A dimensionless ratio, relating inertial forces to gravitational forces, and representing the effect of gravity on the state of flow in a stream.
Future without Action alternative	The option that involves allowing the site to progress without a project. The resources, both physical and ecological, that may be lost by not implementing the project are assessed as part of this alternative.

Gabion	A rock-filled wire mesh basket used to stabilize streambanks and slopes.
Gabion grade control	Grade control structures built with rock-filled wire mesh baskets.
Gage analysis	The use of statistical techniques to estimate probable frequency of flow events from recorded stream or river gage records.
General permits	Permits that are issued nationwide or regionally for categories of activities that are either similar in nature or cause only minimal individual and cumulative adverse impacts.
General scour	Streambed erosion affecting the entire channel cross section.
Geocell	A product composed of polyethylene strips, connected by a series of offset, full-depth welds to form a three-dimensional honeycomb system.
Geogrid	A geosynthetic formed by a regular network of integrally connected elements with apertures greater than a quarter inch to allow interlocking with surrounding soil, rock, earth, and other surrounding materials to function primarily as reinforcement.
Geologic assessment	The review of both the surface and subsurface features of geology and their possible impacts on a stream or river.
Geomorphic analog	The use of a stable stream reach as a template for restoration design.
Geomorphic goals	Goals or objectives based on concepts of landscape position, landforms, and ongoing processes that change them.
Geomorphology	The study of the origin and evolution of landforms, focusing on linking unique landscape attributes to the physics, chemistry, and biology of the formative processes (e.g., tectonics, earth materials, volcanism, surface and subsurface hydrology, slope stability, vegetation, human alterations, waves, currents, etc.). Sub-disciplines include hillslope, fluvial, coastal, soil, submarine, and even planetary geomorphology.
Geonet	A geosynthetic consisting of integrally connected parallel sets of ribs overlying similar sets at various angles for planar drainage of liquids and gases.
Geosynthetic	A planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as part of a human-made project structure or system.
Geotechnical analysis	The evaluation of the forces involved in bank instability problems including cohesion, friction, gravity acting on the soils in the slope, the internal resistance of soils in the slope, and the seepage forces in the soils in the bank.
Geotextile	A permeable geosynthetic comprised solely of textiles.
Glide	The downstream end of *pools*, just upstream of the next *riffle*, where the channel slope becomes adverse as the deeper section is intercepted by the tailing off point bar.

Goals	The overall desired outcome, such as restoring a channel to preflood conditions.
Grade control	See *Grade stabilization techniques*.
Grade stabilization techniques	Techniques used to stop channel degradation, typically accomplished by the construction of in-channel structures.
Grain Reynolds number	The ratio of the product of shear velocity and grain diameter to kinematic viscosity.
Grass-lined channel design method	A threshold channel design technique used where climate and soils can support permanent vegetation and baseflow does not exist. The approach is similar to the allowable velocity channel design method.
Gravelometer	Device used to assist with the measurement of particles sampled as part of a pebble count.
Groundwater	Water in a saturated zone or stratum beneath the land surface.
Grout	See *Grouted riprap*.
Grouted riprap	A riprap bed where the voids have been filled with concrete; often used where the required stone size cannot be obtained or at sites where a significant and damaging debris load is expected.
Gully/gullies	Entrenched channels extending into areas with previously undefined or weakly defined channel conditions.
Gully plug	A small earthen dam constructed at one or more locations along the gully.
Habitat	A specific environment in which a particular plant or animal lives.
Habitat Unit	The area of habitat types (e.g., *pools* or *riffles*) adjusted for habitat preference (e.g., pools have high preference for coho fry in summer but low preference for coho spawning) and by the suitability of that habitat indexed by the habitat suitability index (HIS).
Hybrid design methods	The use of a combination of analytical, as well as analogy and hydraulic geometry, design methods to calculate design variables.
Hydraulic control structure	A type of grade control structure designed to reduce the energy slope along the degradational zone to the degree that the stream can no longer scour the bed.
Hydraulic depth	The ratio of the cross-section area of flow to the free surface or top width.
Hydraulic geometry design method	Design approach based on the concept that a river system tends to develop in a predictable way, producing an approximate equilibrium between the channel and the inflowing water and sediment.
Hydraulic radius	The ratio of the cross-sectional area of flow to the *wetted perimeter* or flow boundary.
Hydro-physiographic area	A drainage basin where the combination of the mean annual precipitation, lithology, and land use produces similar discharge for a given drainage basin.

Hyporheic zone	A region beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water. The flow dynamics and behavior in this zone (termed *hyporheic flow* or *underflow*) is recognized to be important for surface water/groundwater interactions, as well as fish spawning, among other processes. As an innovative urban water management practice, the hyporheic zone can be designed by engineers and actively managed for improvements in both water quality and riparian habitat,
Incentive contracts	A contract type that links the contractor's profit to performance by establishing reasonable and attainable targets that are clearly communicated to the contractor. See *Contract types*.
Incipient motion design	See *Threshold channel design*.
Index of Biotic Integrity (IBI)	A biological assessment technique that uses fish surveys to assess human effects on a stream and its watershed.
Individual permit	A type of permit that involves the evaluation of a specific project.
Infiltration	The downward movement of water into the surface of soil.
Informal contract	Under the Federal Acquisition Regulations as of 2005, informal contracts and contracting procedures can be used for projects with a value of $100,000 or less. Informal contracts are those put in place using simplified acquisition procedures.
Intermittent stream	A stream that flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas. The term may be arbitrarily restricted to a stream that flows continuously during periods of at least 1 month; also may be a stream that does not flow continuously, as when water losses from evaporation or seepage exceed the available streamflow.
Irrigation ditch	A long, narrow, constructed channel used to convey irrigation water from its source to place of use.
Jetties	A flow-changing technique used to stabilize and protect stream and river banks; fence-like structures extending from the bank and into the stream.
J-hook	A rock structure used to provide bank stabilization.
Joint planting	A streambank soil bioengineering technique that includes cuttings of live woody plant material inserted in the voids of riprap and into the ground below the rock.
Jumping height	The maximum height obtained by a specific species and age of fish. Older and larger fish have greater maximum jumping heights, although some species have no jumping abilities at any age.
Key member or log	A critical structural element within an engineered logjam or wood structures.

Key piece	A functional piece of natural wood—one that is large enough to and with a shape that contributes to formation of a stable snag that alters flows and channel form. Diameters tend to be equal or greater than half the bankfull or effective discharge depth and have a rootwad or multiple stems.
Labor-hour contracts	A variation of the time-and-materials contract, differing only in that materials are not supplied by the contractor. See *Contract types*.
Lane's relationship	A qualitative conceptual model, also known as a stream balance, used as an aid to visually assess stream responses to changes in flow, slope, and sediment load.
Lane's tractive force design method	See *Allowable shear stress design method*.
Large wood	Term most commonly used in the literature describing pieces of wood such as branches and tree trunks, as opposed to particulates or small fragments of wood. Some publications define "large" as any piece of wood more than 10 centimeters (4 inches) in diameter and 1 meter (3 feet) in length. Because the word "large" is subjective without an explicit definition, some authors have simply used "wood debris" to describe the same thing. Some authors have thought the word "debris" has negative connotations and prefer using words such as "material." This manual simply uses "large wood."
Letter contracts	Written preliminary contractual instruments that authorize the contractor to begin work immediately.
Letter of map amendment (LOMA)	An amendment to the currently effective Federal Emergency Management Agency map establishing that a property is not located in a Special Flood Hazard Area.
Letter of map revision (LOMR)	An official amendment to the currently effective Federal Emergency Management Agency map.
Letter of permission (LOP)	A type of permit issued through an abbreviated processing procedure.
Lift	The fluid force component on sediment particles perpendicular to the mean flow direction.
Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids (LUNKERS)	A technique providing both streambank stability and edge cover aquatic habitat.
Live bed conditions	Conditions that may be assumed to exist at a site if the mean velocity upstream exceeds the critical velocity for the beginning of motion for the median size of bed material available for transport.
Live brush sills	A soil bioengineering technique that involves rows of live cuttings inserted into an excavated trench. This treatment is intended to promote sediment deposition and can function as erosion stops.

Live pole cuttings	A soil bioengineering technique that involves the use of dormant stems, branches, or trunks of live woody plant material inserted into the ground that are planted for bank erosion control and creation of riparian vegetation.
Live post planting	See *Dormant post planting*.
Live siltation	See *Live brush sills*.
Live stakes	See *Live pole cuttings*.
Local scour	Erosion of the streambed immediately adjacent to some obstruction to flow.
Log crib	See *Crib wall*.
Log-Pearson type III distribution	The most commonly used frequency distribution for peak flows in the United States; applies to nearly all series of natural floods; commonly used for stream gage analysis.
Log vanes/step jams	Single logs or small bundles of logs secured to bed. Also called log *bendway weirs* (if partially spanning channel and angling upstream) or log steps (if fully spanning channel, and usually placed perpendicular to channel).
Log weirs/valley jams	Weir-like accumulations built around one or more large logs (*key members*).
Longitudinal peak stone toe (LPST)	A type of bank protection involving the placement of a windrow of stone in a peak ridge along the toe of an eroding bank.
Loose rock grade control structure	A simple type of a grade control structure consisting of placing natural stone or other nonerodible elements across the channel to form a hard point.
Low flow	A general term that refers to the average low flows in a stream. It is typically due to soil moisture and ground water. Critical habitat conditions often occur during low flows.
Low-flow channel	A portion of a channel that conveys low or baseflows.
Maintenance	Actions taken to ensure that the stream restoration project performs as designed and is attaining project objectives.
Manning's n	An empirical factor in Manning's equation which accounts for frictional resistance of the flow boundary.
Meander	Deviation of the stream direction from the shortest possible path down a stream valley.
Meander geometry	The five parameters commonly used in the description of meander patterns: wavelength, radius of curvature, arc length, amplitude, and beltwidth.
Meander length	The product of the meander wavelength and the valley slope divided by the channel slope.
Meander ratio	The length of the stream divided by the length of the valley.
Mobile boundary stability	The rate at which sediment enters the channel reach from upstream equal to the capacity of the reach to transport sediment of the same composition on downstream.

Model (1D)	One-dimensional models only consider forces that occur in one direction (usually the streamwise). Velocity and other stream properties may vary upstream and downstream, but not from bank to bank and not from the bed to the water surface.
Model (2D)	Models are usually depth-averaged. They simulate variation in the horizontal plane, but assume no variation in the vertical.
Model – conceptual	Describes the objects and relationships either with words or diagrams.
Model – empirical	Contains any empirical relationship, one based on data. An empirical model is based, at least in part, on observed data, rather than a thorough understanding of the underlying physical principles.
Model – lumped	Describes processes on a scale larger than a point, while a *distributed model* describes all processes at a point, and then integrates processes over space and time to produce a total system response.
Model – mathematical	Formal mathematical models representing objects and interactions quantitatively with equations.
Model – parametric	Has parameters that must be estimated in some fashion.
Model – physical	Three-dimensional representations, usually at some relevant scale.
Model – steady	Predicts conditions that occur for a given set of boundary conditions. For example, a flow model might predict the water surface elevation, given a fixed channel geometry and a constant flow.
Model – stochastic	Outputs are predictable only in a statistical sense. Repeated use of a given set of model inputs produces outputs that are not the same but follow certain statistical patterns.
Model – unsteady	Predicted variations that occur with time, such as during the passage of a storm hydrograph, by dividing such an event into a series of steady-state time steps. Complex, unsteady models have feedback loops that allow channel boundaries or other key variables to respond to inputs and change between time steps.
Momentum	The mass of a body times its velocity.
Monitoring	The process of measuring or assessing specific physical, chemical, and/or biological parameters of a project.
Montgomery and Buffington classification	A classification system based on defining channel processes. It is a geomorphic process-based system.
Muddying-in	The practice of pouring a slurry mix of water and soil into the hole around the cutting stem of a plant to achieve good soil-to-stem contact.

Multi-Criteria Decision Analysis	A sub-discipline of operations research that explicitly considers multiple criteria in decision-making environments. Whether in our daily lives or in professional settings, there are typically multiple conflicting criteria that need to be evaluated in making decisions. Cost or price is usually one of the main criteria. Some measure of quality is typically another criterion that is in conflict with the cost. For example, in purchasing a car, cost, comfort, safety, and fuel economy may be some of the main criteria we consider. It is unusual to have the cheapest car to be the most comfortable and the safest.
National Environmental Policy Act (NEPA)	The federal law establishing a national policy for the environment; requires specific actions by federal agencies.
National Flood Insurance Program (NFIP)	A program administered by the Federal Emergency Management Agency providing for flood insurance, flood plain hazard mapping, and flood plain management.
Nationwide General Permit (NWP)	A type of general permit issued nationally by the U.S. Army Corps of Engineers for specific dredge or fill activities.
National Pollutant Discharge Elimination System (NPDES)	A provision of the Clean Water Act regulating point discharges into waters of the United States.
Natural channel	A river, stream, creek, or swale that has existed long enough and without significant alteration to establish a dynamically stable route.
Navigable waters	Defined for U.S. Army Corps of Engineers regulatory purposes as those waters that are subject to the ebb and flow of the tide and/or are presently used, or have been used in the past, or may be susceptible for use to transport interstate or foreign commerce.
Newbury riffle	A type of constructed loose rock grade control structure.
Natural Resources Conservation Service(NRCS) Conservation Practice Standards	Guidance provided for applying conservation technology and setting the minimum criteria for acceptable application of the technology. State variations on these standards may be more restrictive.
NRCS Planning Process	Steps used to develop an appropriate plan for natural resource protection or improvement.
NRCS State Conservation Practice Standards	Each state determines which NRCS National Conservation Practice Standards are applicable in their state. States add the technical detail needed to effectively use the standards at the field office level and issue them as state conservation practice standards. Minimum criteria may be more restrictive than the national standards.
Objectives	The detailed, focused outputs or outcomes that achieve project goals.
Open channel flow	Flow where one surface is open to the atmosphere.
Ordinary high water	The limit of U.S. Army Corps of Engineers jurisdiction in nontidal waters of the United States, in the absence of adjacent wetlands; defined as that line on the shore established by the fluctuations of water and indicated by physical characteristics.

Outliers	Data points that depart significantly from the trend of the remaining data.
Owner	The person responsible for contracting for construction. For NRCS Federal contracts, NRCS is considered the owner during construction.
Partial duration gage analysis	The analysis of the recorded peak flow values above a preselected base value that have occurred for each year in the duration of interest; typically used for the estimate of flows with return intervals less than 2 years.
Pattern	Plan view of a stream reach.
Pebble count	Technique used to sample the surface layer of sediments in gravelbed streams.
Perennial stream	A stream that flows continuously; streams flowing continuously throughout the year and that are generally lower than the water table in the region adjoining the stream.
Performance monitoring	Activity that identifies whether conservation measures are achieving the expected outcomes or targets.
Performance of work agreement	An agreement that requires that the value of work to be performed by the sponsoring local organization be determined by negotiation between the sponsoring local organization and NRCS and be included in the project agreement. NRCS must estimate the cost of the work to establish the maximum value of work before signing the agreement.
Periphyton	Algae, fungi, bacteria, protozoa, and organic matter associated with channel *substrates*.
Pile	A vertical element made of wood, steel, or other material that is embedded deeply into a streambed, either by driving with a hydraulic, diesel or vibratory hammer.
Pile foundations	Used to transfer foundation forces through relatively weak soil to stronger strata to minimize settlement. The most likely applications for pile foundations in stream restoration and stabilization projects are as support for bank stabilization structures (retaining wall) and as anchors for large woody material.
Pin deflectors	Variations of the permeable jetty, generally used in streams where only a small reduction in velocity is needed. Generally wood pilings are used for their construction.
Piston aerial sampler	Device used to facilitate underwater aerial sediment sampling of fine material.
Plan	A sequence of logical steps followed to reach a goal or objective.
Planform	Horizontal alignment of a channel; view is perpendicular to the Earth’s surface.
Point bar	A depositional area formed on the inside bank of a meander that sometimes remains bare of vegetation due to the frequent recurrence of the bankfull discharge.

Pool	The area in a natural channel deeper and somewhat narrower than the average channel section. Pools are stream features that have residual depth and therefore will not drain free of water if flows are curtailed.
Practice standards	See *NRCS Conservation Practice Standards*.
Pressure head	The potential energy of water, usually the result of its mass and the Earth's gravitational pull.
Productivity	The density-independent survival, which, along with density-dependent factors of the environment, determines abundance limited by the total capacity of the environment.
Programmatic General Permit (PGP)	A type of general permit issued to avoid unnecessary duplication of regulatory control exercised by another federal, state, or local agency.
Post	Similar to a pile but placed by excavating a hole, placing the post, and backfilling. Excavated holes are necessary to bury a tree with attached rootwad—an element that has significantly more resistance to pulling out or overturning than a pile driven to the same depth.
Project agreements	Any agreement(s) entered into by NRCS and sponsors, in which detailed working arrangements are established for the installation of cost-shared measures.
Pump intake fish screens	See *Fish screens*.
Quality assurance (QA)	Tasks or procedures undertaken to ensure that procedures are adhered to that will assure that work will meet minimum requirements. Quality assurance activities vary in accordance with the complexity and hazard class of the stream restoration project.
Quality assurance plan (QAP)	Identifies the individuals with the expertise to perform various QA tasks, outline the frequency and timing of testing, estimate the contract completion date, and be co-approved by all responsible supervisors.
Quality control (QC)	Tasks or procedures undertaken to ensure that work installed meets the minimum requirements of the contract.
R2	The coefficient of determination in a regression analysis. This commonly used measure of the goodness of fit is a dimensionless ratio of the explained variation in the dependent variable over the total variation of the independent variable.
Racking debris	Wood debris in a wide range of sizes that would be mobile within the stream or river is retained by a natural or engineered logjam (racked members or racking logs). This is very important material because it tends to decrease permeability of the structure and reduce drag coefficients. It also provides almost all of the aquatic cover and interstitial space for fish.

Reach	A subjective term describing a segment of stream or river. Typically defined as a length of stream or river having some defined uniform characteristics, typically about 20 channel widths, or a segment with uniform planform, gradient, and width measures.
Reclamation	A series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery. The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose, such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses.
Reconnaissance	A preliminary investigation not involving detailed investigation and relying heavily on existing data and observations.
Recurrence interval	The anticipated period in years before a given flood will reoccur.
Redirective structure	A flow-changing bank stabilization technique; designed to be placed in the stream, minimize direct impact, and rely more on the characteristics of fluid mechanics to modify the streamflow direction.
Reference reach design method	An alluvial channel design approach whereby channel dimensions are selected from a similar stable channel.
Regime design method	An alluvial channel design approach whereby channel dimensions are selected with the aid of empirically derived equations.
Regional curves	A tool frequently associated with the Rosgen geomorphic channel design approach, but also applicable to other design methods. It involves bankfull dimensions correlated to a drainage area. See *Hydraulic geometry design method*.
Regional general permit (RGP)	A type of general permit issued regionally.
Regression equations (gage analysis)	Used to transfer flood characteristics from gaged to ungaged sites through use of watershed and climatic characteristics as predictor variables.
Regulated stream systems	Streams or rivers that are cleared of wood, dammed, channelized, leveed, or constrained by other types of hard structures.
Rehabilitation	Making the land useful again after a disturbance; it involves the recovery of ecosystem functions and processes in a degraded habitat.
Replacement	The minimum number of spawners required to maintain a given abundance.
Resistance	Capacity of species and ecosystems to tolerate some changes in the intensity of ecological stressors.
Resource management systems (RMS)	Sets of approved conservation practices.
Restoration	The reestablishment of the structure and function of ecosystems. Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions.

Retard	A flow-changing bank stabilization technique. A retard structure increases flow resistance by increasing drag, thereby slowing the velocity in the vicinity of the structure. These structures are more porous with a high percentage of open area.
Reynolds number	A dimensionless ratio, relating the effect of viscosity to inertia, used to determine (index) whether fluid flow is laminar or turbulent.
Riffle	The area in a natural channel that is wider and shallower than the average channel section.
Riffle pool spacing	The distance between the *riffles* and the *pools* in a channel.
Rigid boundary stability	Attained when the interaction between flow and the material forming the channel boundary is such that the soil boundary effectively resists the erosive efforts of the flow.
Rigid drop grade control structure	A complex type of grade control structure that is used for large drops. These structures are frequently constructed of concrete or a combination of sheet pile and concrete.
Riparian forest	Forested or wooded area of land adjacent to a body of water such as a river, stream, pond, lake, marshland, estuary, canal, sink, or reservoir.
Riparian zones	The areas between aquatic and upland habitats. Often defined as the "zone of influence" between aquatic and terrestrial environments.
Riprap	Large stone used to provide immediate and permanent stream and river bank protection.
Riprap sizing	See *Stone sizing*.
Risk	The exposure of life, property, and/or the environment to loss or harm. The product of a likely occurrence times its consequence.
Risk analysis	The assessment of the consequences of specific action or inaction to life, property, and/or the environment.
Risk tolerance	The level of risk a decision maker is willing to accept, or the risk response determined by law or policy.
River	A large natural waterway confined within a bed and banks. In the context of this handbook, the term *stream* is used and encompasses *river*.
River classification	See *Classification*.
River Continuum Concept	Reaches form a continuous ecological system that processes organic material and produces a distinct pattern of biological communities.
Rolled erosion control products	Consist of both erosion control blankets used for temporary erosion protection and turf reinforcement mats for more permanent erosion protection.
Rootwad	The root systems of upended trees.
Rootwad revetments	Use of locally available logs and root fans to add physical habitat to streams in the form of coarse woody debris and deep scour pockets.

Rosgen classification	A stream classification system based on measurements of existing morphology.
Rosgen geomorphic channel design method	A hybrid channel design approach that incorporates geomorphic measurements, hydraulic geometry and some analytical calculations.
Rosgen stream type	See *Rosgen classification*.
Rotary drum fish screens	See *Fish screens*.
Run	The steepest section and shortest longitudinally, starting at the downstream end of a *riffle* as the channel enters the next *pool*.
Salmonid	Family of fish that includes salmon, trout, and char. All of the species breed in freshwater, are migratory, and spend part of their life cycle in the ocean.
Scour	Downward vertical erosion in a channel bed.
Se or SY,X	The standard error of estimate, typically expressed as Se or SY,X. This is a measure of the quality of a regression equation and is the root mean square of the estimates. It is a measure of the scatter about the regression line of the independent variable.
Seasonal stream	An intermittent stream that flows only during a certain climatic season, such as a winterbourne. A stream (or segments of a stream) that normally goes dry during a year of normal rainfall. Seasonal streams often receive water from springs and/or long-continued water supply from melting snow or other sources.
Sediment budget analysis	A quantitative sediment impact assessment of channel stability using the magnitude and frequency of all sediment-transporting flows done by comparing the mean annual sediment load for the project channel to that of the supply reach.
Sediment competence	The ability to move the largest particle made available to the channel.
Sediment continuity analysis	The volume of sediment deposited in or eroded from a reach during a given period of time is computed as the difference between the volumes of sediment entering and leaving the reach.
Sediment impact assessment	An evaluation of a designed channel's ability to transport the inflowing water and sediment load, without excessive sediment deposition or scouring on the channel bed.
Sediment rating curve	Correlates sediment flow to discharge for a stream reach or section.
Sediment rating curve analysis	Sediment impact assessment technique used to assess the sediment transport characteristics of an existing or proposed stream project. This approach uses sediment rating curves to compare the sediment transport capacity of the supply reach to the existing and proposed project reach conditions.
Sediment sampling	Technique used to quantify sediment in streams and rivers.
Shear	The pull of water on the wetted area in the direction of flow; measured in units of force/area.

Shear stress (average)	The product of the energy slope, hydraulic radius, and unit weight of water. Spatial and temporal variation may result in a higher or lower point value for shear stress.
Sheet pile	Flat panels of steel, concrete, vinyl, synthetic fiber, reinforced polymer, or wood. Typical applications include toe walls, flanking and undermining protection, grade stabilization structures, slope stabilization, and earth retaining walls.
Shields diagram	Classic method for determining critical shear stress.
Shields parameter	See *Dimensionless shear stress*.
Sinuosity	The channel centerline length divided by the length of the valley centerline.
Skin friction	The friction acting on a solid body when it is moving through a fluid.
Slash	Wood debris that often is considered waste in logging or site clearing operations that consists of a wide range of diameters and lengths (generally small diameter). May also include dirt and rocks. This is excellent material to supplement *racking debris* or for soil erosion protection.
Slope stability	See *Geotechnical analysis*.
Soil anchor	Technique used to anchor woody material to the streambed or bank to resist fluvial forces.
Soil bioengineering	The use of live and dead plant materials in combination with natural and synthetic support materials for slope stabilization, erosion reduction, and vegetative establishment.
Soil cement grade control	Structures constructed with a mix of Portland Cement and onsite soils.
Specific energy	The energy per unit weight of water at a given cross section with respect to the channel bottom.
Specific force	The horizontal force of flowing water per unit weight of water.
Spur dikes	Short dikes that extend out perpendicular from the bank into the channel along a reach of eroded bank.
Stability	A channel is considered stable (or in dynamic equilibrium) when the prevailing flow and sediment regimes do not lead to long-term *aggradation* or *degradation*.
Stability – Wood	Large wood placements are stable when the forces resisting motion are greater than those acting to move the wood.
Stakeholders	Individuals or groups who fund a project or are affected by the project.
Standard individual permit (SP)	A type of permit issued for activities that have more than minimal adverse impacts on waters of the United States. The evaluation of each permit application involves more thorough review of the potential effects of the proposed activity.
State administrative officer (SAO)	The person responsible for all administrative matters for contracts and most agreements.

State conservation engineer (SCE)	The person responsible for the design and ultimately for ensuring proper construction of projects in a given state.
Steady state models	Models that predict conditions that occur for a given set of boundary conditions.
Stinger	Metal rod used to facilitate planting live cuttings into rock riprap.
Stone sizing	Technique used to determine the minimum size stone to resist stream velocity.
Stream	A small natural waterway or channel that conveys overland flow continuously (perennial) or seasonally (ephemeral). Defined within a bed or banks. In the context of this handbook, stream encompasses river.
Streambank	The embankments on either side of a stream or river channel.
Stream barbs	A flow-changing bank stabilization technique that uses low dikes or sill-like structures that extend from the bank towards the stream in an upstream direction. As flow passes over the sill of the stream barb, it discharges normal to the face of the weir.
Streambed	The bottom of a stream or river.
Stream classification	See *Classification*.
Stream corridor	Includes the stream and extends in cross section from the channel's bankfull level towards the upland (perpendicular to the direction of streamflow) to a point on the landscape where channel-related surface and/or soil moisture no longer influence the plant community.
Stream corridor restoration	One or more conservation practices used to overcome resource impairments and reach-identified purposes.
Stream order classification	A stream classification system based on the degree of channel branching. An nth order stream is formed by the intersection of two or more (n-1) order streams.
Stream power	The product of shear stress and mean velocity. A measure of the available energy a stream has for moving sediment, rock, woody, or other debris.
Stream setbacks	A width required to allow a stream to self-adjust its meander pattern.
Structured Decision Making	An organized approach to identifying and evaluating creative options and making choices in complex decision situations.
Substrate	The base on which an organism lives; for example, the soil is the substrate of most seed plants.
Surcharge	The gravitational load acting on wood.
Surface sediment sampling	Techniques used to characterize the surface of a gravel bed.
Sustained swimming speed	Refers to the low swimming speeds of a fish species. In general, such speeds can be maintained for extended time periods with little to no fatigue.

Thalweg	The deepest portion of the channel; sometimes referred to as the low-flow channel.
Threshold channel	A channel in which channel boundary material has no significant movement during the design flow. The term “threshold” is used because the channel geometry is designed so that applied forces from the flow are below the threshold for movement of the boundary material.
Threshold channel design	A design approach whereby a channel configuration is selected so that the stress applied during design conditions is below the allowable stress for the channel boundary.
Timber crib	See *Crib wall*.
Time-and-materials contract	Contract used to procure supplies or services on the basis of direct labor and materials costs. See *Contract types*.
Toe zone	The portion of the bank between the average water level and the upper edge of the bottom of the channel.
Top width	The width of a channel cross section at the water surface.
Tractive power design method	A threshold channel design technique used in the assessment of channels in cemented and partially lithified (hardened) soils.
Transfer methods (gage analysis)	Technique used to extrapolate peak discharges upstream or downstream from a stream gage or from gage data from a nearby stream with similar basin characteristics.
Transition channel	A stream or river that may behave as an alluvial channel in one flow condition and as a threshold channel in another flow condition.
Tree revetments	See *Brush revetments*.
Tributary	A continuous perennial stream.
Trophic level	The position an organism occupies in a food chain.
Turbidity	The cloudiness or haziness of a fluid caused by large numbers of individual particles that are generally invisible to the naked eye, similar to smoke in air. The measurement of turbidity is a key test of water quality.
Turf reinforcement mats (TRM)	Used to provide permanent erosion protection.
Two-stage channel design method	A hybrid channel design approach that incorporates a natural alluvial channel nested with a constructed flood plain bench.
U.S. Army Corps of Engineers Regulatory Program	Program that evaluates permit applications for most construction activities that occur in the nation’s waters, including wetlands.
U.S. Forest Service: Framework of Aquatic Ecological Units	An aquatic framework containing standard terms and classification criteria for aquatic systems and their linkages to terrestrial systems at all spatial scales.
Uncertainty	The likelihood of a consequence occurring.

Undrained soil conditions	This is not a description of the water level in the soils, but rather a description of the pore pressure condition in the soil when loaded. An undrained condition assumes pore pressures will develop due to a change in load. The assumption is that the pore pressures that develop are not known and thus must be implicitly considered in the methods used to test samples for this condition. See *Drained soil conditions*.
Uniform flow	Occurs when the gravitational forces that are pushing the flow along the channel are in balance with the frictional forces exerted by the wetted perimeter that are retarding the flow.
Unsteady models	Predict variations that occur with time, such as during the passage of a storm hydrograph, by dividing such an event into a series of steady-state time steps.
Valley slope	The maximum possible slope for the channel invert; determined by the local topography; a channel with a slope equal to the valley slope would be straight.
Vanes	Flow-changing structures constructed in the stream designed to redirect flow by changing the rotational eddies normally associated with streamflow. They are used extensively as part of natural stream restoration efforts to improve instream habitat.
Vegetated gabion	Incorporates topsoil into the void spaces of the gabion. Woody plantings and/or grass are planted into or through the structure.
Vegetated geogrid	See *Vegetated reinforced soil slope*.
Vegetated reinforced soil slope (VRSS)	A soil bioengineering technique that is made up of layers of soil wrapped in synthetic geogrid or geotextile, with live cuttings or rooted plants installed between the wrapped soil layers.
Vegetated riprap	See *Joint planting*.
Vegetated rock wall	A mixed-construction soil bioengineering streambank stabilization technique. The structural-mechanical and the vegetative elements work together to prevent surface erosion and shallow mass movement by stabilizing and protecting the toe of steep slopes.
Vegetated soil lifts	See *Vegetated reinforced soil slope*.
Vegetated stone	Combining rock with soil bioengineering treatments can achieve benefits from both techniques.
Velocity head	The kinetic energy of water.
Vertical fixed plate fish screen	See *Fish screens*.
Vertical traveling fish screen	See *Fish screens*.
Visual geomorphic assessment	A qualitative assessment that includes judgment of current conditions, expected future conditions, and the river's anticipated response to the designed project.

Volumetric sediment sampling	The techniques generally considered to be the standard sediment sampling procedure; involves the removal of a predetermined volume of material that is large enough to be independent of the maximum particle size.
W-weir	Technique used to provide grade control.
Waterjet	See *Waterjet stinger*.
Waterjet stinger	A device that uses high-pressure water to hydrodrill a hole in the ground to plant unrooted cuttings.
Watershed	A topographically bounded area of land that captures precipitation, filters and stores water, and regulates its release through a channel network into a lake, another watershed, or an estuary and the ocean.
Wattle	A soil bioengineering technique made up of rows of live stakes or poles with live plant materials woven in a basket-like fashion. A wattle fence can be used to deter erosion in ditches or in small dry channel beds to resist the formation of rills and gullies.
Weir	A barrier across a river designed to alter its flow characteristics.
Wetlands	Defined for U.S. Army Corps of Engineers regulatory purposes as those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions.
Wetted perimeter	The length of cross-section boundary between water and ground.
Width-to-depth ratio	The *bankfull width* divided by the mean *bankfull depth* (dimensionless).
Wolman pebble count	See *Pebble count*.
Wolman walk	See *Pebble count*.
Work	Force applied over a distance.

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LIST OF ACRONYMS

°C	degrees Centigrade
°F	degrees Fahrenheit
1D	one-dimensional
2D	two-dimensional
ACHP	Advisory Council on Historic Preservation
AFDM	ash free dry mass
amsl	above mean sea level
BFW	bankfull flow width
BMPs	best management practices
BSTEM	Bank Stability and Toe Erosion Model
CEQA	California Environmental Quality Act
CLOMR	Conditional Letter of Map Revision
CPOM	coarse particulate organic matter
dB	decibel
DBH	diameter at breast height
DF	Douglas fir
DOC	dissolved organic carbon
EDT	Ecosystem Diagnosis and Treatment
EFC	Evergreen Funding Consultants
ELJs	engineered logjams
EMA	Expected Moments Algorithm
ERs	Engineer Regulations
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FEMAT	Forest Ecosystem Management Assessment Team
FHWA	Federal Highway Administration
FIRMs	flood insurance rate maps
FISRWG	Federal Interagency Stream Restoration Working Group
GF	grand fir
GIS	geographic information system
GPS	global positioning system
HEC-RAS	Hydrologic Engineering Centers River Analysis System
HEP	Habitat Evaluation Procedure
HIS	Habitat suitability index
IFB	Invitation for Bids
IFIM	Instream Flow Incremental Methodolog
IUCN	International Union for Conservation of Nature
JHA	Job Hazard Analyses
LID	Low Impact Development
LiDAR	Light Detection and Ranging
LOMA	letter of map amendment

LOMC	Letter Of Map Change
LOMR	Letter Of Map Revision
MCDA	Multi-Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MH	mountain hemlock
NEPA	National Environmental Protection Act
NHPA	National Historic Preservation Act
NIOSH	National Institute of Occupational Safety and Health
NMFS	National Marine Fisheries Service
NRCS	Natural Resources Conservation Service
NSD	Natural Systems Design
NWP	Nationwide Permit
OSHA	Occupational Safety and Health Administration
PHABSIM	Physical Habitat Simulation Model
PP	ponderosa pine
PPE	personal protective equipment
PS&E	plans, specifications, and estimates
QA/QC	Quality control and quality assurance
RCC	River Continuum Concept
RiverRAT	River Restoration Analysis Tool
SAF	Subalpine fir
SDM	Structured Decision Making
SEPA	Washington's State Environmental Policy Act
SF	silver fir
SS	Sitka spruce
SWPPP	stormwater pollution prevention plan
T&M	Time and Material
USACE	U.S. Army Corps of Engineers
USC	United States Code
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VSP	Viable Salmonid Population
WH	western hemlock
WUA	Weighted Useable Are

LIST OF SYMBOLS

A	Area of structure projected in the plane perpendicular to flow
B_d	Width of ditch
c	Cohesion of soil
C_D	Drag coefficient
C_L	Lift coefficient
C_w	Coefficient that captures interaction between ditch walls and fill
d	Diameter of log
D	Distance from top bank to top of log buried in bank
$D50$	The grain diameter at which 50% of the sediment sample is finer than the rest.
$D90$	The grain diameter at which 90% of the sediment sample is finer than the rest.
d_b	Representative boulder diameter
D_p	Mean number of days in the month with 0.01 inch or more of precipitation
D_w	Distance from top bank elevation to water table elevation
d_{wn}	Water depth at which the structure becomes neutrally buoyant
F_n	Force normal (perpendicular) to bed
F_{sh}	Safety factor with respect to horizontal movement
F_{sv}	Safety factor with respect to vertical movement
$\vec{F}_b$	Buoyant force
$\vec{F}_L$	Lift force
$\vec{F}_f$	Force of friction
$\vec{F}_d$	Drag force
$\vec{F}_c$	Restraining force due to anchors or ballast
$\vec{F}_{av}$	Vertical restraint force provided by anchors
$\vec{F}_{gh}$	Horizontal restraint force provided by geotechnical processes (buried posts or piles, embedded logs)
$\vec{F}_{gv}$	Vertical restraint force provided by geotechnical processes (buried posts or piles, embedded logs)
$\vec{F}_p$	Passive soil pressure force
$\vec{F}_{soil}$	Vertical loading on buried log due to weight of soil
g	Acceleration of gravity

H_s	Height of large wood structure (mean distance from stream bed to structure crest at upstream face)
K_p	Rankine coefficient of passive earth pressure
$\vec{l}$	Unit vector along the axis of the buried log—positive in the direction away from the buried tip
L_s	Length of large wood structure (dimension perpendicular to width, W)
L	Length of log
L_c	Appropriate moment arm about buried tip of horizontal log embedded in bank
L_{em}	Embedment length—length of log that is buried in bank
L_{ex}	Exposed length of horizontal log partially buried in bank such that $L_{ex} + L_{em} = L$
l_k	Length of kth log, exclusive of rootwad
$\vec{M}_d$	Driving moment about buried tip of horizontal log embedded in bank
n	Number of boulders used as ballast
Q_x	x-year return interval discharge
r_κ	DBH radius of the kth log
T	Mean monthly temperature, degrees Fahrenheit
t_k	Thickness (measured in direction parallel to trunk) of kth rootwad
U_o	Mean velocity of approach flow in the absence of large wood structure
V_w	Volume of displaced water
V_d	Volume of wood
W_s	Width of large wood structure (dimension perpendicular to length, L)
$W_{bl(sub)}$	Submerged weight of ballast
$\vec{W}_{bl}$	Weight of ballast
w_k	Radius of the kth rootwad
ϕ	Friction angle of soil
γ_{bl}	Specific weight of ballast
γ_s	Bulk unit weight of soil
$\gamma_{\text{structure}}$	Bulk density of large wood structure
γ_w	Unit weight of water
γ_d	Unit weight of wood
μ_{bed}	Coefficient of friction between large wood and bed
σ_p	Passive soil pressure
σ'_v	Vertical effective stress on buried log

Chapter 1

LARGE WOOD INTRODUCTION

Complex timber revetment along South Fork Nooksack River, Washington
(Tim Abbe 2012)

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1.1 Need for and Purpose of this Manual

This national manual was developed to provide a broad range of resource managers (surface and ground water, forestry, fish and wildlife, watershed, land, etc.) and specifically restoration practitioners (engineers, geomorphologists, ecologists, landscape planners, etc.) with a basic understanding of the role of wood in fluvial aquatic and riparian ecosystems and how it should be maintained, reintroduced, and/or managed. It highlights the best available science, creative engineering, and policies associated with restoring wood in rivers and underscores the significance of wood in fluvial ecosystems. It is also a source of practical information on how to assess the need for wood, use wood in restoration projects, and manage wood that naturally enters rivers and streams. To this end, this national manual provides resource managers and restoration practitioners with comprehensive guidelines for the planning, design, placement, and maintenance of large wood in rivers and streams with an emphasis on restoring ecosystem process and function.

Resource managers and restoration practitioners with objectives to restore ecological functions of streams and rivers are faced with many questions when using large wood, such as the following:

Questions that define the problem:

- What are current problems with the ecosystem?
- Is there degradation of:
    - Instream habitat (pools, cover, substrate conditions)
    - Floodplain environment (immature forests, loss of wetlands)
    - Water quality (excess fine sediment, nutrients, high temperatures, pollution)
- What are potential contributing factors?
    - Has the flow been altered?
    - Has the channel been altered? (e.g., armored banks, levees, straightening, incision)?
    - Is there point or non-point pollution?
    - Has there been a loss of riparian vegetation?
    - Has there been a reduction in the hyporheic exchange?

Questions that help define solutions:

- Has wood in the watershed ever been harvested?
- How large were riparian trees under old-growth conditions?
- What are the width, depth, and gradient of the channel in which you are working?
- How have riparian forest conditions changed over time?
- How do undisturbed historic channel characteristics compare to current conditions?
    - Bed substrate 7
    - Sinuosity
    - Anabranching (presence of ephemeral and perennial side channels)
    - Hydraulic geometry (unvegetated width and depth)
    - Alluvial landforms
- What was undisturbed historic floodplain?
- What is current floodplain?
- Has the channel experienced aggradation or incision?
- What is the current instream wood loading in terms of pieces and volumes?
- How have infrastructure decisions governed the management of wood?

GUIDANCE

To make this national manual a practical tool that speaks to these types of questions and assists resource managers and restoration practitioners, it includes the following subjects:

- Ecological restoration, large wood, an overview of the ecological functions of wood, and history of wood management and restoration in streams (*Chapter 1, Large Wood Introduction*).
- Application of the ecological restoration process and decision support tools for projects using large wood (*Chapter 2, Large Wood and the Fluvial Ecosystem Restoration Process*).
- Maintaining and restoring biological function in streams with wood (*Chapter 3, Ecological and Biological Considerations*).
- Understanding the role of wood in geomorphologic and hydrologic function (*Chapter 4, Geomorphology and Hydrology Considerations*).
- Large wood management considerations at a large geographic as well as long-term temporal scale (*Chapter 5, Watershed-Scale and Long-Term Considerations*).
- Designing and engineering wood projects (*Chapter 6, Engineering Considerations*).
- Recognizing the risks of using wood for restoration (*Chapter 7, Risk Considerations*).
- Identifying the regulatory requirements associated with wood products, and implementing wood restoration projects (*Chapter 8, Regulatory Compliance, Public Involvement, and Implementation*).
- Understanding and documenting project success (*Chapter 9, Assessing Ecological Performance*).

1.2 Ecological Restoration

An ecosystem is a complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space. An ecosystem's abiotic (nonbiological) constituents include minerals, climate, soil, water, sunlight, and all other nonliving elements; its biotic constituents consist of all its living members. Ecosystems at any site are governed by hierarchical regional, watershed, and reach-scale processes controlling hydrologic and sediment regimes; floodplain and aquatic habitat dynamics; and riparian and aquatic biota. In 1978, the U.S. Forest Service (USFS) recognized these relationships and categorized ecosystems with similar characteristics across the United States by mapping them into ecoregions (USDA 1980). Ecoregions are characterized by climax species, tree size, and density of forest stands as influenced by climate and fire disturbance intervals (Agee 1993). The distribution of tree species, heights, diameters, and stem densities in distinct ecoregions often differs due to variations in elevation, aspect, precipitation/soil moisture, and temperature (Henderson et al. 1992; Agee 1993). In 1981, the map of ecoregions was expanded to include the rest of North America (Bailey 2009), and an explanation of the basis for the regions delineated on the map was provided later (Bailey 2009). In 1993, as part of USFS's National Hierarchical Framework of Ecological Units (ECOMAP 1993), the ecoregions were adopted for use in ecosystem management (Figure 1-1) (Bailey 1995). As such, resource managers and restoration practitioners can expect ecosystems within these areas to have similar functions.

For the purposes of this manual, we have used the term "ecosystem function" to define the biological, geochemical, and physical processes and components that occur and interact within an ecosystem. This includes the functional processes and mechanisms that maintain the ecological structure and services produced by ecosystems. For example, ecosystem functions include primary productivity (production of biomass), decomposition, and trophic interactions. Studies of ecosystem function have greatly improved human understanding of sustainable production of forage, fiber, and fuel, as well as the provision of clean water.

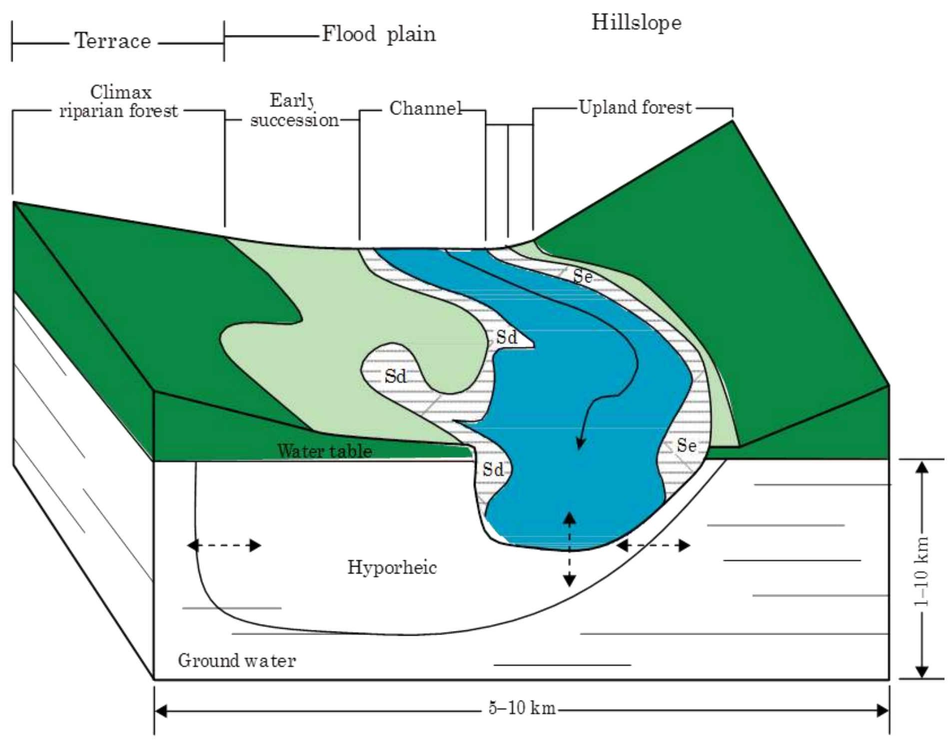
Figure 1-1. Map of Ecosystem Divisions, Regions, and Providences Across North America

Source: eathsciences.org.

Rivers and streams are a defining component of the landscape and the foundation of fluvial ecosystems (Figure 1-2). For the purposes of this manual, a fluvial ecosystem includes the river corridor that extends in cross-section from the channel's invert or thalweg to a point on the landscape where channel-related surface and/or soil moisture no longer influence the plant community (Ward et al. 1999, 2002). Ecological attributes of rivers and streams are defined by their geographic location, underlying geology, topography (e.g., slope), climate and hydrologic characteristics, and biological characteristics (i.e., aquatic, terrestrial, and subterranean species).

The length of a river corridor is typically characterized by the valley that encompasses the channel from the headwaters to the mouth of the watershed (Figure 1-2). Rarely does an alluvial valley consist of a single channel, but usually comprises a complex mosaic of both perennial and ephemeral channels and floodplain wetlands (Abbe and Montgomery 2003; Montgomery and Abbe 2006; Abbe and Brooks 2011).

Figure 1-2. Schematic of a Fluvial Aquatic Ecosystem



Modified from Stanford and Ward (1998).

Restoring process and function to damaged or altered fluvial aquatic ecosystems is a basic tenant of ecological restoration. Ecological restoration encompasses a set of intentional activities that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity, and sustainability. The Society for Ecological Restoration defines ecological restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (Society for Ecological Restoration International 2004). An ecosystem is considered restored when it contains sufficient biotic and abiotic resources to continue its development without further human assistance or intervention. It will sustain itself structurally and functionally, and will demonstrate resilience to normal ranges of environmental stress and disturbance. As a central component of these restoration activities, the use of wood plays a critical role in the restoration of fluvial aquatic ecosystems.

GUIDANCE

Adherence to four process-based principles can ensure river restoration actions will be guided toward maintaining and/or establishing sustainable ecosystems (Beechie et al. 2010):

1. Restoration actions should address the root causes of degradation.
2. Restoration actions must be consistent with the physical and biological potential of the site.
3. Restoration actions should be at a scale commensurate with environmental problems.
4. Restoration actions should have clearly articulated expected outcomes for ecosystem functions.

Within this broad context, restoration actions that restore fluvial aquatic ecosystem function by enhancing wood in streams and river channels can include activities that range from protecting riparian forests and the sources of wood in channels to replacing wood in channels. As such, any decision to place wood in channels should only be made after carefully assessing the need and benefits associated with that action. As stated earlier, this manual provides guidance for resource managers and restoration practitioners faced with making those types of decisions.

1.3 Large Wood

Wood is part of a continuum of allochthonous plant material from outside the stream itself and can include leaves, twigs, branches, trunks, and root masses. All of these provide structure at various scales, nutrients (decomposing at varying rates), and habitats for aquatic species including fish.

Large wood generally refers to tree trunks or root masses of varying dimensions that contribute especially to the physical structure of the fluvial system as it relates to larger organisms, especially fish. It is worth noting that even with widespread usage in both scientific and agency literature, "large wood" has no universal definition. Although the type of material—logs, branches, rootwads—is generally accepted by all, there are no absolute size criteria for what is sufficiently "large." Minimum diameters of between 10 and 25 centimeters (4 and 10 inches) are common criteria in the published literature (Keller and Swanson 1979; Bilby and Ward 1989; Beechie and Wyman 1992; Montgomery et al. 1995a; Schuett-Hames et al. 1999; Fox and Bolton 2007). The minimum length of large wood, however, has less agreement. Bilby (1984) suggests that any piece shorter than 2 meters (7 feet) may be unstable, and Bilby and Ward (1989) counted none shorter than 2 meters in their study; Montgomery et al. (1995a) counted any piece longer than 1 meter (3.3 feet); meanwhile, the Oregon Department of Forestry (1995) requires a length double to that of the bankfull width, and the National Marine Fisheries Service (1996) requires lengths of 15.25 meters (50 feet) in west Washington State and 10.7 meters (35 feet) in east Washington State. Researchers such as Wohl et al. (2010) recognize the importance of reporting the specific minimum sizes measured, the proportions relative to the low-flow and bankfull channel zones, and actual dimensions for sorting data and enabling more universal comparisons among data sets. For the purposes of this manual, minimum dimensions are only provided where necessary for clarity. The most important concept associated with the definition of large wood is the functional role it plays in fluvial ecosystems. As such, the specific size of a given piece of wood and its specific ecosystem function can change based on the relative size and location of the alluvial ecosystem in which it is located.

Wood has been used as a principal structural material for thousands of years, including applications in water bodies such as bulkheads, piers, docks, and abutments. The use of wood to improve fish habitat in streams goes back at least to the late nineteenth century (e.g., Van Cleef 1885). Guidelines on using wood to enhance habitat and protect stream banks continued through the twentieth century (e.g., Hewitt 1934; Tarzwell 1936; Ahmad 1951; Saunders and Smith

1962; Sedell et al. 1982; Seehorn 1985; Thompson 2002, 2005). Despite this historical context and the recognition that natural wood had significant effects on river morphology (e.g., Wolff 1916; Guardia 1933), research into the form and function of natural wood didn't begin until late in the twentieth century (e.g., Keller and Swanson 1979; Bilby and Likens 1980; Harmon et al. 1986; Maser et al. 1988).

Historically, wood placements focused on simple structures (e.g., deflectors and steps) and a static simple view of stream channels (e.g., Thompson 2002, 2005). Recent recognition of the inherent spatial and temporal physical complexity of natural wood accumulations and their beneficial influence on fluvial ecosystems has driven increased efforts to re-introduce wood to streams throughout the United States. Current wood placement strategies such as engineered logjams differ markedly from historic wood placements in both the complexity of the structures and intent to restore complexity and natural process to disturbed stream channels and floodplains (e.g., Abbe et al. 1997; Abbe and Brooks 2011).

1.3.1 Importance of Riparian Forests

Most sites that are candidates for large wood placement are in areas where humans have played a substantial role in the history of the riparian zone, reducing the size and abundance of trees relative to what might be found in a pristine setting. Human activities may have also altered the stream channel; for example, by altering fluvial disturbance regimes or by engineered channel alterations, thereby altering interactions between the riparian forest and the stream. The potential array of impairments is extensive, including all aspects of riparian forest function, and is usually highly site-specific.

Although riparian forest types vary widely throughout the coterminous United States, they can broadly be characterized according to the type, size, and density of trees; the width of the forest; and the degree of channel confinement.

1.3.1.1 Tree Type

The types or species of trees in a riparian forest affect many functional characteristics. Evergreen trees provide shade and perform other microclimate functions throughout the year, while deciduous trees provide few such functions when leaves have fallen. It is important to realize, however, that in many settings deciduous trees may outperform evergreen trees because they shade when seasons are hot and then allow warming when seasons are cold, thereby improving primary productivity during times of food shortages. Trees with strong, decay-resistant wood provide more durable woody debris than trees with weak or easily decayed wood (Harmon et al. 1986). Trees in the willow family fix nitrogen in a form available to organisms in the forest and the stream (Wuehlisch 2011), whereas other tree species lack this capacity. Trees also vary in their response to channel disturbance; for instance, some can survive having their roots buried by layers of sediment, while others cannot.

1.3.1.2 Tree Size and Stand Density

Tree size affects the potential for the riparian forest to provide functional large wood in the channel, to shade the channel, to provide root reinforcement of stream banks, and to survive channel disturbance. Large trees produce larger woody debris that is more likely to remain in the stream and provide geomorphic and ecological functions, compared to smaller trees that may not be recruited to the stream or, if recruited, may be swept away during high flows (Harmon et al. 1986; Lienkaemper and Swanson 1987). Tall trees can shade wider streams or provide greater shade in small streams (Beschta et al. 1987). Large trees also have extensive root systems and may provide a barrier to trap flood-borne debris; both functions can reduce the risk and rate of channel migration or avulsion (Coho and Burges 1994).

Stand density affects the magnitude of the functions described above. For instance, a less dense stand will provide less shade and less wood recruitment than a similar stand with greater tree basal area.

1.3.1.3 Riparian Forest Width

Riparian forests are commonly long and narrow. There are notable exceptions, the principal one being forests on the floodplains of large rivers. However, in most of the United States, riparian forests are narrow due to natural reasons (soil moisture becomes limited with increasing distance from the stream) or from human activity (removal of trees away from the stream, leaving a riparian forest strip, the width of which often reflects a regulatory requirement). Many studies have attempted to describe the progressive loss of function that occurs in progressively narrower strips of riparian forest (reviews by FEMAT 1993; Castelle et al. 1994) and have generally found that different ecological functions diminish at different rates with distance from the stream. Effects of the forest on wind speed, for instance, continue to accrue even over distances of hundreds of meters (Chen et al. 1995), while large wood recruitment primarily occurs over distances of less than one tree height (McDade et al. 1990; Robison and Beschta 1990).

1.3.1.4 Channel Confinement

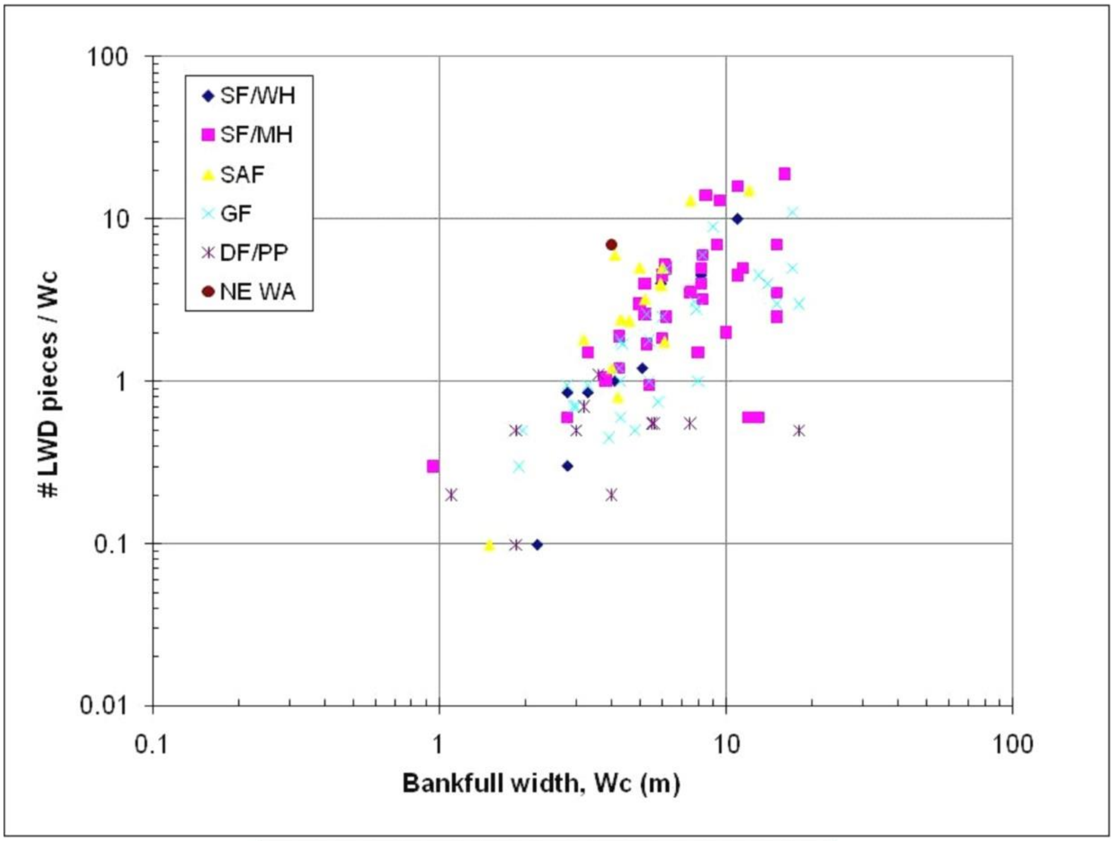
Stream channels can be broadly categorized according to degree of channel confinement, represented as the ratio of valley bottom width to bankfull width (Montgomery and Buffington 1993). The riparian forest is largely confined to the valley bottom. On the valley sides, soil moisture is usually reduced and vegetation changes to a different type. On many sites, the riparian forest is confined to a fraction of the valley bottom, as described above (Section 1.3.1.3, *Riparian Forest Width*). In a tightly confined channel, the riparian forest is necessarily very narrow. Principal functions of the riparian forest on these sites primarily relate to bank reinforcement by roots and to other mechanisms by which the forest may alter the severity of channel disturbance, either by resisting or by failing to resist peak flow events that may entrain trees; for example, debris torrents or dam-break floods (Coho and Burges 1994). As channel confinement reduces, the riparian forest is potentially much wider and is capable of providing all of the physical and chemical ecosystem functions described earlier. With further reductions in channel confinement, the stream has the potential to shift its channel by migration or avulsion, and to develop side channel environments that may host valuable natural resources such as wetlands or sensitive species habitat. In such settings the riparian forest may provide the functions described above to multiple channels and larger water bodies such as ponds or small lakes.

1.3.2 Wood Loading in Natural Settings

As described above, one common question for restoration projects is “how much wood is enough?”. There is very little to no data from around the country on natural wood loading, but there are several important concepts to remember. Natural wood loading varies widely and thus offers designers a great deal of flexibility if using reference conditions, assuming they are available. Practitioners should therefore focus on the function of the wood, not just whether the quantity is representative of “natural” loading.

Fox and Bolton (2007) show that wood loading, as measured by the number of pieces per bankfull channel width, increases with channel size and drainage area (Figure 1-3). This runs counter to common views that wood loading diminishes in larger channels. While the spacing of wood accumulations tends to increase in larger channels, the size of the accumulations increases dramatically. Some of the largest wood accumulations historically were found in the response lower reaches of large rivers such as the Red and Colorado rivers described earlier. Large logjams were once common in the distributary channels of large river deltas in the Pacific Northwest (Abbe 2000). In 2005 a logjam began forming in the main channel of the Nooksack River delta in northwestern Washington, growing to 14 acres by 2011. The formation of these types of logjams reflects natural processes and a positive sign of passive restoration (Figure 1-4).

Figure 1-3. Wood Loading Tends to Increase With Channel Size When Normalized to Bankfull Width



SF/WH	Sitka spruce/western hemlock
SF/MH	Silver fir / mountain hemlock
SAF	subalpine fir
GF	Grand fir
DF/PP	Douglas fir / ponderosa
NE	NE region of WA

Adapted from Fox and Bolton (2007).

Figure 1-4. Example of High Wood Loading in a Large Channel (Nooksack River Delta, Northwest Washington)

A logjam began forming about 2005 in what had been the dominant channel (initiating at point A). Most of the 46-meter-wide (150-foot-wide) channel was filled with wood by 2011, and most of the flow is in the western channel. The logjam covers about 14 acres, and the larger logs are about 0.6 meter (2 feet) in diameter and 21 meters (70 feet) long. The logjam represents an example of passive restoration (formed naturally) that is increasing physical, hydrological, and ecological complexity in the delta. These types of logjams are well documented in gulf coast deltas (e.g., Clay 1949; Wadsworth 1966; Hartopo 1991; Phillips 2012).

1.3.3 Historical Instream Wood Conditions

Historically, fish and other aquatic species adapted to stream systems where wood was abundant and distributed in the form of individuals and groups (jams) recruited from riparian trees, beaver dams, and other means (Sedell and Luchessa 1981). Large river systems contained so much wood that river navigation was nearly impossible, with some jams up to 1,500 meters (4,920 feet) long (Sedell and Luchessa 1981). Collins et al. (2002) determined that wood in some lowland Puget Sound rivers was one to two orders of magnitude greater prior to European settlement based on historical data, journal accounts, and observations in undisturbed river reaches of the Nisqually River. These authors found reports from early surveyors, U.S. Army documents, and others referencing the vast amounts of wood in the major rivers:

> ….the channels are strewn with immense trunks, often two hundred feet long, with roots, tops, and all …[forming] jams, which frequently block the channels altogether (Major Hiram Chittenden 1907)
>
> Snags are numerous and large, and so deeply imbedded in the bottom that a steam snag-boat would be required for five or six months to open a channel 100 feet wide… (U.S. Army's Robert A. Habersham 1897)

The amount of wood was so abundant and well-lodged into riverbeds that logging and upstream settlement was stymied until settlers and USACE could pull, blast, and cut wood from rivers in the 1870s to 1890s (Sedell and Luchessa 1981).

In terms of large wood piece sizes, Collins et al. (2002) found that the annual maximum diameter between 1889 and 1909 ranged from 3.6–5.3 meters (11.8–17.4 feet) (U.S. War Department 1889–1909), based on snag boat captains' records and confirmed by engineers' observations (e.g., U.S. War Department 1895).

Historic instream wood loads in other parts of North America may have been similar to those in the Pacific Northwest. Whitney (1996) reported that remnant stands of eastern old-growth mixed conifer-hardwood or hemlock-white pine stands have a biomass of 560 to 820 tons per hectare (Whitney 1996). This is nearly as much as that of the productive coniferous forests of the Pacific Northwest (Franklin and Dyrness 1973). Whitney also estimated that white pine trees often grew to diameters of 2–3 meters (7–10 feet) and heights of 45–60 meters (148–197 feet); while sycamores attained diameters greater than 4 meters (13 feet), tulip trees almost 2 meters (7 feet), and cottonwood and oak well in excess of 2 meters (7 feet), which is also within the range of unmanaged Pacific Northwest stand characteristics. Sedell et al. (1982) reported that snags in the lower Mississippi River, pulled over a 50-year period, had diameters averaging 1.5 meters (5 feet) at the base. Triska (1984) reported diameters of 1.75 meters (5.75 feet) in the Red River of Louisiana. Based on the similarities in historic stand characteristics between eastern and northwest forests in North America, similarities of instream wood loads are a reasonable assumption. Verification may be supported by the same approach taken by Montgomery et al. (2003), who suggest using references to historical records of instream wood removal and clearing of riparian forests to reconstruct and evaluate how the role of wood in some river systems has changed in the last 200 years.

The use of wood for improving instream fish habitat goes back at least to the late nineteenth century (e.g., Van Cleef 1885; Hewitt 1934; Tarzwell 1936; Thompson 2002, 2005). In reviewing historic stream improvement, Thompson (2002, 2005), concluded there is little evidence the constructed structures made a measureable improvement to habitat or restoring natural channel conditions, and in some cases had negative impacts. Thompson (2002, 2005) argues that much of the recent restoration work using wood is similar to historic structure types (such as log steps and log crib deflectors), and thus is unlikely to achieve the desired results, recommending that restoration avoid static structures and focus on restoring riparian corridors and unsecured wood placements. This argument is challenged by Roni et al. (2014a) who demonstrate that recent wood placements are successfully restoring habitat and natural processes. While Thompson (2002, 2005) is correct that there are similarities between the simple static structures constructed throughout the 1900s and some of the current restoration design commonly associated with "natural channel design" (Rosgen and Silvey 1996), there is a significant difference with regard to the recent engineered logjam approach, in which wood structures are not just intended to emulate natural structures, but restore and accommodate fluvial processes such as bank erosion, hydraulic variability, and wood recruitment (e.g., Abbe and Brooks 2011). Most of the current stream restoration involving wood placement includes land acquisition or conservation easements with aggressive riparian reforestation. There is certainly consensus in the scientific community (including Thompson 2002, 2005; Abbe and Brooks 2011; Roni et al. 2014a) that long-term stream restoration depends on understanding and accommodating processes at both the reach and watershed scale. Key to this is establishing a *geomorphic response corridor* that includes restoration of mature riparian forests and sufficient portions of the floodplain, channel migration zone (e.g., Rapp and Abbe 2003), and adjacent hillsides to accommodate fluvial processes and wood recruitment. Roni et al. (2014a) point out that wood placement projects that did not take into account processes such as hydrology or sediment, tended to be the projects that did not show improvements.

CAVEAT

Stable wood placements can be essential project elements but should always be designed in a reach and watershed context that help to restore and accommodate the natural spatial and temporal dynamics of wood and channel processes essential to sustain healthy streams.

1.3.4 Wood Recruitment Processes

Every stream has a unique hydrologic and sediment regime linked to the climate, geology, relief, vegetation, and landscape disturbance within its watershed. Hydrologic regimes vary substantially around the country, such as the range of flows that can recruit, move, and deposit wood. In some regions these will differ by orders of magnitude. Fluvial processes can also vary. In some cold regions of the country, river ice can play a dominant role in channel morphology (e.g., Pariset et al. 1966; Keller and Swanson 1979; Smith 1979; Beltaos 1983; Smith and Pearce 2000), and, in steep terrains, debris/mud flows have pronounced effects on channel form and wood. Similarly, the frequency and magnitude of processes delivering wood from hillslopes and floodplains vary geographically, and the characteristics of individual forest trees (size, shape, specific gravity) have a major effect on the deposition and transport, and, therefore, the distribution of, wood within a channel network.

Geomorphically, fluvial disturbance rates in large, unconfined rivers dictate both the size of trees and the species recruited to the channel, where deciduous trees colonize rapidly following disturbance and are later succeeded by coniferous stands (Naiman et al. 1992; Fetherston et al. 1995; Johnson et al. 2000). Recruitment also comes from non-fluvial means, where Palik et al. (1998) reported wood enters the channel due to the natural mortality of trees in reaches having narrow valleys with riparian landforms elevated above the channel. Collins et al. (2012) demonstrate how logjams in the Pacific Northwest formed by large trees create "islands" where the disturbance frequency associated with channel migration (bank erosion) is reduced and allows for large trees to develop within floodplains characterized by much smaller trees. In a detailed wood budget covering 177 kilometers (110 miles) of the Roanoke River in the Mid-Atlantic Coastal Plain (North Carolina), a large low-gradient sand-bedded channel, Moulin et al. (2011) found that bank erosion accounted for over 70% of the wood. Of the instream wood, 75% was available for transport, over 50% of which was stored in logjams, most formed by stable snags. The same researchers also looked at wood transport in the Roanoke River, tagging 344 pieces of wood (290 with radio frequency tags, 54 with aluminum tags) (Schenk et al. 2014b). They found that 5% of the instream wood turns over (losses from export, decomposition, and burial equal inputs from mass wasting and bank erosion) and that 16% is moving through the system. The remaining population consists of individual snags and logjams.

Fire is also a dominant influence that affects timber age (Henderson et al. 1992), tree diameter (Rot et al. 2000) and height (Agee 1993; Henderson et al. 1992), and recruitment to streams. Patches of timber unscathed by a fire (often termed fire refugia) can diversify timber ages along riparian areas (Camp et al. 1996).

Other important recruitment processes in the eastern, southern, and Midwest regions are linked to severe weather, particularly hurricanes and wind storms (e.g., Frangi and Lugo 1991; Foster and Boose 1992; Boose et al. 2001; Chambers et al. 2007; Phillips and Park 2009), and ice storms (e.g., Millward et al. 2010). Recruitment processes are discussed in Section 1.3.4.2, *Wood Recruitment through Natural Disturbance Regimes*. These processes drive the rate of wood recruitment as well as the structure and composition of instream wood.

1.3.4.1 Riparian Contribution

As introduced above, geomorphic processes, disturbance patterns, and regional climate differences influence the structure and composition of riparian forests, both spatially and temporally. The effects of fluvial activity on riparian forests are predominantly associated with large rivers, because smaller streams do not have the same energy and consequent rates of channel migration and bank erosion sufficient to affect large swaths of riparian forest. In contrast, the riparian floodplains of large, unconfined channels are developed by fluvial disturbances that promote the colonization of deciduous species (Naiman et al. 1992; Fetherston et al. 1995; Johnson et al. 2000). During periods of high flows, channel avulsion, accelerated lateral migration, and bank land sliding can topple trees from riparian areas (Johnson et al. 2000). Deciduous trees typically are first to colonize riparian areas following disturbances, the causes of which can be both direct channel action and debris flows (Grant et al. 1984; Wilford et al. 1998) or snow avalanches (Fetherston et al. 1995; Cushman 1981). Following these disturbances, conifer succession may not occur for 80 years or more (Jenkins and Hebertson 1998). Disturbance patterns can affect the characteristics of the riparian area and thus influence the characteristics of wood loads. Wind throw, insect infestations, drought, disease, ice storms, and fire all affect recruitment rates, stand age, wood diameter, and species composition.

The ability of wood to have a significant effect on hydraulics and stream channel morphology is dependent on its stability. Wood that is easily transported is unlikely to remain in the channel for any length of time unless it encounters stable obstructions. Unstable wood that doesn't simply pass through the system usually ends up entangled on a pre-existing snag or log jam (flow obstruction) or on a depositional surface such as a bar or floodplain. When wood forms a stable obstruction within a zone of active sediment transport, it begins to alter channel-forming processes by influencing flow conditions, scour, and deposition. Those pieces of wood that have sufficient resistance to withstand the forces imposed by peak flows are most likely to become local hydraulic and geomorphic controls that define riffle formation. The effect of these key pieces is further exaggerated when they trap additional wood debris that would otherwise have passed through the channel. Key pieces commonly form obstructions where they first enter the channel, and if they do move downstream, they don't tend to go far. The presence of key members is strongly dependent on a local sources of trees capable of creating stable snags, either because of their size or shape (e.g., intact rootwad, large branches, or clump of multiple stems attached to same rootwad). The supply of mobile wood debris to the channel will affect the development of wood accumulations or jams downstream. Streams that have young riparian areas of small trees and channels that have been cleared of natural obstructions can have an artificially high supply of mobile wood, which can end up forming massive logjams in depositional areas (e.g., deltas, reservoirs) or at artificial obstructions such as bridge piers and culverts, The restoration of key pieces or ELJs in unconstrained stream segments will trap mobile debris and thus help to control the downstream flux of wood that may pose a threat and will also increase carbon sequestration. Kennard et al. (1998) present a model for managing riparian forests based on the supply of adequate large wood to stream channels. They start with a simple prediction of the probability of a tree falling due to mortality or windfall.

Equation 1-1:

$$P_F = (1-(1-T_F)^t)$$

where:

P_F = probability of a given tree falling after time, t, in years

T_F = tree fall rate, assumed to be 20% for first decade, 15% for second decade, and 10% thereafter (equilibrium rate based on Murphy and Koski 1989)

The probabilistic tree-fall model of Van Sickle and Gregory (1990) is used to predict large wood recruitment to a channel.

Equation 1-2:

$$P_S = \frac{\cos^{-1}(z/h)}{\pi}$$

where:

P_S = probability of a tree falling

z = perpendicular downslope distance from standing tree to nearest channel boundary

h = tree height

The number of fallen trees that enter a stream, NI, is predicted as a function of the riparian forest width, WF, and length, LF; the density of trees; the probability of a tree falling, P_F (1); and the probability of a tree falling into the stream, P_S.

Equation 1-3:

$$NI = D\ L_F\ W_F\ P_F\ P_S$$

Data of large wood and channel dimensions from western Washington were used to develop an empirical means of estimating the diameter of functional wood. Using an empirical estimate:

Equation 1-4:

$$dbh = 3.06\ W_C + 22.10$$

where:

dbh = tree diameter at breast height in centimeters

W_C = channel bankfull width in meters

Kennard et al. (1998) present the following wood depletion model for estimating the percentage of large wood pieces remaining after time t:

Equation 1-5:

$$y = (1-x)t$$

where

x = annual depletion rate 0.015 (based on values of 0.014–0.016 from Murphy and Koski 1989)

t = elapsed time in years

y = % of large wood pieces remaining after time, t

Kennard et al. (1998) offer the following means of estimating pool spacing based on the number of functional large wood pieces, NF, in a channel.

Equation 1-6:

$$G = \left(\frac{1}{N_F}\right)\left[\frac{(J(K)+S)}{W_C\ (R)}\right]$$

where:

G = number of channel widths, WC, per pool

L = length of stream segment

R = recruitment factor

J = proportion of pools from debris jams

S = proportion of single large wood pools

K = number of functional large wood pieces in debris jams

The above discussion can provide guidance on the recovery of riparian areas to the point where they are making a geomorphic difference for both passive and active approaches to restoration.

1.3.4.2 Factors of Variability

There are several means by which wood finds its way into a stream. At the reach scale, trees can fall directly into a channel due to bole breakage or by being uprooted. These are often the result of various forms of chronic tree mortality such as stem suppression/exclusion, wind throw, disease, and old age, and also the result of fluvial processes such as channel avulsion or lateral migration and bank erosion. At the watershed scale, other processes such as debris flows and snow avalanches can deliver trees into downstream channels (Cushman 1981; Grant and Swanson 1995). The river can also exhume buried wood within floodplains (Fetherston et al. 1995). Ultimately, the quantity of wood in a stream at any point in time is a result of input and output balances over the previous centuries (Swanson et al. 1982; Martin and Benda 2001).

Instream large wood biomass is positively correlated to tree density (Bilby and Wasserman 1989), tree maturity (Bilby and Ward 1991; Rot et al. 2000), and the percentage of conifers (Harmon et al. 1986). Source distance is correlated to tree height (McDade et al.1990; Robison and Beschta 1990), but McDade et al. (1990) could not attribute 47.7% of identified wood pieces to an adjacent source, suggesting that many pieces are routed in from upstream sources. Clearly, instream wood loads are dynamic and fluctuate according to various natural processes at the reach and watershed scales. The following elaborates on these processes.

Geomorphic Influence

Channel reach morphology, such as the types identified by Montgomery and Buffington (1997), also influences instream wood loads. Rot et al. (2000) found significantly more large wood pieces in forced pool-riffle channels than in bedrock or plane-bed channels, where wood volume followed a similar trend. However, these authors and others found that confinement was significantly related to large wood volume only in forced pool/riffle channels, where less wood was found in confined channels. They report that confinement had no effect on large wood volume in plane-bed channels.

Fox and Bolton (2007) illustrate an increase in large wood piece numbers and volumes as channels increase in width. Fox and Bolton found 0.38 pieces/meter in the smallest channels (>0–6 meters [0–20 feet] bankfull flow width [BFW]) to 2.08 pieces/meter in the largest rivers (30–100 meters [98–328 feet] BFW). This difference between the studies could be attributed to the inclusion of large rivers (20–100 meters [66–328 feet] BFW) studied by Fox (2001), which displayed many multi-piece log jams.

Fox (2001) reported that small channels are likely to obtain a significant proportion of riparian trees for instream wood by bole breakage and passive tree mortality, rather than by active recruitment such as the lateral bank avulsion common to larger streams. Similarly, confined streams draining large basins are also likely to obtain wood passively. Fox observed that confined reaches often had resistant banks, which likely slow the rate of avulsion compared to banks composed of unconsolidated material. Due to the resistance to lateral migration, trees adjacent to these channels are afforded greater intervals between disturbances and thus have the potential to grow older and perhaps larger (given favorable soils and climate). As a result, confined channels often have greater potential to recruit fewer but larger trees than unconfined channels, where the lateral migration rate within the floodplain limits tree growth.

The frequency of fluvial disturbance also dictates stand age, which influences large wood size. Latterell and Naiman (2007) found that larger trees are not recruited from floodplain riparian areas, but rather from higher surfaces less prone to frequent fluvial disturbance. These authors reported that 72% of large trees (<1-meter [3-foot] diameter) entering the Queets River in Washington were recruited as the river undercut higher fluvial terraces. These terrace surfaces had not been disturbed by the river since the forest stand origin. This is supported by the research of O'Connor et al. (2003), who report that channel and floodplain dynamics and morphology are affected by interactions involving time frames similar to 200–500-year floodplain half-lives in the Queets River.

Riparian vegetation can influence the rate of lateral migration of rivers. Dense root systems can armor banks, reducing bank erosion and processes that promote lateral river movement. For example, Collins and Sheikh (2005) found an 1898 USACE report describing dense growth of alder, willow, and vine maple on the shores of the White River in Washington: "This brush affords complete protection from washing and undermining effects of the current. In a majority of cases where the brush has been removed, the river has begun to eat into its bank."

Regional Ecological Influence

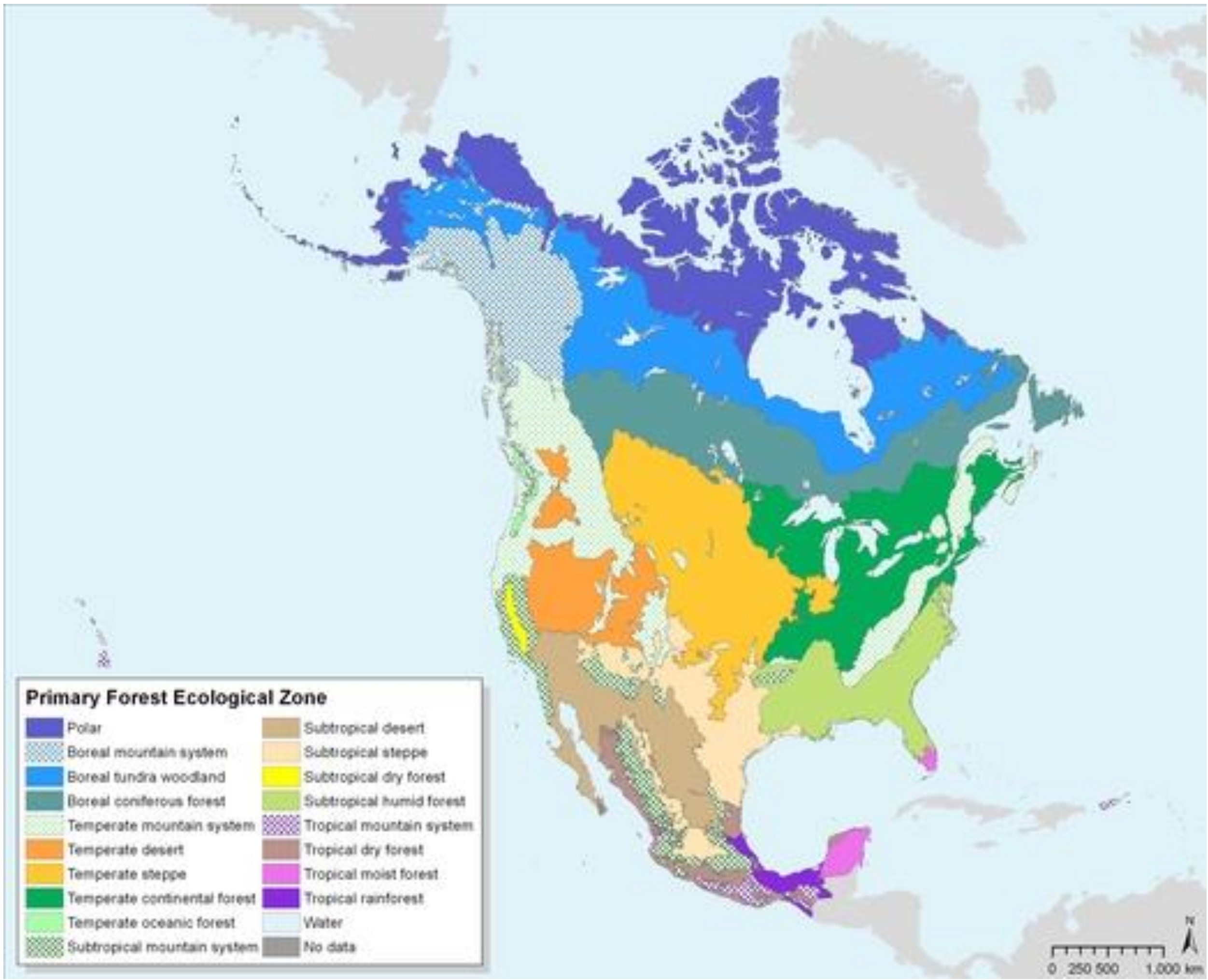
Adjacent forest vegetation, as noted above, influences the sizes and quantities of instream wood. Regional climatic variations that control the characteristics of forest vegetation can be grouped by a forest zone or forest series (Franklin and Dyrness 1973; Agee 1993). Ecoregions are characterized by climax species, tree size, and density of forest stands as influenced by climate and fire succession (Agee 1993). The distribution of tree species, heights, diameters, and stem densities in distinct ecoregions often differs due to variations in elevation, aspect, precipitation/soil moisture, and temperature (Henderson et al. 1992; Agee 1993). These in turn influence wood loads.

Each region in North America provides a unique set of characteristics (Figure 1-5). The example used herein is from the Pacific Northwest, where instream wood loading data was compiled for specific forest types. Comparisons could be made to forests with similar stand characteristics to estimate the relationship of riparian sources to potential wood loading. Seven major forest types compose ecoregions in the Pacific Northwest and are described below.

Sitka Spruce Forests

This forest type is generally limited to the coastal west-slope of the Pacific Northwest mountain ranges, particularly the western Olympic Peninsula due to the unique climate characteristics found there. The elevation of these forests is typically less than 300 meters (984 feet) above mean sea level (amsl), and normally within 20 kilometers (12 miles) of the coast; however, sites can be found farther inland up low-elevation river valleys (Agee 1993). Dominant tree species are the Sitka spruce (*Picea sitchensis*), with co-dominants of western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*), and, to a lesser degree, Douglas-fir (*Pseudotsuga menziesii*) (Agee 1993). The annual precipitation of the Sitka spruce (SS) region is 200–300 centimeters (79–118 inches) and includes a component of fog-drip. The air temperatures are mild year-round (Franklin and Dyrness 1973). The large dense timber of this region is attributed to climate, which facilitates tree growth. Indeed, Edmonds et al. (1993) found stem densities in this region between 476 and 508 per hectare (>5 centimeters [>2 inches] in diameter at breast height [dbh]), and tree stem basal areas between 77 and 94 square meters (92 and 112 square yards) per hectare. The date of the last fire in these forests has been identified by some researchers as over 1,100 years ago (Fahnestock and Agee 1983). Although this is not generally applicable to the entire SS forest type, it suggests that stand-replacement fires are rare.

Figure 1-5. North American Forests



Source: North American Forest Commission (2011).

Western Hemlock Forests

This forest type is generally found in the interior low elevations of western Washington, Oregon, and Northern California. The elevation is typically less than 800 meters (2,623 feet) amsl, although this may vary + 60 meters (197 feet) depending on aspect and local climate differences (Henderson et al. 1992). The dominant tree species is western hemlock, with Douglas-fir (DF) co-dominant (Agee 1993). Although Douglas-fir is dominant in the early seral stages following fire, it will eventually be succeeded by western hemlock at late succession (Agee 1993; Henderson et al. 1992). The western hemlock (WH) forest type has greater extremes of moisture and temperature than the SS forest type (Franklin and Dyrness 1973). The dryer summers are reflected in the wide spectrum of plant associations across this zone (Zobel et al. 1976). Fire frequency intervals are generally less than 750 years, although ignitions from Native Americans may have increased this frequency in some areas (Agee 1992).

The physical characteristics of the timber in this forest type are well documented. Spies and Franklin (1991) reported that the average stem densities of Douglas-fir (>100 centimeters [39 inches] dbh) in late-successional stands ranged from 18–29 trees per hectare, while Hershey (1995) reported 6–90 trees per hectare with stems >54 centimeters (22 inches). Tappeiner et al. (1997) reported basal areas in old-stands range between 46 and 91, with a median of 66 (square meters per hectare). Tree heights for two common plant association groups in this forest type average between 60 and 60 meters (200 and 225 feet), with mean maximum heights reaching 87 meters (285 feet) after about age 300 (years) (Henderson unpublished 1996).

Silver Fir Forests

This forest type is generally found at moderate to upper elevations on the west-slope of the Cascades. The typical elevation is between 800 and 1,200 meters (244 and 366 feet) amsl, although this may vary + 60 meters (197 feet) depending on aspect and local climate differences (Henderson 1996). The dominant tree species is Pacific silver fir (*Abies amabilis*), with western hemlock and Douglas-fir co-dominant at lower elevations and mountain hemlock (*Tsuga martensiana*) co-dominant at upper elevations (Agee 1993). Winter temperatures are moderate, but with a 1- to 3-meter (3- to 10-foot) winter snow pack (Franklin and Dyrness 1973). Droughts are infrequent, and summer precipitation usually exceeds 15 centimeters (6 inches) (Minore 1979). Fire return intervals are estimated to be between 300 and 600 years, but can be more frequent at lower elevations (100–300 years) (Agee 1993). Silver fir (SF) trees seldom survive major fires (Agee 1993); thus, fire return intervals often are points of stand origin.

Mountain Hemlock Forests

This forest type is generally found on upper elevations to the west of the Cascade crest, but below subalpine regions. There is substantial overlap with the silver fir forests; however, mountain hemlock (MH) is generally more prevalent at higher elevations. The elevation of this forest type is typically between 1,000 and 1,375 meters (3,280 and 4,511 feet) amsl, although this may vary + 60 meters (197 feet) depending on aspect and local climate differences (Henderson 1996). The dominant climax tree species is mountain hemlock, with the Pacific silver fir and subalpine fir (*Abies lasiocarpa*) as co-dominants (Agee 1993). Mountain hemlock has been found at elevations up to 1,800 meters (5,900 feet) in Washington where aspect, latitude, and local climates are favorable. Winter temperatures are cool, but summer temperatures can reach extremes of 26–30 degrees Centigrade (°C) (79–86 degrees Fahrenheit [°F]) (Arno and Hoff 1989). Fire return intervals are estimated to be around 500 years (Dickman and Cook 1989).

Subalpine Fir Forests

This forest type is generally found along the Cascade crest and the interior of the Pasayten Wilderness in the North Cascades at elevations above 1,300 meters (4,265 feet) amsl (Henderson 1996; Agee 1993) although this may vary +60 meters (197 feet) depending on aspect and local climate differences (Henderson 1996). The annual precipitation is typically between 100 and 200 centimeters (30 and 79 inches) (Agee 1993). The prolonged winter snow-pack (often between 7 and 8 meters [23 and 26 feet] in wetter zones), along with the coldest winter temperatures of all Pacific Northwest forests, limits growth compared to trees in lower elevation forests (Agee 1993). Summer temperatures can be relatively high, reaching 26–30°C (79–86°F) (Agee 1993). Mountain hemlock is often found at the lower boundaries of this forest type. The dominant climax tree species is subalpine fir (*Abies lasiocarpa*), with co-dominants of mountain hemlock, lodgepole pine (*Pinus contorta*), and Englemann spruce (*Picea englemanni*) (Agee

1993). Subalpine fir (SAF) and co-dominants are not well-adapted to surviving fires (Agee 1993) and fire return intervals, estimated to be around 250 years (Fahnestock 1976) or 109–137 years (Agee 1990), often are points of stand origin.

Grand Fir Forests

Grand fir (GF) (*Abies grandis*) are typically found at elevations between 1,100 and 1,500 meters (3,610 and 4,921 feet) amsl east of the Cascade crest, although populations of grand fir can be found at low elevations of inland western Washington (Agee 1993). GF forests generally separate ponderosa pine (*Pinus ponderosa*) forests (see below) from SAF forests. A mixture of species characterizes this forest type, with Douglas-fir as the climax dominant. Rarely is GF the late-successional dominant species. Hardwood species are often found as co-dominants. Fire intervals are frequent, often due to lightning strikes, producing a return interval of 50–100 years in drier sites.

Ponderosa Pine Forests

This species is typically found in dry, lower elevation (1,200–1,800 meters [3,937–5,905 feet amsl) sites east of the Cascades (Franklin and Dyrness 1973). Ponderosa pine (PP) forests contain a large co-dominant component of Douglas-fir (Agee 1993). Douglas-fir is always the co-dominant species in this forest type and is typically suppressed by fire (Agee 1993).

A natural fire-recurrence interval is typically between 11 and 24 years (Agee 1993). Due to frequent burns, fires are typically of low intensity; therefore, the older ponderosa pines are rarely killed unless fires are fueled by excess wood buildup in the under-story (Agee 1993). Camp et al. (1996) found ponderosa pines in portions of these forests (Swauk Late Successional Reserve) to have ages between 13 and 597 years, with a mean of 127 and a standard deviation of 100. Fire refugia are common in this forest type, and are typically found on north-aspect slopes and in confined channels (Camp et al. 1996). With fire suppression, beginning in 1909 in the Wenatchee Mountains (Holstine 1992), Douglas-fir has become more prevalent in many areas (Harrod pers. comm. 2000). Ponderosa pine typically can reach 35–45 meters (115–148 feet) in height with some exceeding 55 meters (180 feet) (WWPA 1995).

GUIDANCE

Other Forest Regions of North America

North America had some of the largest forested areas on earth. Forest regions across North America each have unique attributes, some of which provide distinctions for instream wood loading. The continent is surrounded by oceans and seas of various temperatures and climate. The National American Forestry Commission has identified 19 forest ecological zones of North American (Figure 1-5), with the 5 major zones defined as (1) the tropical climate in Southern Mexico; (2) the mild climate with wet winters and dry summers of the Pacific zone along the coastal regions from southern Alaska to southern California; (3) the mountainous and dry western interior of the United States and much of northern Mexico; (4) the humid eastern two-thirds of the United States and southern Canada, which have a humid climate with defined seasonal changes; and (5) the northern two-thirds of Canada and Alaska, as well as all of Greenland, which have arctic and sub-arctic climates. The most notable forest in North America is the taiga or boreal forest, which is a large expanse of mainly coniferous trees that covers much of central and southern Canada and Alaska. There is also a large area of redwood forests in California in the United States and tropical forests in Mexico. These forests have various levels of productivity, as indicated by their biomass, a measure of organic carbon.

1.3.4.3 Wood Recruitment through Natural Disturbance Regimes

Natural Disturbances

Instream wood loads vary over space and time due to an array of natural disturbance processes (e.g., Hickin 1984; Keller and Swanson 1979; Abbe and Montgomery 2003; Phillips and Park 2009). All channels have been affected by disturbance of some kind, whether historic or recent. Therefore, the characterization of wood from a single survey provides a temporal "snap-shot," documenting only a single instant in the patterns of fluctuation. Wood accumulations are not constant, but rather fluctuate with disturbance cycles. The accretion of wood may continue over time until capacities exceed an ecological or morphological threshold, some of which result in a catastrophic removal by disturbance. The amount of instream wood, therefore, represents a time since the last disturbance and the temporal conditions during the recovery period. Several natural disturbances responsible for wood recruitment to channel networks are discussed below.

Bank Erosion

Bank erosion occurs throughout the channel network of a watershed. It occurs when the erosive forces acting upon a bank (shear stress, pore pressure) exceed the resisting forces (material internal shear strength and cohesion, root reinforcement). Bank stability decreases with increasing slope, height, and shear stress. It is also directly related to material properties of the bank that define its strength or resistance, such as grain size distribution, internal shear strength/friction angle, cohesion, water pore pressure, stratigraphy, shear planes, and root reinforcement. Processes triggering bank erosion include the following:

- Shear stress imposed on bank by high flows.
- Shear stress at bank toe that undermines and over-steepens and destabilizes the bank.
- Channel incision that over-steepens and destabilizes adjacent banks.
- Lateral channel migration resulting from instream sedimentation (sand and gravel bars) that directs flow against channel banks.
- Removal of riparian vegetation that reduces bank strength.
- Flow constriction due to channel obstructions such as landslides, snags, and logjams.

Bank erosion can be the dominant wood mechanism in many parts of the channel network. Erosion over-steepens adjacent hillslopes and triggers landslides that deliver trees to the channel. Volumes of wood recruitment are typically highest in larger alluvial streams prone to channel migration. Large, low-gradient channels characterized by high banks of unconsolidated fine sediments are particularly prone to bank erosion. As discussed earlier, Moulin et al. (2011) found that bank erosion accounted for over 70% of the instream wood in the Roanoke River in Eastern North Carolina.

Wood recruitment, transport, and deposition in cold regions can be directly influenced by ice flows and ice jams. Ice flows can entrain wood and mow down riparian vegetation (e.g., Keller and Swanson 1979; Smith 1979; Smith and Reynolds 1983; Hickin 1984; Smith and Pearce 2000; Prowse 2001). Large accumulations of wood and logjams also occur in many northern rivers that are subject to freeze up (e.g., Hickin 1984; Makaske et al. 2002) but not to large ice flows that scour the channel (Pariset et al. 1966; Smith 1979; Beltaos 1983; Prowse 2001).

Severe Weather and Wind Throw

Storms that bring severe winds and rainfall can be a major wood recruitment mechanism to streams throughout the United States. Severe wind capable of tree "blow down" is often associated with major storm fronts and can be further exasperated by local orographic effects. Hurricanes contribute huge quantities of wood to streams within their path, primarily impacting states along the Gulf Coast and Eastern seaboard (e.g., Frangi and Lugo 1991, Foster and Boose 1992, Boose et al. 2001, Chambers et al. 2007). Chambers et al. (2007) predicted that Hurricane Katrina in 2005 resulted in the mortality and severe structural damage to approximately 320 million large trees, equal to 50-140% of the net annual U.S. forest carbon sink. Zeng et al. (2009) estimated that tropical cyclones result in the mortality and damage of 97 million trees annually from 1851 to 2000 in the continental

United States, primarily in the Gulf Coast region. Hurricanes and severe thunder storms often are associated with flooding which is called out as a separate recruitment process below. Ice storms also result in major wood inputs, particularly in deciduous forests of the Midwest and Northeast states (e.g., Millward et al. 2010).

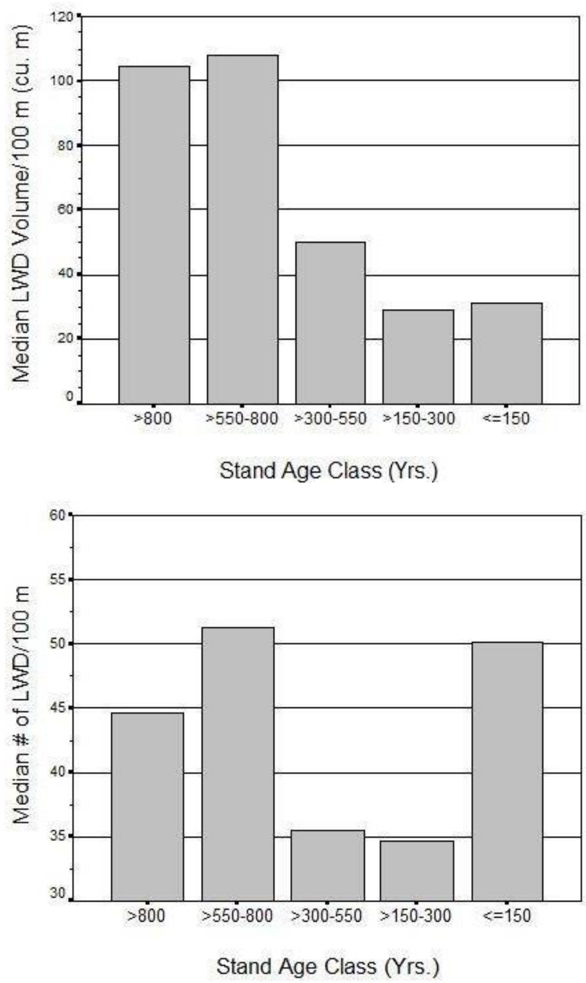
Wind throw, usually associated with severe storms, is a significant source of large wood recruitment to streams in all parts of the United States (Lienkamper and Swanson 1987; Robison and Beschta 1990; Frangi and Lugo 1991; Foster and Boose 1992; Boose et al. 2001; Chambers et al. 2007; Phillips and Park 2009), and ice storms (e.g., Millward et al. 2010).). In old-growth riparian forests, wind throw does not topple whole trees as much as it recruits a greater proportion of branches and treetops to the channel than in younger riparian stands, especially in areas prone to strong winds or heavy snowfall (Bisson et al. 1987). However, wind throw accelerates mortality in riparian areas abutting newly harvested forests, disrupting the rate of recruitment to streams (Grizzel and Wolff 1998). A riparian stand's orientation to prevailing winds and soil wetness can exacerbate wind throw (Bisson et al. 1987). Wind throw and subsequent recruitment to the channel is thus chronic or episodic, and it can be influenced by both natural and anthropogenic conditions.

Fires

Although fires do not directly deliver wood to streams, they are responsible for increasing tree fall and slope erosion, which do deliver wood. Disturbance that kills some or all the vegetation in a particular location is an intrinsic part of ecosystem development (Raup 1957; Oliver 1981). Effects will vary with climate, geomorphology, topography, soils, and vegetation (Swanson et al. 1988). The return intervals for fires, which vary by ecoregion (Agee 1993), affect timber age (Henderson et al. 1992). In turn, timber age influences mean tree diameter, which influences the diameter of instream wood (Rot et al. 2000). Timber age also influences tree height (Agee 1993; Henderson et al. 1992), and wood recruitment distance is a function of height (McDade et al. 1990). Therefore, fire affects instream wood diameter and recruitment patterns.

Fires do not burn forests evenly. The variability in timber age due to stand-replacement fires illustrates that "old-growth" forests are clearly not homogenous in their life cycles among forest zones or within basins. Forest growth frequently is interrupted prior to the maximum life span of many trees in forested basins, as suggested by the heterogeneity in forest ages within forest zones. This likely adds diversity in tree sizes, densities, and rates of stem exclusion and mortality. Patches of timber unscathed by a fire (fire refugia) can diversify timber ages along riparian areas (Camp et al. 1996). Fire affects the rate of recruitment when the regenerated forest selectively thins, dropping the younger trees, out-competed by larger, more dominant trees. This occurs in stands <220 years old (Rot et al. 2000). This may also explain why measured instream large wood volumes increase as stands become older, because the recruited trees are larger (Fox 2001). Fox (2003) found a relationship between instream wood loads and riparian stand age as a good indicator of succession. In that study, the distribution of number of large wood pieces by age class suggested that stem-exclusion processes provide large initial inputs of wood numbers over the first 150 years, but they are low in volume (Figure 1-6A) likely due to their small diameter. Pollock and Beechie (2014) also found large numbers of recruited trees to the channel as stands naturally thin through stem seclusion. Wood recruitment (both piece number and volume) is relatively low as stands mature over the next 400 years, after much of the stem-exclusion process has occurred but before age-related mortality takes place.

Figure 1-6. The Median Instream Large Wood Volume (A) and Number of Pieces (B) According to Adjacent Riparian Stand Age Class, at the Time of 1999–2000 Surveys



Source: from Fox (2003), with age data courtesy of Ian Henderson, unpublished data,

This data also suggests that as the forests reach late-succession at approximately 550 years, the mortality of the remaining older seral species becomes most prominent, combined with some mortality of late-successional dominants associated with aging stands. This likely explains the increases of instream large wood pieces at this age class (Figure 1-6B), as well as the fact that these large trees are likely to be more stable and resist entrainment, and so more readily accumulate in the channel.

At 800 years, younger trees are released by canopy openings during vertical stratification of the late-successional stands and the mortality rate decreases, resulting in a seemingly paradoxical decrease of instream large wood abundance. This concept is supported by the findings of McDade et al. (1990), who report that approximately half of the large wood found in the channel adjacent to second-growth forests came from the previous old forest rather than from newly regenerated stands.

Floods

Floods can entrain wood from areas adjacent to stream reaches due to floodplain inundation and an increase in fluvial forces. High flows associated with floods increase the shear stress on and buoyancy of instream wood and carry wood downstream or perhaps completely out of a system. Rootwads inhibit large wood movement because they increase displacement and draft (such as keel on a sailboat), and scour around the rootwad allows logs to become embedded in the channel (Abbe and Montgomery 1996; Abbe et al. 2003a; Abbe and Brooks 2011). Floods not only remove wood from streams but can also recruit new trees. Palik et al. (1998) found an average of 22 new trees per kilometer recruited into a coastal plain stream during a large flood.

Despite the potential mobilization of wood due to floods, Fox (2001) found that floods had little influence on the overall instream wood loads of natural systems. He explained this by two observations: (1) much of the wood in these systems has previously resisted mobility during large floods, as broadly interpreted by the overall age of pieces (as estimated by decay classifications) found in the channel during the surveys—even small pieces of wood in some streams had advanced decay, which suggests these pieces have also prevailed within the system despite floods; and (2) floods may replace wood flushed from a system with newly recruited trees from bank avulsion, debris flows, or upstream sources. Therefore, net loss of wood from floods may not occur in unmanaged basins. However, this phenomenon may not extend to heavily managed watersheds where natural hydrological regimes have been altered to increase the frequency of flooding; banks have been hardened to minimize lateral migration; and instream wood is smaller, less stable, and more susceptible to mobilization.

Landslides and Debris Flows

Landslides and debris flows are most common in mountain regions. They are a natural process that occurs in every region of the United States. These hillslope or mass-wasting processes can be triggered by human disturbance such as deforestation, unstable earthen fill, and poor drainage from roads and developments. Landslides and debris flows affect stream channels and influence the quantity, quality, and distribution of instream wood. The often-violent mobilization of material in channels where this occurs may either transport wood out of a reach or bring in new wood from upstream sources. Debris flows tend to deposit wood on slopes of 3–6 degrees (approximately 5–10% gradient) (Ikeya 1981; Benda and Cundy 1990; Fox 2001) and remove it from streams with gradients >10% (Fox 2001). In older forests, large standing trees and instream logs can retard debris flow propagation and run-out lengths compared to debris flows in industrialized forests (Coho and Burges 1993). Small, high-elevation regions of the country experience snow avalanches that recruit wood into streams (Keller and Swanson 1979) and influence the riparian vegetation (Fetherston et al. 1995). Snow avalanche paths are typically less confined than debris flows, and they often form a broad fan where the channel gradient flattens, such as at the channel bottom intersecting with the floodplain of a larger system. Snow avalanches are most common in small headwater channels within the snow zone (Keller and Swanson 1979). Due to the snow pack buffering of the channel bed, substrates are often undisturbed following a snow avalanche; however, most trees larger than 10–15 centimeters (4–6 inches) in the path are sheared off at the level of snow depth (Fox 2001).

The loss of riparian vegetation is likely to influence instream wood quantities due to the disturbance of the recruitment source. Most likely, snow avalanches occur at frequent intervals in certain channels, maintaining a level of disturbance to the channel and riparian area. This can preclude new wood recruitment to the adjacent and downstream channel. Fox (2001) reports that low-gradient channels (<6%) impacted by snow avalanches had nearly the same number of wood pieces per 100 meters (328 feet) as channels with no recent disturbance; however, both the median numbers and volumes of wood per 100 meters (328 feet) were lower in steep channels (>10% gradient) with snow avalanches compared to channels without disturbance. This could likely be attributed to the lack of riparian trees available for recruitment.

Human Influence

The difference in the distribution and characteristics of wood between managed and unmanaged basins has been clearly established. Wood can be limited due to riparian vegetation modifications (Ralph et al. 1991), whether due to forest practices, urban development, or agricultural practices. Unmanaged channels, often defined by streams draining un-roaded and unlogged basins, typically have more channel roughness due to instream wood than managed channels (Bilby and Ward 1991; Ralph et al. 1991), especially if the stream has been channelized. These factors, especially if peak flows are exacerbated due to land uses, may lead to less retention of recruited wood than in streams draining unmanaged basins.

Other forms of human influence on wood loading besides forest clearing can also result in disruptions of the process by which wood reaches streams and is distributed.

Hydromodifications

Disruptions to flow and subsequent transport of wood by hydromodifications can alter wood loads. Features such as dams, levees, road revetments, culverts, and similar facilities can intercept or impede the recruitment and entrainment of wood. Alterations to flow regimes can hinder or accelerate fluvial distribution of wood.

Road Networks

Roads also influence instream wood loading and transport. Maintenance activities often remove wood and clear jams to keep culverts and bridges free of debris and reduce structural damage during storms (Singer and Swanson 1983). Wood mobilized during high flows frequently becomes trapped on channel-spanning bridges and culverts, leading to road overtopping and eventual structure failure. Managers clear jams to keep structures free of obstructions and reduce damage to river crossings. Such management may completely eliminate large wood or remove only the largest pieces that pose the greatest hazard, but which are the most important to habitat formation. Additionally, roads themselves can encroach upon riparian forests, permanently removing sources of wood recruitment as long as the road is maintained.

Forest Practices

Timber harvest activities in streamside forests can directly affect wood input (Lienkaemper and Swanson 1978; Bilby and Bisson 1998). Clear-cut logging, often with inadequate buffer strips surrounding the stream channel, was a common management practice throughout the Pacific Northwest and Alaska until the late 1980s (Dominguez and Cederholm 2000). The harvesting of streamside forests may temporarily reduce or eliminate large wood recruitment to the stream (Bryant 1980), and the recovery time for input to return to pre-harvest conditions will take many decades. For example, Andrus et al. (1988) reported that in a stream flowing through a second-growth forest 50 years after logging, 86% of the instream wood was remnants of the pre-existing forest. The old wood accounted for 93% of the pools. The results indicate that some second growth stands will take much longer than 50 years for the new forest trees to make a significant contribution of large wood. A decay model calibrated in southeastern Alaska predicted a 70% reduction in wood 90 years after clear-cutting, and that full recovery exceeded 250 years (Murphy and Koski 1989).

Logs derived from second-growth forests have smaller diameter and lower volume than old-growth large wood, contributing to lower instream loading in logged streams (Bilby and Ward 1991; Ralph et al. 1991). Second-growth wood loads tend to be composed of deciduous riparian species and small conifers that degrade more easily and have less of an effect on long-term channel morphology (Dominguez and Cederholm 2000).

A comparison between unlogged, moderately logged, and intensively logged catchments found that undisturbed streams contained more logs in the largest size categories (>50 centimeter [20 inches] in diameter) than managed streams, which reduce the amount of pool habitat (Ralph et al. 1991). Bilby and Ward (1991) found that wood-formed pools were less abundant in second-growth forests compared to old-growth forests. This is supported by Chesney (2000), who found that wood within the low-flow channel was greater in unmanaged forests compared to streams within second-growth forests.

Logging can have indirect effects on wood loads. Harvest activities can destabilize hillslopes and increase the likelihood of debris avalanches (Lienkaemper and Swanson 1978). The use of buffer strips is a common technique for reducing logging effects on forests and streams; however, buffer strips adjacent to clear-cuts are exposed to higher wind velocities, increasing the occurrence of wind thrown logs to the stream channel (Reid and Hilton 1998). Higher rates of wind throw may lead to rapid depletion of available wood from the remaining adjacent forest, increasing short-term large wood input, but decreasing long-term input.

Urbanization

The paucity of large wood in streams within developed and developing parts of the world is common, even where vast forests once covered the landscape (e.g., Wiltshire and Moore 1983; Petts et al. 1989). Navigation and conveyance interests motivated widespread removal of instream wood obstructions and riparian trees. Data from Horner et al. (1997) show a clear general trend that the more urbanization, the less large wood in the encompassed stream.

GUIDANCE

Common Means by Which Large Wood Is Lost From the Urban Channel

- *Peak Flows*. As the magnitude of channel flow increases due to proliferations in impervious surface, the peak discharges of annual and multi-year floods increase typically two- to five-fold (Hollis 1975) and the duration of flood flows may increase more than ten-fold (Barker et al. 1991). The consequences are high rates of wood depletion through entrainment. The scour of bank vegetation that may normally assist in the stabilization of wood further compounds wood depletion.
- *Channel Incision*. With increased flows and sediment transport comes channel down-cutting. The immediate consequences of such a process is a deep and narrow channel that vertically strands wood that once was in contact with the bed, and further increases erosion due to less resistance (Booth 1990).
- *Human Removal*. Wood has been removed for various reasons from the urban landscape. Stream beautification and tidiness, the perception of better fish passage, better safeguards against avulsion and lateral migration, and improved water craft navigation, for example, compelled humans to remove wood from streams.

Although not necessarily an artifact of urbanization, the presence of humans has implications for instream wood loads. Across much of North America, particularly the Pacific Northwest, wood has been extirpated from our streams, and the riparian sources have been compromised in their ability to recruit wood. A common practice to improve fish passage and flow conveyance in the Pacific Northwest was to have crews remove wood from streams (also known as "stream cleaning"), particularly between the 1950s and 1970s (Bisson et al. 1987). Wood was eradicated so successfully from many streams (Reeves et al. 1991) that there are still consequences to fish habitat (Bisson et al. 1987). The removal of wood from rivers was a major endeavor to promote navigation and log transport to mills, particularly in Pacific Northwest streams. The removal of hundreds to thousands of snags per year by the USACE continued in the region's rivers through at least 1960 (Collins et al. 2003).

1.3.5 Wood Management

Not all forms of human influence have led to the depletion of wood from our streams. Because of the correlations wood has to channel morphology, aquatic habitat, and salmonid production, and due to the paucity of instream wood stemming from past land-use practices, wood placement projects have become a common method for restoring or enhancing salmonid habitat (Kauffman et al. 1997). Resource managers have been successful at inducing salmonid response by placing wood in streams (House and Boehne 1986; Cederholm et al. 1988; Nickelson et al. 1992; Murphy 1995; Riley and Fausch 1995; Solazzi et al. 2000; Roni and Quinn 2001). As a long-term approach, many researchers have advocated the maintenance of wood loads by restoring natural riparian processes (Sedell and Luchessa 1981; Elmore and Beschta 1988; Cederholm et al. 1997b; Roni and Quinn 2001).

1.3.5.1 Forest Characteristics

Various forest characteristics, perhaps independent of large-scale climatic or disturbance-related factors, will influence the number, volume, and size of instream wood. Rot et al. (2000) found the diameter of instream large wood increased with riparian stand age, and that stand age and mean stem diameter were correlated. Tree age varies considerably within older forests. For example, Tappeiner et al. (1997) found age in old-growth stands ranged between

50 and 414 years at one site. They saw median age differences of 187 years across ten sites in the same region. Timber on the Olympic Peninsula, Washington, often older than 700 years (Henderson unpublished data), can produce very large-diameter instream wood. Within streams draining old-growth forests, McHenry et al. (1998) found a mean large wood diameter of 0.3 meter (1 foot) and diameters up to at least 2.5 meters (8 feet). However, because most wood pieces could not be attributed to an adjacent source (McDade et al. 1990), upstream riparian areas and basin processes may provide a better predictor of instream wood quantities than adjacent riparian areas.

In much of the forestry literature, riparian forests are characterized with general forest attributes only. However, significant distinctions are likely to exist between upland and riparian stands. Naiman et al. (1998) reported that the basal area of riparian forests is generally as great as or greater than that of upland forests; riparian forests have relatively high rates of biomass production in comparison with upland forests, likely influenced by moisture, nutrients, and temperature gradients. They also often promote deciduous seral species regeneration in response to channel-associated disturbances (Naiman et al. 1998). Collins et al. (2003) tallied the occurrence of tree species along the major rivers of western Washington as reported in surveyors' notes from the mid- to late nineteenth century; they found an average of 84% hardwood species by stem count and about 55% by biomass, particularly from the presence of red alder (*Alnus rubra*). This contrasted to the dominance of Douglas-fir and western hemlock on adjacent upland terraces, together with a significant component of riparian western red cedar. Finally, Gregory et al. (1991) and Pollock et al. (1998) found that microclimate gradients also contribute to greater plant and animal species diversity in riparian forests than in upland forests. Riparian forest structure and characteristics are therefore apparently different from, and generally more productive than, typical upland forests.

1.3.5.2 Instream Wood Quantities

The composition and character of riparian vegetation can dictate the species composition, numbers, size, and volume of large wood recruited to the channel, and lateral and vertical distribution of that large wood within the channel (Grette 1985; Bisson et al. 1987; Bilby and Wasserman 1989; Bilby and Ward 1991; Ralph et al. 1991; Bryant and Sedell 1995; Bilby and Bisson 1998; Fox and Bolton 2007). Factors that influence the spatial distribution of instream wood include both the regional context and the local geomorphic setting.

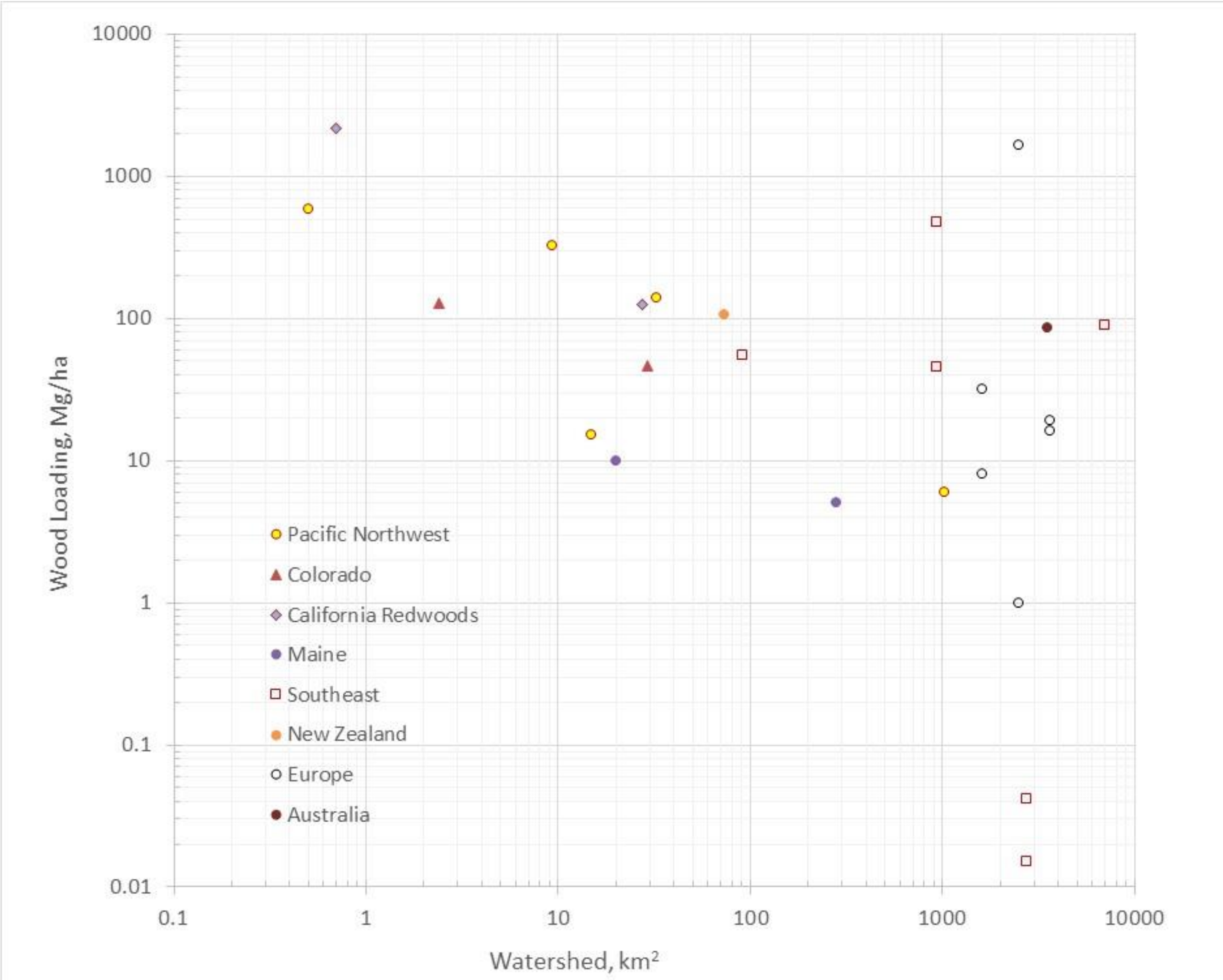
Regional factors influence the quantities of wood in a system but do not appear to vary their spatial organization. Fox (2003) found that forest regions did not have a pronounced effect on the grouping or clustering of large wood pieces, which were proportionally the same in streams of similar widths regardless of forest type.

Fox and Bolton (2007) counted pieces of wood in 150 sites totaling nearly 38 kilometers (24 miles) of streams draining unmanaged Pacific Northwest forests. Sampled stream gradients ranged between 0.04 and 49% and represented a diverse array of channel types, confinement classes, bedforms, dominant water origins, disturbance histories (fire, debris flows, snow avalanches, and floods), basin sizes, elevations, and forest types common in the Pacific Northwest. These authors quantified wood loads within forest types and channel sizes based on statistically discrete groupings, where they found similarities between the SS/WH and SF/MH ecoregions, and between the SAF and GF ecoregions. These large wood quantities are provided in Table 1-1, using data only from fully unmanaged watersheds. The watersheds in this data set are characterized by forests that are all loosely termed as "old-growth" and also meet the following criteria: (1) no part of the basin upstream of the survey site was ever logged according to forest practices commonly employed since European settlement; and (2) the basin upstream of the survey site contains no roads or human-made modifications to the landscape that potentially could affect the hydrology, slope stability, or other factors affecting the natural processes of wood recruitment and transport in streams. Some of these basins may be managed to remain pristine, however, which may also include fire suppression. It is assumed that these forest conditions incorporate the range of variability and disturbance frequencies to which many aquatic species have adapted.

Estimations of wood loading around the world vary from less than 1 to 2,000 megagrams per hectare of channel with no strong correlation to region or channel size (Moulin et al. 2011) (Figure 1-7). Cordova et al. (2007) report that average wood loading in pieces per kilometer range from a high of 362 in the Northwest to 326 in the Midwest, to 161 in the Northeast to 61 in the Southeast. Recent surveys by Krause and Roghair (2014) found the average piece count in six North Carolina streams measured in 2007/2008 and 2012/2013 ranged from 206 to 170 pieces per kilometer, respectively. Wood loading per unit channel area tends to decrease with increasing channel size, but differences in forest trees, channel substrate, and flow regimes may account for major differences independent of channel size. The size of wood and whether or not it includes a rootwad (e.g., Abbe and Montgomery 1996; Abbe et al. 2003b; Abbe and Brooks 2011; Moulin et al. 2011) directly influence piece stability. Abbe and Montgomery (1996) discuss the importance of large trees in the formation of key pieces or snags that initiate logjams in large rivers. Fox and Bolton (2007) identified individual logs (i.e., key pieces) that exhibited indicators of long-term stability (persisting through at least moderate floods) and related them to channel size (Table 1-2).

Fox and Bolton (2007) suggest that minimum piece volumes used to define a key piece should consider the role rootwads play in achieving stability. In channels greater than 30 meters (98 feet) BFW, more than 91% of all key pieces had rootwads attached. Therefore, in order to meet the objective of defining a key piece, not only do the prescribed minimum volumes need to be met, but also rootwads must be considered in the definition.

Figure 1-7. Wood Loading in Streams Throughout the United States and Other Regions Typically Range from 1 to 2,000 Megagrams per Hectare



Although there is a generally reduction in wood loading with increasing channel size, there is significant variance due to tree size and the size, slope, and substrate of channels. (Data compiled from Keller and Swanson 1979; Bryant 1983; Wallace and Benke 1984; Hauer 1989; Shields and Smith 1992; Keller and MacDonald 1995; Lisle 1995; Richmond and Faush 1995; Gippel et al. 1996; Piégay and Marston 1998; Piégay et al. 1999; Cordova et al. 2007; Baillie et al. 2008; Magilligan et al. 2008; Moulin et al. 2011.)

Table 1-1. Distributions of Wood[1]

Region	BFW Class (meters)	75^{th} Percentile	Median	25^{th} Percentile
Number of Pieces per 100 meters of channel length				
Western Washington	0–6	>38	29	<26
	>6–30	>63	52	<29
	>30–100	>208	106	<57
Alpine	>0–3	>28	22	<15
	>3–30	>56	35	<25
	>30–50	>63	34	<22
DF/PP Forest Zone	0–6	>29	15	<5
	>6–30	>35	17	<5
Volume (cubic meters per 100 meters of channel length)				
Western Washington	0–30	>99	51	<28
	>30–100	>317	93	<44
Alpine	>0–3	>10	8	<3
	>3–50	>30	18	<11
DF/PP Forest Zone	0–30	>15	7	<2
Number of Key Pieces per 100 meters of channel length				
Western Washington	0–10	>11	6	<4
	>10–100	>4	1.3	<1
Alpine	>0–15	>4	2	<0.5
	>15–50	>1	0.3	<0.5
DF/PP Forest Zone	0–30	>2	0.4	<0.5

Source: Fox and Bolton (2007, Table 4).

[1] Number, volume (cubic meters), and number of key pieces, all per 100 meters of channel by Forest Regions in Washington State and bankfull width class. Wood includes pieces exceeding 10 centimeters (4 inches) in diameter and 2 meters (6 feet) in length.

Table 1-2. Minimum Wood Piece Volume Required to Qualify as a Key Piece (by Bankfull Width Class)

BFW Class (meters)	Minimum Volume (cubic meters)
0–5	1.00[1]
5–10	2.50[1]
10–15	6.00[1]
15–20	9.00[1]
20–30	9.75
30–50	10.50[2]
50–100	10.75[2]

[1] Current WFPB (1997) definition.
[2] Piece must have an attached rootwad.

1.3.5.3 Stability Factors

Factors inducing wood stability are seemingly dependent on the interaction of pieces within groups and how groups are assembled during fluvial processes. Fox (2003) and Parrish and Jenkins (2012) found that the stability of wood increases with jam size due to a larger matrix of pinned logs. However, Fox suggests that the percentage of stable logs decreases as channel size increases because much wood is loosely assembled as pieces become stranded on gravel bars as flows recede. Conversely, gravel bars and highly sinuous channels were less commonly observed in small streams; thus, accumulations of wood along the banks and channel margins may require greater proactive fluvial force to impinge wood because there are fewer collection points for wood during flow recession.

1.3.6 Wood Performance Standards

The percentile distributions for large wood quantity, volume, and key-piece quantity (Table 1-1) represent the range of conditions found in streams draining unmanaged forests that are subject to a natural rate of disturbance (except fire suppression) in the Pacific Northwest. Assuming these data include both favorable and unfavorable salmonid habitat conditions as they relate to instream wood, this range can be used to set management targets in the Pacific Northwest for riparian recruitment objectives, regulation, habitat restoration, enhancement, and evaluation. For restoration and enhancement of instream wood loads, streams should be managed to meet this natural distribution at a basin scale, where restoring the natural heterogeneity of wood loads is the primary objective. Streams in a degraded state (e.g., below the median) should be managed for wood inputs exceeding the median of this range. The top of these distributions, the 75th percentile and above, should be used as an interim management "target" until the basin-scale wood loads achieve the central tendencies of natural and unmanaged wood-loading ranges.

The precise quantities and volumes of wood needed by salmonids for successful production are not well understood. Statistically sound studies to link instream wood loads to salmonid production would be expensive and have high levels of uncertainty owing to the multiple variables influencing salmon production (Roni et al. 2003). However, historic salmonid populations were much higher than those found today, and, as noted earlier, unmanaged forests offer the best source of information on wood loads as one component of habitat to which salmonids have adapted. In degraded streams, where management is needed to restore favorable conditions, wood loads are often no longer found in the upper distribution of these ranges, or the distribution is centered around a lower mean. In these cases, merely managing for the mean or median will not restore the natural ranges of heterogeneity. Therefore, for management purposes intending to restore natural wood-loading conditions, establishing instream wood targets based on the upper portion of the distribution observed in natural systems (i.e., the 75th percentile) rather than the lower portion of the distribution is reasonable as well as prudent to restore natural ranges.

The reported wood loading ranges of Fox and Bolton (2007) are not likely representative of all streams across North America due to differences in wood source characteristics and loading mechanisms. For example, wood loads in the sparsely forested regions of the western desert are likely to be much lower than those of the densely forested Pacific Northwest; therefore, it may be unrealistic to apply these wood loads as a performance standard everywhere. In this regard, performance standards could be formulated in a similar manner using reference site surveys, river snagging records, old forest characteristics, and other information as available. However, it can be acknowledged that restoration endeavors that aim to create favorable habitat conditions in a degraded system may benefit from using overly conservative wood loading conditions. Assuming the wood conditions in target restoration reaches are far below the median range (and hence need enhancement), a reach or more with higher-than-expected wood loads may help restore heterogeneity and provide ecological elements that are in short supply.

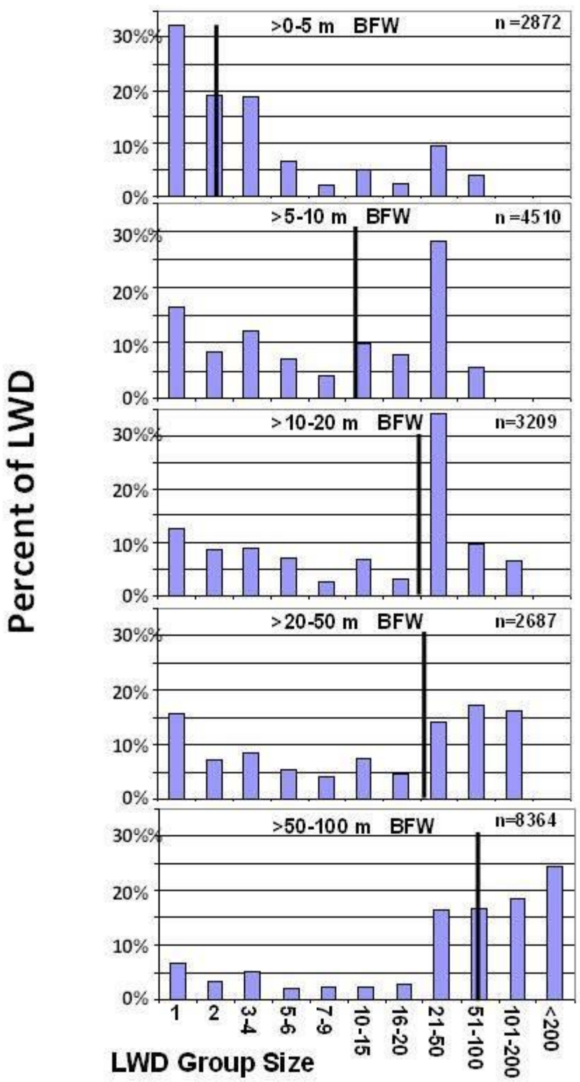
1.3.7 Wood Distribution within Channel Networks

Fox (2003) found that channel size (as represented by bankfull width) is a significant geomorphic influence on group size distribution. Figure 1-8 illustrates that the percentage of wood allocated to larger group sizes increases with channel size. With each greater channel size class, the percentage distribution of large wood shifts to larger group size classes, as depicted by the shift in the median in Figure 1-8. These data together with observations of Abbe and Montgomery (2003) support the theories and hypotheses of Keller and Swanson (1979) and Swanson et al. (1982) that wood becomes more clumped (i.e., organized into larger jams) with increasing channel size.

The lateral channel position of wood is also an important design consideration. Wood placed too high on the bank may serve to resist channel migration, but fail to provide habitat at lower flows. Wood organization in unmanaged systems may also provide a reference for conditions to which salmonids have adapted. Fox (2003) also looked at lateral distribution of wood as broken into four zones: Zone 1 is the wetted low-flow channel, Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel, Zone 3 is above the high-flow channel but within the vertical confines of bankfull, and Zone 4 is laterally beyond the bankfull width. Wood in these four zones provides different purposes, from summer rearing habitat in Zone 1 to stability functions when wood extends far into Zone 4. Distributions of wood from small groups of wood (less than 10 pieces per group) are presented in Figure 1-9A and for large groups (10 or more pieces per group) in Figure 1-9B.

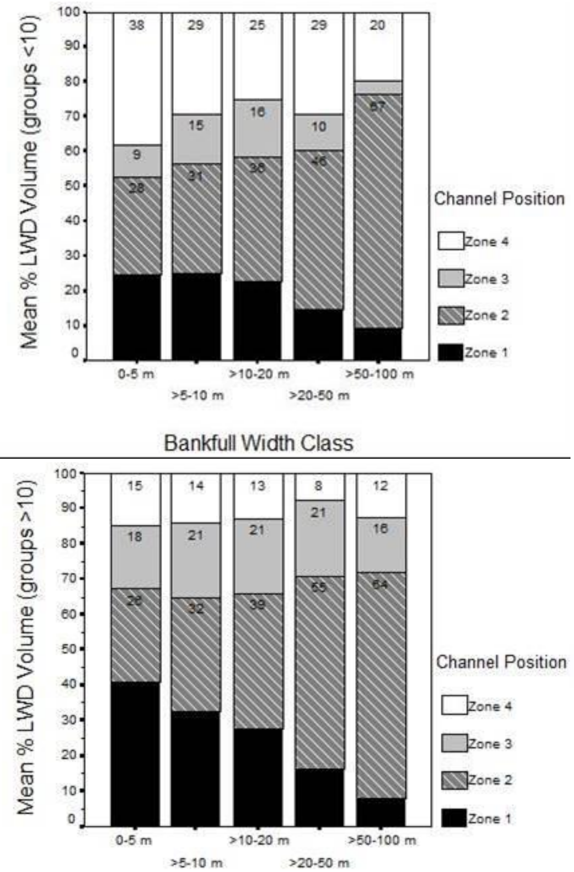
Restoration projects involving wood as a restoration tool often utilize ELJs, where all aspects of the design are carefully planned using the principles of physics, hydraulics, biology, safety factors, and other considerations to ensure the project meets the intended project objectives. The questions “how many jams,” “how much wood should be placed within them,” and other specifics are valid points to consider. Some questions are best answered on a hydraulic and geomorphic basis; however, replicating the natural range and heterogeneity of conditions to which salmonids are accustomed will provide greater certainty in ecological success. Therefore, it may be more prudent to couple the wood loads from Table 1-1 and distribute them in proportions reported in Figure 1-8. For example, place the targeted number and volume of wood into jam grouping percentages provided in the appropriate channel size of that figure, combined with the lateral distributions provided in Figures 1-9A and B.

Figure 1-8. The Percent Distribution of Large Wood to Group Size Class According to Five Bankfull Width Classes



The vertical bars represent the median values. From Fox (2003).

Figure 1-9. Comparison of the Mean Percent Large Wood Volume by Four Lateral Zone Distributions[1]



[1] Between (A) small groups (<10 pieces per group) and (B) large groups (≥10 pieces per group) according to five BFW classes. Zone 1 is the wetted low-flow channel, and Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel. Zone 3 is above the high-flow channel but within the vertical confines of bankfull, and Zone 4 is laterally beyond the BFW. The numbers in parentheses are the standard deviations, and n= the number of large wood groups. From Fox (2003).

When restoration projects involving the artificial placement of instream wood are warranted, the reference conditions of instream wood in natural systems can offer guidance for restoring the heterogeneity and structure of wood in adversely impacted systems.

The following steps provide an example of how to use such comparisons to proceed with a restoration endeavor, based on the findings of Fox and Bolton (2007) and Fox (2003):

1. Through monitoring and assessment, determine the current status of instream wood in a potential restoration project reach.
2. Based on natural distributions of large wood piece numbers and volumes, assess if wood additions are warranted, and how much more is needed to attain natural loads. Tables 1-1 and 1-2 provide a summary of natural large wood distributions based on Fox and Bolton (2007).
3. Organize spatial wood distributions according to those found in natural systems. Figure 1-8 provides the natural distribution of wood to various group sizes based on Fox (2003), enabling a comparison to the existing organization of wood in the stream targeted for restoration. The filling of voids in this distribution within the project area can then be facilitated in order to mimic a more natural spatial distribution.
4. Organize lateral wood distributions according to those found in natural systems. Figures 1-9A and 1-9B provide the natural distribution of wood according to lateral channel zones based on Fox (2003), enabling a comparison to the existing organization of wood in the stream targeted for restoration. The filling of voids in this distribution within the project area can then be facilitated in order to mimic a more natural distribution.

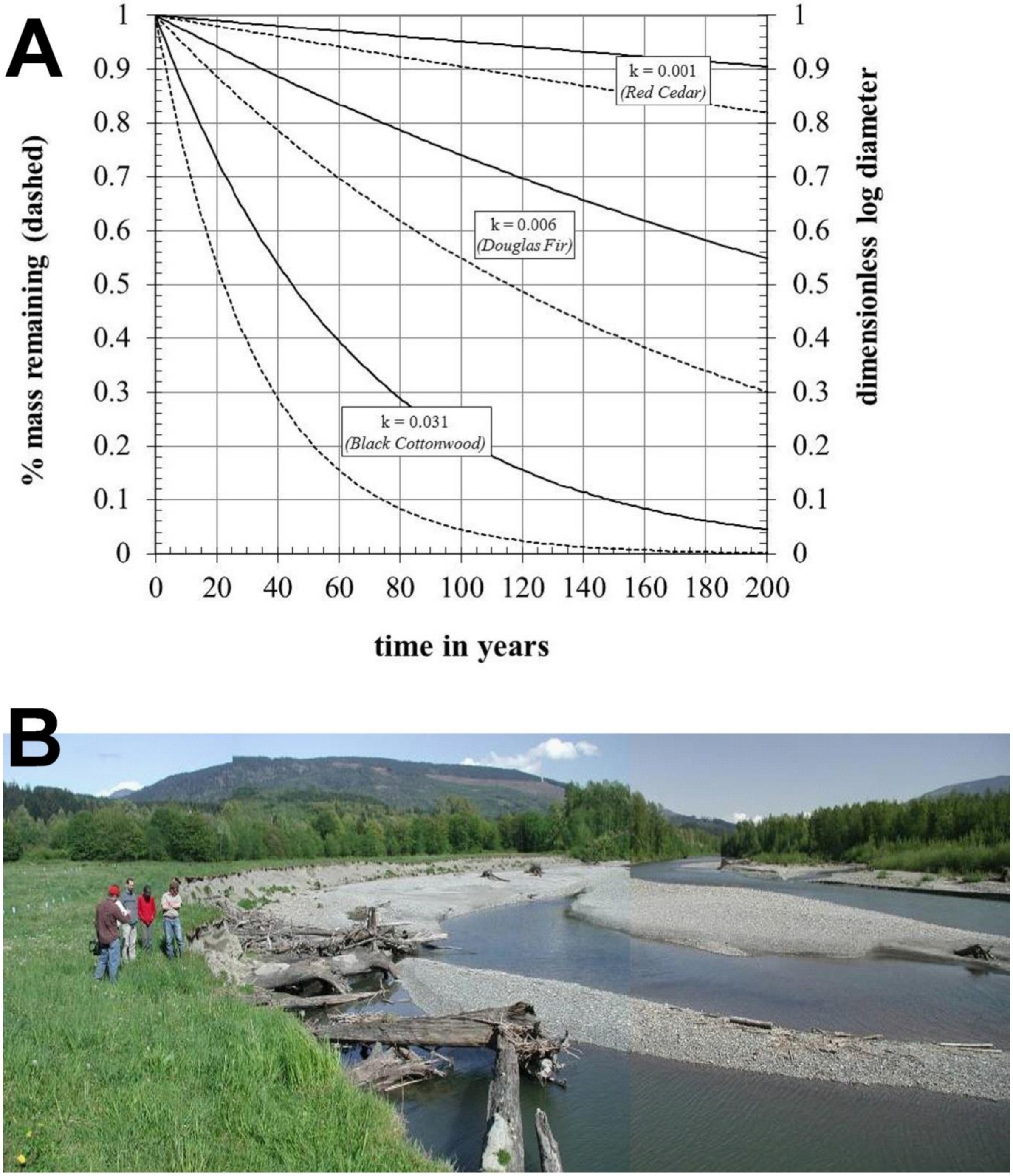
Other design objectives to consider are the replications of habitat features useful to salmonids and in short supply within the reach of interest. Restoring specific habitats while maintaining certain engineering standards may be challenging but valuable objectives. For example, Parrish and Jenkins (2012) found that many natural jams consisted of numerous racked members that allowed flow to pass through the interior, which provided excellent cover and pool habitat for fish. Despite not having buried members or rock ballast (commonly used in ELJs), these jams were highly stable and had persisted in the system for decades. Replicating natural jams may serve as a better template for restoration than jams designed to merely remain stable and un-deformable through large floods at the expense of ecological functions.

1.3.8 Wood Longevity

The longevity of wood is another concern. Observations on the longevity of natural instream wood are briefly discussed here, and the longevity of wood placements is discussed in more detail in Chapter 6, *Engineering Considerations*. Wood deposited in saturated or anaerobic conditions within a stream bed will essentially last forever (e.g., Gastaldo and Demko 2011). In settings where it is subject to wetting and drying, wood is subject to rapid decay. The rates of wood decomposition vary by species, submergence, burial, and climatic conditions (e.g., Graham and Cromack 1982; Melillo et al. 1983; Means et al. 1986; Sollins et al. 1987; Spänhoff et al. 2001; Scherer 2004; Beets et al. 2008; Guyette et al. 2008) and is covered in Chapter 6. Wood, or evidence of wood, can be found in fluvial sediments deposited since trees appeared about 360 million years ago in the Devonian Period. During this time they have not only left abundant evidence of their presence in the geologic record, but they have played an important role in the evolution of landscapes and biota. The geologic record shows that logjams began to have a notable influence on river channel morphology within the Pennsylvanian subperiod of the Carboniferous Period 323.2 million years ago (e.g., Gastaldo and Degges 2007; Gibling et al. 2010).

Using known decay rates of the wood, estimates can be made on how long it will last or what its effective size will be after a given time (Figure 1-10A) (Abbe 2000; Abbe et al. 2003b; Abbe and Brooks 2011). Examples of buried wood found exposed in eroding river banks have shown that natural logjams can last hundreds to thousands of years (Figure 1-10B).

Figure 1-10. (A) Example of Decay Curves for Three Common Pacific Northwest Tree Species; (B) Example of Ancient Logjam More than 120 Years Old Exposed in the Right Bank of South Fork Nooksack River, Washington



Sources: (A) Abbe (2000) and Abbe and Brooks (2011); (B) Abbe and Brooks (2011).

Abbe (2000) and Montgomery and Abbe (2006) dated Pacific Northwest logjam ages ranging from several decades to over a thousand years. Guyette et al. (2008) radiocarbon dated 200 tree boles exposed in eroding banks of eight streams in north Missouri and found that oak trees have been accumulating in alluvial sediments since the late Pleistocene, 14,000 years ago. The median age of oak boles was 3,515 years B.P.[1] Wood samples from buried logjams exposed along the montane Queets River in the Olympic Peninsula in Washington were considerably younger with radiocarbon ages of 0 to 1400 years B.P. (Abbe 2000; Hyatt and Naiman 2001; Montgomery and Abbe 2006). Samples of buried logs exposed in the banks of the Ducktrap River, a low-gradient coastal stream in Maine had radiocarbon dates of 1180 and 1650 years B.P. (Magilligan et al. 2008). Brooks and Brierly (2002) dated wood in the Thurra River of southeast Australia as tens of thousands of years old. These observations and the success of engineered wood placements used over the last several decades indicate wood placements may have a positive role in carbon sequestering.

1.4 Ecological Functions of Wood

Large wood can be found in nearly all streams and rivers where trees populate riparian areas. It has multiple functions in these systems, such as trapping sediment, forming pools, providing shade and cover for aquatic organisms, and diversifying flows. It is a key ecosystem component for stream organisms, particularly for fish. Large wood has been part of virtually all forested freshwater systems for many thousands of years, and its role is significant for life stages of many aquatic species.

The historic reduction in wood found in streams has been grossly under-appreciated; likewise, the magnitude of the effect wood has on habitat formation has largely been overlooked. For most of the industrial revolution, right up to the late twentieth century, science ignored the possible role of wood on fluvial systems. It has only been in the last several decades, long after the alteration of river valleys across the Northern Hemisphere, that scientific research began to recognize that wood could influence fluvial ecosystem processes. Research on wood has increased exponentially in the last decade when it has become more evident that wood in streams has influenced our landscape for millions of years.

In terms of evaluating fluvial aquatic ecosystem conditions and developing restoration strategies, the introduction of large wood and natural wood has impacts on the local geology that affect the evaluation. Research and the observed results of wood reintroduction have clearly demonstrated the beneficial role of large wood in creating and sustaining healthy river ecosystems. Large wood influences channels of all sizes by introducing physical complexity to the system. Wood accumulates in any river or stream that has riparian forests, from New England (Figure 1-11) to the arid west (Figure 1-12).

Figure 1-11. Naturally Occurring Snag Embedded in Channel Thalweg, Androscoggin River near Bethel, Maine

[1] B.P. rabiocarbon dating reference "before present" referring to time prior to 1950.

Figure 1-12. Lush Riparian Areas Even Occur in Arid Regions Where They Deliver Wood to Streams, North Central Oregon

The recognition of the importance of wood has led to its increased use in river restoration projects and changes in river management, such as leaving natural wood in place and protecting riparian forests, which are necessary for wood recruitment. Stable wood traps small wood, which creates large amounts of complex environments and increased surface area for biologic activity that supports more complex food webs.

The role of wood in aquatic fluvial ecosystems can be categorized into two basic functions: biological and physical. The biological functions include how wood provides a unique growth medium and nutrient source for invertebrates and also its use in creating vegetation and other ecological niches for habitat. The physical functions include how wood influences channel structure and energy dissipation, hydrology, sediment and organic debris transport, substrate conditions, and channel and floodplain morphology. These functions are closely linked and are influenced by other factors such as flood events, fires, and human development.

GUIDANCE

The Function of Wood
Associated With Aquatic Fluvial Ecosystems

- Shade.
- Hydraulic influence raising local water elevations, scouring pools, and creating low-velocity refugia.
- Channel grade control.
- Reduction in rate of water flow and increase in residence time.
- Retention and storage of sediment and flotsam (small wood and organic material).
- Retention of nutrients.
- Side channel formation.
- Increased floodplain connectivity.
- Maintaining biological structure and ecosystem productivity.
- Maintaining channel and floodplain physical complexity.
- Providing complex cover for aquatic organisms.
- Increased hyporheic exchange.
- Improved water quality.
- Increased recharge and aquifer storage
- Creating habitat for fish and macroinvertebrates.

1.4.1 Biological Functions

Large wood is a key structural element in forested stream ecosystems worldwide (Maser and Sedell 1994; Nagayama and Nakamura 2010). Wood serves as a food resource for microbes, fungi, and macroinvertebrates. In addition, a primary ecological role of large wood and accumulations of large wood (wood jams) is associated with its influence on the physical environment of streams and the creation of habitats for aquatic species (Roni et al. 2014a).

In most cases, restoration of large wood is undertaken to achieve some biological goal. Hence, the inherent assumption of restoration of large wood is that habitat features in streams associated with word wood are positively related to the survival, persistence, and abundance of desired species and communities and ecological functions (Whiteway et al. 2010). While intuitively appealing, the relationship between individual habitat attributes and fish survival or abundance can be difficult to prove in a quantifiable and statistically meaningful way (Conquest and Ralph 1998; Bradford et al. 2005). Consequently, some researchers have reasonably questioned the benefits of stream restoration activities (Thompson 2006; Stewart et al. 2009), or called for a better accounting of the costs and benefits of restoration investments (Bernhardt et al. 2007). Benefits are challenging to detect, in part, because of the number of confounding factors affecting fish abundance in any year or over time, especially at a population scale for far-ranging anadromous species such as salmon (Rose 2000).

When scientists documented the decline in salmonid populations in the Northwestern United States and correlated that decline with stream simplification following wood removal , efforts to replace large wood in streams received national attention from researchers, resource managers, and restoration practitioners. Efforts highlighted the importance of woody debris in forming salmonid habitat in fluvial ecosystems, and restoration efforts using wood became widely accepted (Bisson et al. 1987; Kauffman et al. 1997).

CROSS-REFERENCE

A detailed description of biological functions related to wood and fluvial ecosystems is provided in Chapter 3, *Ecological and Biological Considerations*.

Large wood structures not only provide cover for fish, mammals, and birds, they also increase invertebrate and aquatic plant productivity that enhances the ecosystem food web (Coe et al. 2009). The following provides a discussion of the biological functions associated with wood and fluvial ecosystems.

1.4.1.1 Habitat Formation

Habitat consists of elements of the environment that affect the persistence and performance of a species in a specific location (Whittaker et al. 1973; Hall et al. 1997). The quality and quantity of habitat across the life history of the species shape biological performance in terms of abundance, persistence, and fitness (Southwood 1977). Habitats for species can overlap but are usually separated temporally, spatially, or in terms of function. For example, large wood can be an element of habitat for both juvenile salmonids and benthic insect life stages, but the nature of that habitat differs; wood generally provides cover for juvenile salmonids while it provides a substrate on which benthic insects move and feed.

1.4.1.2 Aquatic Food Webs

A food chain is the linkage between primary resources (plants, detritus) and secondary consumers (e.g., insects and fish) (Pianka 1994). A network of linked food chains forms a *food web*, and stream food webs are among the most complex. Like most ecosystems, aquatic foodwebs begin with the capture of energy from the sun that is fixed by terrestrial and aquatic plants via photosynthesis. This energy is stored in the tissue of the plant where it is available to secondary consumers.

1.4.1.3 Biogeochemical Functions

Large wood plays a key role in nutrient cycling in streams (Bilby and Bisson 1998). In general, wood itself is a poor carbon source. The amount of nitrogen and phosphorous relative to carbon is low, and the lignin in wood is particularly difficult for many organisms to break down (Webster and Benfield 1986). In temperate ecosystems, few macroinvertebrates or fish eat wood directly, but there is a suite of microbes and fungi that break down wood, which, in turn, form food for benthic invertebrates and other biota (Webster and Benfield 1986; Findlay et al. 2002; Spänhoff and Cleven 2010). The stream macroinvertebrates that do eat wood tend to eat smaller particles, and/or they ingest wood as a byproduct of feeding on microbial biofilms on wood surfaces (Johnson et al. 2003; Coe et al. 2009). The rate of wood decay by microbes and fungi varies by species. As a rule, trees with more nitrogen per unit of carbon (such as alders maples, and poplars) decay faster that those with lower nitrogen–to- carbon ratios (such as oaks, firs, and spruce) (Spänhoff and Meyer 2004).

Large wood can enhance stream nutrient cycling in multiple ways. First, large wood retains leaf litter and fine particulate organic matter. The breakdown of this organic matter by microbes and fungi creates an elevated demand for nutrients, especially nitrogen and phosphorous. This elevated demand increases the rate at which nutrients are taken up from the water column and increases the retention of nutrients in the stream (Mulholland et al. 2009). Second, when channel-spanning wood and wood jams retain a combination of organic material and fine inorganic material they can create areas of saturated sediment behind and around the wood where oxygen can be locally depleted. Under these anaerobic conditions available nitrogen can be converted to nitrogen gas through a process referred to as denitrification (Steinhart et al. 2000). This conversion is highly variable across streams and across regions but it can be an important loss of nitrogen from these systems, especially in areas of the northeastern and midwestern United States where excess nitrogen pollution is a particular concern.

1.4.1.4 Wetted Area of the Channel

Large wood creates bedform roughness (resistance to flow, or drag) that effectively slows flow down, consequently raising the water surface level. This may facilitate a hydraulic "backwater effect," whereby the water level immediately upstream of the obstruction is raised, which in turn raises the level of water upstream of it, resulting in an expanse of slower and higher water extending upstream from the obstruction. The backwater effect can result in higher water surface elevations along the banks and, in unconstrained reaches, enhanced floodplain connectivity with an increased volume of water spilling out onto the floodplain. The ability of large wood to alter water levels and influence habitat varies based on local conditions, including the volume of assembled wood and its size relative to channel morphology.

1.4.1.5 Hyporheic Zone

The hyporheic zone is the water-saturated sediment volume below the stream bed and adjacent stream banks where mixing between surface water and groundwater occurs (Bencala 2005). It may extend 30 meters (98 feet) or more into the adjacent floodplain (Hinkle et al. 2001; Boulton et al. 2010). Definitions may vary with the scale and intent of a given study and include hydrological, hydrogeological, biological, and physiochemical criteria (Environmental Agency 2009; Boulton et al. 2010).

Although the hyporheic zone may only extend as little as 5 centimeters (2 inches) into the streambed it is extensive because it extends from the uppermost headwaters through the lowermost reaches of rivers and into the estuarine zone (Krause et al. 2014). The cumulative effect of large-scale wood placement can improve water quality by trapping sediment and increasing hyporheic flow (e.g., Lautz et al. 2006; Mutz et al. 2007; Wondzell et al. 2009). Increasing hyporheic exchange moderates water temperatures (Hester and Gooseff 2010) and improves water quality by increasing uptake of phosphate (Warren et al. 2007) and buffering pollutants (Hester and Gooseff 2010).

The hyporheic zone is both a physical space and a biological habitat for microbes, invertebrates, insect eggs and pupae, fish eggs, and fish embryos (the hyporheos). In the hyporheic zone surface water and solutes exchange into and out of the stream bed having mixed with groundwater to varying extents. Numerous biogeochemical reactions occur in this zone, and it can influence mineralization, major ions, and nutrient and contaminant components in the stream system (Bencala 2005; Gandy and Jarvis 2006; Mulholland and Webster 2010; Krause et al. 2014).

Hyporheic flow also has localized influences on stream temperature and dissolved oxygen. All of these aspects argue for hyporheic zone consideration in restoration and large wood placement projects (Hester and Gooseff 2010). Krause et al. (2014) point out that much of the research on large wood and its hydrological, ecological, and biogeochemical roles has focused on headwater and upland streams (e.g., Tonina and Buffington 2009; Buffington and Tonina 2009). Their review considers these influences and previous studies from the perspective of lowland rivers. Wondzell (2011) evaluates data from a fifth-order mountainous stream and shows that the size of hyporheic exchange flows relative to stream discharge was large only in very small streams and at low discharge. In the larger streams and at higher flows this ratio was small.

1.4.2 Physical Functions

Forest cover, or canopy, within a watershed directly affects the hydrology and supply of sediment to a river. Riparian forests along a river aid in stabilizing the bank, which influences bank resistance to erosion, which in turn affects the hydraulic geometry of a river. Increases in bank strength result in narrower, deeper channels. Conversely, decreases in bank strength result in wider, shallower channels (Eaton and Lawrence 2006). Stable instream wood provides hydraulic and morphologic complexity to a channel. Wood defines water surface profiles, flow energy expenditure, sediment transport, channel morphology, and aquatic habitat. The removal of large wood increases the river's energy to move sediment, erodes its bed and banks, simplifies channel morphology, and severely degrades fish habitat. Impacts such as channel incision are not limited to the channel but affect floodplain connectivity and propagate upstream to degrade an entire drainage network.

This following provides a discussion of the physical functions associated with wood in fluvial ecosystems.

CROSS-REFERENCE

A detailed description of physical functions related to wood in fluvial ecosystems is provided in Chapter 4, *Geomorphology and Hydrology Considerations*, and Chapter 5, *Watershed-Scale and Long-Term Considerations.*

1.4.2.1 Grade Control

For millions of years wood in streams has been responsible for controlling much of the grade in alluvial systems of all sizes, whether as individual tree trunks spanning a channel (Figure 1-13), as logjams, or in beaver dams. A majority of channels in a small drainage network could easily be impounded by a single tree, particularly in the old-growth forests that dominated landscapes across North America. In larger channels, logjams were a common obstruction that controlled a river's morphology (Wolff 1916; Abbe and Montgomery 1996; Abbe and Brooks 2011) and even impounded large rivers (Guardia 1933).

Figure 1-13. Large Trees Can Play a Major Role in the Morphology of Rivers, Such as this 2.4-Meter Douglas Fir Across Carbon River, Washington

Caddo Lake in Texas, one of the largest natural lakes in the southern United States, was formed by a logjam in the Red River (Veatch 1906).

Natural log "steps" are a familiar feature in small streams throughout North America where log length exceeds the channel width (e.g., Marston 1982). The presence of larger trees can extend the influence of wood into large channels, whether as single pieces (Figure 1-13) or logjams (Figure 1-14). Within steep channels large boulders and logs both create stable obstructions. In most lower gradient alluvial rivers, large snags were naturally the principal flow obstructions. Where snags and large riparian trees have been removed, human structures such as bridge piers may be the only obstructions. With conversion of riparian areas to younger forests and fewer natural obstructions to trap and moderate the movement of mobile wood, the accumulation of wood at human structures becomes a greater risk. The removal of large trees that once lined rivers throughout the country has contributed to the much lower volumes of wood currently found in rivers. Most of the rivers in the Mississippi watershed once were lined with massive trees such as American sycamores and cottonwoods that often attained diameters well over 2 meters (6.6 feet). In every region of the country, the largest trees were usually found in riparian areas where there is abundant moisture and nutrients (e.g., Muir 1878). These streamside trees were also the first to be removed for timber, agriculture, and development.

Figure 1-14. Logjam Deflecting the Hoh River in Northwest Washington

The logjam is approximately 70 meters (230 feet) wide and forms a 2.8-meter (10-foot) deep pool. The logjam creates a hardpoint that allows riparian trees to mature.

1.4.2.2 Riparian Forests

The principal physical functions of a riparian forest are mediation of microclimate and shade, generating effects on channel form by root reinforcement and recruitment of large wood, and resulting mediation of channel disturbance regime.

The riparian forest affects stream microclimate by attenuating wind, shading the stream surface, and in many cases buffering the stream from microclimatic conditions in nonforest areas (such as logged or developed lands) located farther from the stream. Chen et al. (1995), studying microclimate in a forest adjacent to the edge of a recent clearcut, found that the forest attenuated variation in soil and air temperature, soil moisture, relative humidity, solar radiation, and wind speed, relative to the adjacent clearcuts. Brosofske et al. (1997) and Anderson et al. (2007) corroborated these findings for the riparian areas of small streams in western Washington and Oregon, finding that forested stream buffer strips moderate microclimate above the stream. Similarly, Danehy and Kirpes (2000) found increased variation in relative humidity in riparian areas of harvested forests along eastern Washington streams. These studies examined relatively small (second- and third-order) streams; riparian forest effects on a microclimate would presumably be reduced on larger streams.

The potential for a riparian forest to provide shade to the stream surface, and thereby to moderate stream temperatures, has been studied extensively, and a variety of models exist to provide estimates of stream temperature as a function of riparian shade (e.g., Program SSSHADE [Bartholow 1988]). In general, the potential of riparian shade to affect stream temperature depends upon the fraction of water surface receiving shade, especially during the warmest part of the day; the temperature of the stream when it enters the shaded reach; and the importance of other factors influencing stream temperatures (e.g., stream gradient, relative humidity, ambient air temperature, channel morphology, and groundwater or hyporheic flow inputs) (Beschta et al. 1987; Sedell and Swanson 1984; Sullivan et al. 1990). Overall loss of riparian canopy cover is also associated with increased stream temperatures, as is forest clearing at the basin-wide scale (Pollock et al. 2009).

Riparian forests can influence channel form when their roots stabilize streambanks and when large wood from the forest enters the channel. Root stabilization of streambanks is effective at retarding erosion, although the magnitude of effect depends heavily upon soil pore water pressure, reaching a minimum value in saturated soils (Pollen-Bankhead and Simon 2010). Gibling and Davies (2012) provide evidence that riparian forest has been affecting channel form for almost as long as there have been trees, with broad sand-bed rivers of the early Paleozoic era (circa 400 million years ago) giving way to well-defined channels constrained by roots and logjams by the later Paleozoic (250 million years ago). Triska (1984) relates the reverse of this process on the Red River in Louisiana; during presettlement time the river channel consisted of over 225 kilometers (140 miles) of debris jams derived from floodplain hardwood forests, but since then removal of debris dams to support navigation and flood control has reduced the stream's average width from 185 to 40 meters (607 to 131 feet), and produced a greatly simplified floodplain with little in the way of riparian tree cover. Similar changes have been described for lowland rivers in western Washington (Collins et al. 2002) and Oregon (Sedell and Froggatt 1984).

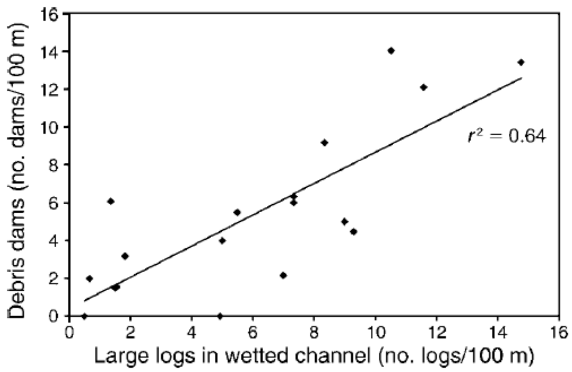
These studies also show that riparian forests mediate the channel disturbance regime. Streams with frequent and substantial inputs of large wood, either from catastrophic inputs (e.g., debris torrents and dam-break floods in tributary channels) or from episodic channel processes (e.g., bank cutting or channel avulsion) are more likely to develop woody debris jams either within or along the channel. These wood jams protect the forest from channel migration for long enough to allow development of large trees that will, when recruited to the channel, continue to produce debris jams (Collins et al. 2012).

1.4.2.3 Channel Features and Characteristics

Large wood plays an important role in increasing channel length and creating side channels, thereby increasing overall channel complexity. This decreases the radius of curvature, traps nutrients, provides complex channel features, and increases floodplain connectivity by raising streambeds and water levels (Abbe and Montgomery 2003; Stock et al. 2005; Abbe and Brooks 2011). Wood is also a critical factor in how floodplain forests develop (Collins et al. 2012; Wohl 2013). Channel conditions and wood loading are closely linked to the flow regime and sediment supply, and the characteristics of disturbances such as storms, floods, and human modifications (Keeton et al. 2007). River morphology is the cumulative result of numerous variables and how they change over time. Where trees are large enough to create stable flow obstructions, wood becomes one of the dominant variables controlling channel form (e.g., Abbe and Montgomery 1996, 2003; Abbe and Brooks 2011). In a study of streams in northern New York with bankfull widths of 2 to 16 meters (6.6 to 53 feet), Keeton et al. (2007) found a direct relationship between forest age, basal tree area, and instream wood volumes. Old-growth forests (205–410 years old) had instream wood loading volumes five times those found in mature forests (85–145 years old): 200 cubic meters (262 cubic yards) per hectare versus 34 cubic meters (45 cubic yards) per hectare, respectively. They also found that the presence of large logs (>30 centimeters [12 inches] in diameter) was directly linked to the number of debris dams that were primarily responsible for wood and sediment retention (Figure 1-15). An aquatic fluvial ecosystem can quickly respond to human actions that alter a channel's morphology, flow regime, or riparian forests.

Removing wood from a river can lead to rapid channel incision and floodplain disconnection (Figure 1-16; Veatch 1906; Guardia 1933; Brooks and Brierly 2002; Abbe and Brooks 2011). Human development of the landscape has had a major impact on the quantity of instream wood, from both direct removal and the deforestation of riparian areas.

Figure 1-15. Relationship Between Large Logs (>30 Centimeters) and Debris Dams in Adirondack Streams with Bankfull Widths of 2 to 16 Meters, Northern New York



Source: Keeton et al. (2007).

Figure 1-16. Removal of Wood Leads to Channel Incision, Converting Alluvial Pool-Riffle Channels to Bedrock and Damaging Habitat and Infrastructure, Such as this Bridge Failure in the Mashel River, Western Washington

1.4.2.4 Water and Sediment Retention and Floodplain Connectivity

Placing a series of channel-spanning logs or logjams can slow the movement of water and sediment and increase floodplain connectivity that sustains productive side channels, wetlands, hyporheic flow, and riparian forests. When done in a large enough area, this strategy has the potential benefit of improving downstream flood protection by lowering peak stage and discharge (Anderson 2006). This strategy can involve the placement of large "key" logs, engineered logjams (ELJs), or beaver dams in portions of the drainage network with relatively undeveloped floodplains.

1.4.2.5 Hydraulic Influence

Wood placements can be used to create pools by generating different hydraulic conditions ranging from plunging flow (log steps), vortex flows associated with channel obstructions (flow deflectors), or constriction scour associated with narrowing the cross-sectional area. Wood can also be used to develop and enhance riffles by sorting bed material and setting up hydraulic gradients that drive hyporheic flow. Complex wood placements such as ELJs have been repeatedly demonstrated to provide excellent bank protection while also enhancing habitat by creating pools and cover.

1.5 History of the Use of Wood for Restoration in Streams

Wood has been humanity's primary building material throughout history. Timber cribbing and piles have been used for centuries in rivers to build bridge abutments, small dams, flood walls, and bulkheads. The historical application of large wood for river restoration did not begin until well after the impacts of deforestation, agriculture, and development. Beginning in the 1930s, coincident with efforts to improve soil conservation, the use of large wood was focused on minor "improvements," such as log weirs and timber cribbing to create overhanging cover for enhancing trout habitat (Tarzwell 1934; Saunders and Smith 1955). For most of the twentieth century, large wood was removed from streams and rivers with the intent to improve navigation, reduce local flooding, or improve fish passage (White and Brynildson 1967). The practice of wood removal has occurred all around the world (e.g., Ruiz-Villanueva et al. 2014a) and severely impacted the hydraulic, geomorphic, and ecologic role wood has played for millions of years.

The American Fisheries Society published guidelines on wood in 1983, citing the potentially beneficial habitat that small wood placements could create. However, the guidelines, which are still available through the agency's website, continued to encourage the removal of wood occupying significant portions of the river channel (American Fisheries Society 1983).

While the physical and biologic effects of wood are remarkably similar across diverse ecological regions (Figure 1-1), the policies regarding wood vary markedly across the country. In the Pacific Northwest millions of dollars are spent annually on reintroducing large wood to restore salmonid habitat. But large wood is still considered a nuisance across much of the country and is regularly cleared. The removal of instream wood is based more on tradition and misconceptions, not science. Large wood removal should be carefully considered because leaving the wood not only improves aquatic and riparian habitat, but can provide real benefits such as preventing channel incision that can threaten infrastructure, lowering groundwater tables, and exacerbating downstream flooding.

Over the last 150 years there was a concerted resource management directive that cleared wood from streams and rivers in an effort to enhance navigation and increase flood conveyance, while many land and resource management practices diminished sources of wood available within streams, riparian corridors, and watersheds. For example, a common practice to "improve" fish passage and flow conveyance in the Pacific Northwest was to have crews remove wood from streams (also known as "stream cleaning"), particularly between the 1950s and 1970s (Bisson et al. 1987). Wood was eradicated so successfully from many streams (Reeves et al. 1991) that consequences to fish habitat still exist (Bisson et al. 1987). Wood was often considered a nuisance when it impinged on undersize culverts and in-channel bridge spans, and was a threat to structures built along the banks when it deflected flows or created unpredictable hydraulic conditions.

As a result, across much of North America, particularly the Pacific Northwest, wood has been greatly reduced in many of our streams and rivers. The consequences of these actions include increased magnitude and frequency of flows, which has increased channel incision, resulting in even more severe and detrimental hydraulic conditions that damage habitat and infrastructure (Figure 1-16). The alterations of ecosystem functions mean long-term impacts on water quality and ecosystem structure, but they also significantly affect the human infrastructure built around an entirely different river than once existed.

When the United States began its westward expansion, wood was commonly present in river systems, which created obstacles for those pioneers. The U.S. Army was tasked with clearing wood from rivers to improve navigation and development (Gillespie 1881; Ruffner 1886; Dacy 1921; McCall 1984; Collins et al. 2002).

At the same time, recognition of wood's role in defining the geomorphology and ecology of fluvial systems appeared in some of the classic textbooks in geology and physical geography. Lyell (1830) described the formation of massive logjams and the lakes they created in the Red River valley of Louisiana. Davis (1901) clearly describes the geomorphic effect of wood in the Red River as not just "dividing the current into many small channels," but in aiding in "building of the flood plain" (Davis 1901:279–280). Veatch (1906) and Guardia (1933) describe how removal of Red River logjams led to channel incision and disconnected large areas of floodplain. Similar logjam–dominated systems were described in the Colorado River of Southeast Texas (Clay 1949) and occurred in many lowland alluvial rivers. The geomorphic role of wood was described by Muir (1878) in how giant Sequoia trees impound the streams of the high Sierra to trap water and create lush bogs. Russell (1909) presents similar observations of large trees impounding the Teanaway River of central Washington State, a river that experienced 2 meters (6.6 feet) of channel incision after large wood was historically removed (Stock et al. 2005). Wolf (1916) clearly noted the role of large snags in deflecting the course of the White River of western Washington and trapping large quantities of sediment and organic debris. Despite these observations, there was almost no scientific research conducted on the role of large wood for most of the twentieth century, coincidently during a time when streams were being aggressively cleared and simplified (Sedell and Luchessa 1982; Sedell and Frogatt 1984; Abbe 2000; Collins et al. 2002).

After a long hiatus, scientific recognition about the beneficial role of wood in river ecology and morphology began to be published in the last 40 years (Zimmerman et al. 1967; Heede 1972; Keller and Swanson 1979; Keller and Tally 1979; Triska and Cromack 1979; Marston 1982; Sedell et al. 1984; Harmon et al. 1986; Hogan 1987; Linkaemper and Swanson 1987; Abbe and Montgomery 1996; Gippel et al. 1996; Wallerstein et al. 1997; Montgomery et al. 2003; Wondzell and Bisson 2003; Montgomery et al. 2003; Abbe and Brooks 2011; Collins et al. 2012). The listing of Pacific Northwest salmon as threatened or endangered in the 1990s began to change perceptions about large wood and drive more aggressive efforts to restore large wood to streams after over 150 years of removal.

Large wood reintroduction as part of rehabilitating streams began in the 1980s in U.S. National Forests of the Pacific Northwest (e.g., House and Boehne 1985). Early wood placements typically entailed placing log “dams” across relatively small channels and often resulted in significant biological benefits (e.g., Wallace et al. 1995). Unstable or simple wood placements along the banks of channels tended to have little or no benefit (Frissell and Nawa 1992; Beamer and Henderson 1998; Peters et al. 1998). After assessing 211 restoration projects involving instream structures, Whiteway et al. (2010) found the projects increased salmonid density by 167% and biomass by 162%. In a similar review of 24 stream restoration projects, Miller et al. (2010) found that wood restoration projects had the largest and most consistent benefits to macroinvertebrate communities. Efforts to stabilize wood began without much scientific basis regarding the hydraulic forces the placements would be subjected to, or how the stabilizing method would perform, which could explain the failure of some projects (Frissell and Nawa 1992; Abbe et al. 1997). As an example, cable earth anchors were a popular stabilizing method that had limited success. This method involves attaching a log with some length of cable (typically 3 to 30 meters [3 to 98 feet]) to an existing structure (e.g., tree) or some sort of buried anchor, either a simple dead weight (e.g., boulder) or a mechanism intended to maximize resistance (e.g., duckbill anchor). If the log began to move (float, vibrate), so would the cable, creating a situation that could quickly damage the bank (e.g., acting similar to a backpacker’s cable saw). In many cases, the forces on the log were simply too great for the anchor or bank erosion exposed the anchor (Figure 1-17).

Research demonstrated the key role that the size and shape of trees entering the channel plays and how it affects river morphology (Abbe and Montgomery 1996; Abbe 2000; Abbe and Montgomery 2003). Replicating the massive trees that once existed throughout North America is one of the principal challenges faced in restoration, particularly in creating stable wood structures. Restoration designs must rely on engineering designs that can emulate the natural role of old-growth timber. It is this premise under which ELJs were developed, not only to demonstrate the physical significance wood plays in defining channel morphology and habitat, but how wood can be used to protect infrastructure by limiting bank erosion and channel incision (Abbe et al. 1997, 2003a, b, c; Abbe and Brooks 2011). In the 18 years since the first ELJ prototype was built in 1995, there have been hundreds of ELJs and thousands of wood placements in the Pacific Northwest. Wood stability has been a critical issue in many restoration programs and a variety of techniques have been developed to increase their design life and ensure wood remains in the original location (Abbe et al. 2003a; Abbe and Brooks 2011).

Figure 1-17. Stable Wood Bifurcates Flow Leading to Anabranching Channels when Undisturbed, and Creates a Complex and Productive Habitat

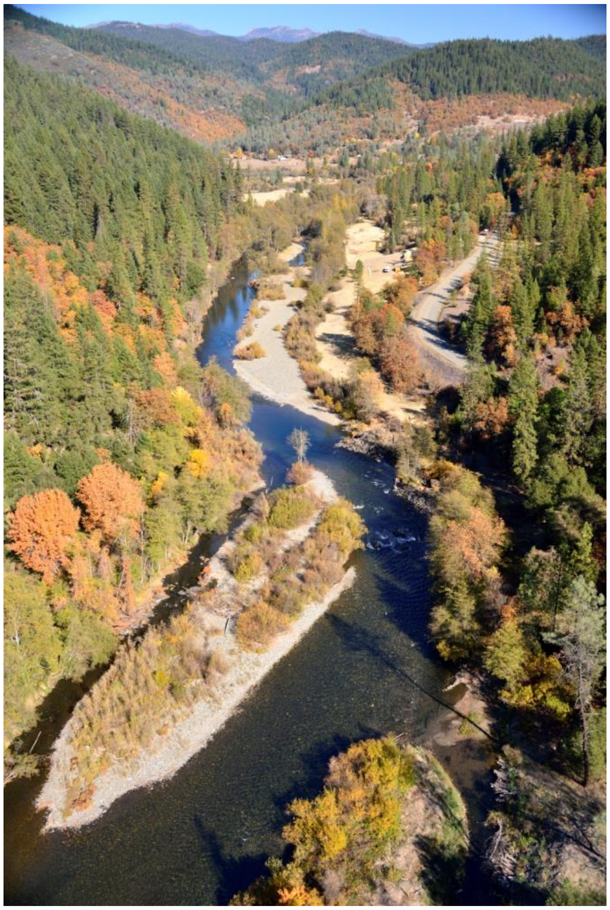


Photo credit: Ken DeCamp

The extensive application of ELJs in the Pacific Northwest has led to a general standard of practice that has greatly improved structure stability. Stable large wood placements in the Pacific Northwest are now common, and numerous ELJs have successfully weathered severe floods, including events equal to or exceeding the 100-year flood (Abbe and Brooks 2011). Observations of natural wood and ELJs are also demonstrating that wood can last for many decades under various conditions, and even for centuries where it is submerged (Figure 1-18) (Abbe and Brooks 2011).

Figure 1-18. A Buried Log More than 500 Years Old Forming Grade Control, Coal Creek, 2004, Ozette River Tributary, Washington

The fate of wood in rivers is integrally tied to how riparian forests are managed. Large mature trees are essential in providing wood large enough to influence habitat formation. Concerns about wood stability and life expectancy should be anticipated, but can always be addressed with good science and engineering. There are situations where large wood is not appropriate or where it can pose unacceptable hazards, but it is clear that instream wood is beneficial and should be an integral part of watershed management throughout the country.

1.6 References

Abbe, T. B. 2000. *Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System*. Ph.D. dissertation. University of Washington, Seattle, WA. 222 pp.

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers: Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, and C. Petroff. 1997. Design of Stable In-Channel Wood Debris Structures for Bank Protection and Habitat Restoration: An Example from the Cowlitz River, WA. Pages 809–816 in S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, F.D. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi, Oxford, MS.

Abbe, T. B., J. Carrasquero, M. McBride, A. Ritchie, M. McHenry, and K. Dublanica. 2003a. *Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington*. Proceedings of the Georgia Basin/Puget Sound 2003 Research Conference, Vancouver, B.C., March 31–April 1, 2003, T. Droscher (ed.). Puget Sound Action Team, Olympia, WA.

Abbe, T. B, A. P. Brooks, and D. R. Montgomery. 2003b. Wood in River Rehabilitation and Management. Pages 367–389 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003c. Integrating Engineered Log Jam Technology into River Rehabilitation. In D. R. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies.

Agee, J. K. 1990. The historical role of fire in Pacific Northwest forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1992. The Historical Role of Fire in Pacific Northwest Forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1993. *Fire Ecology of Pacific Northwest Forests*. Washington, D.C.: Island Press

Ahmad, M. 1951. Spacing and Projection of Spurs for Bank Protection. *Civil Engineering and Public Works Review.* March:172–174; April:256–258.

Allan, J. D., M. S. Wipfli, J. P. Caouette, A. Prussian, and J. Rodgers. 2003. Influence of Streamside Vegetation on Inputs of Terrestrial Invertebrates to salmonid Food Webs. *Canadian Journal of Fisheries and Aquatic Sciences* 60(3):309–320.

American Fisheries Society. 1983. *Stream Obstruction Removal Guidelines. Stream Renovation Guidelines Committee*. The Wildlife Society and American Fisheries Society. Published by AFS, Washington D.C. 9 pp.

Anderson, D. B. 2006. *Quantifying the Interaction between Riparian Vegetation and Flooding: from Cross-Section to Catchment Scale*. University of Melbourne.

Anderson, N. H., R. J. Steedman, and T. Dudley. 1984. Patterns of Exploitation by Stream Invertebrates of Wood Debris (Xylophagy). *Verhandlungen der Internationalen Vereinigung für theoretische und angewandte Limnologie* 22:1847-1852.

Anderson, P. D., D. J. Larson, and S. S. Chan. 2007. Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon. *Forest Science* 53(2):254–269.

Andrus, C. W., B. A. Long, and H. A. Froehlich. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging: *Canadian Journal of Fish and Aquatic Science* 45:2080–2086.

Bailey, R. G. 1995. *Description of Ecoregions of the United States*, 2nd Edition, USDA, US Forest Service. Washington, D.C. Miscellaneous Publication No. 1391.

Bailey, R. G. 2009. *Ecosystem Geography – From Ecoregions to Sites*. New York, NY: Springer Science and Business Media.

Baillie, B. R., L. G. Garret, and A. W. Evanson. 2008. Spatial Distribution Influence of LWD in an Old-growth Forest River System, New Zealand. *Forest Ecology and Management* 256:20–27.

Barker, B. L., R. D. Nelson, and M. S. Wigmosta. 1991. Performance of detention ponds designed according to current standards. *Puget Sound Water Quality Authority, Puget Sound Research '91: Conference Proceedings*. Seattle, Washington.

Bartholow, J. 1988. Stream Segment Shade Model (SSSHADE) Version 1.4. *Temperature Model Technical Note #3*. U.S. Fish and Wildlife Service, Fort Collins, CO.

Baxter, C. V., K. D. Fausch, and W. Carl Saunders. 2005. Tangled Webs: Reciprocal Flows of Invertebrate Prey Link Streams and Riparian Zones. *Freshwater Biology* 50(2):201–220.

Beamer, E. M., and R. A. Henderson. 1998. *Juvenile Salmonid use of Natural and Hydromodified Stream Bank Habitat in the Mainstem Skagit River, Northwest Washington*. Miscellaneous Report. Skagit System Cooperative. La Connor, WA.

Beechie, T. J., and K. Wyman. 1992. *Stream Habitat Conditions, Unstable Slopes and Status of Roads in Four Small Watersheds of the Skagit River.* Skagit System Cooperative, Fisheries services for the Swinomish Tribal Community, Upper Skagit and Sauk-Suiattle Indian Tribes.

Beets, P. N., I. A. Hood, M. O. Kimberley, G. R. Oliver, S. H. Pearce, and J. F. Gardner. 2008. Coarse Woody Debris Decay Rates for Seven Indigenous Tree Species in the Central North Island of New Zealand. *Forest Ecology and Management* 256:548–557.

Beltaos, S. 1983. River Ice Jams: Theory, Case Studies, and Applications. *Journal of Hydraulic Engineering* 109(10):1338–1359.

Bencala, K. E. 2005. Hyporheic Exchange Flows. *Encyclopedia of Hydrological Sciences*, M. G. Anderson and J. J. Mcdonnell (eds.). Wiley-Blackwell. 3,456 pp.

Benda, L. and T. W. Cundy. 1990. Predicting Deposition of Debris Flow in Mountain Channels. *Canadian Geotechnical Journal* 27:409–417.

Benke, A. C., and J. B. Wallace. 2010. Influence of Wood on Invertebrate Communities in Streams and Rivers. *American Fisheries Society Symposium* 37:149–177.

Benke, A. C., R. L. Henry III, D. M. Gillespie, and R. J. Hunter. 1985. Importance of Snag Habitat for Animal Production in Southeastern Streams. *Fisheries* 10:8–12.

Berg, N. A., A. Carlson, and D. Azuma. 1998. Function and Dynamics of Woody Debris in Stream Reaches in the Central Sierra Nevada, California. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1807–1820.

Beschta, R. L., R. E. Bilby, L. B. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions. Pages 191-232 in E. O. Salo and T. W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Seattle, WA. 471p.

Bilby, R. E. 1984. Removal of Woody Debris May Affect Stream Channel Stability. *Journal of Forestry*, 609–613. October.

Bilby, R. E., and P. A. Bisson. 1998. Function and Distribution of Large Woody Debris. Pages 324–346 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coast Ecoregion*. New York, NY: Springer-Verlag.

Bilby, R. E., and G. E. Likens. 1980. Importance of Debris Dams in the Structure and Function of Stream Ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E., and J. W. Ward. 1989. Changes in Characteristics and Function of Woody Debris With Increasing Size of Streams in Western Washington. *Transactions of the American Fisheries Society* 118:368–378.

Bilby, R. E. and J. W. Ward. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48:2499–2508.

Bilby, R. E., and L. J. Wasserman. 1989. Forest Practices and Riparian Management in Washington State: Data Based Regulation Development. In R. E. Gresswell, B. A. Barton, and J. L. Kershner (eds.), *Practical Approaches to Riparian Management.* U.S. Bureau of Land Management, BLM MT PT 89 001 4351, Billings, Montana.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future. Pages 143–190, in E. O. Salo and T. W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Seattle, Washington.

Boose, E. R., K. E. Chamberlin, and D. R. Foster. 2001. Landscape and Regional Impacts of Hurricanes in New England. *Ecological Monographs* 71:27–48.

Booth, D. B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. *Water Resources Bulletin* 26:407–417.

Boulton, A. J., T. Datry, T. Kasahara, M. Mutz, and J.A. Stanford. 2010. Ecology and Management of the Hyporheic Zone – Groundwater Interactions of Running Waters and Their Floodplains. *Journal of the North American Benthological Society* 29:26–40.

Braun, A., K. Auerswald, and J. Geist. 2012. Drivers and Spatio-Temporal Extent of Hyporheic Patch Variation: Implications for Sampling. *PLOS One* 7:e42046.

Brooks, A. P., and G. J. Brierly. 2002. Mediated Equilibrium: The Influence of Riparian Vegetation and Wood on the Long-Term Evolution and Behavior of a Near-Pristine River. *Earth Surface Processes and Landforms* 27:343–367.

Brosofske, K. D., J. Chen, R. J. Naiman, and J. F. Franklin. 1997. Harvesting Effects on Microclimatic Gradients from Small Streams to Uplands in Western Washington. *Ecological Applications* 7(4):1188–1200.

Bryant, M. D. 1980. Evolution of large, Organic Debris after Timber Harvest: Maybeso Creek, 1949 to 1978. USDA Forest Service, General Technical Report, PNW-101.

Bryant, M. D. 1983. The Role and Management of Woody Debris in West Coast Salmonid Nursery Stream. *North American Journal of Fisheries Management* 3(3):322–330.

Bryant, M. D., and J. R. Sedell. 1995. Riparian Forests, Wood in the Water, and Fish Habitat Complexity. Pages 202–224 in N. B. Armantrout and R. J. Wolotira, Jr. (eds.), *Conditions of the World's Aquatic Habitats. Proceedings of the World Fisheries Congress Theme 1.* Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Buffington, J. M. and D. Tonina. 2009. Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange. *Geography Compass* 3:1038–1062.

Camp, A., C. Oliver, P. Hessburg, and R. Everett. 1996. Predicting Late-Successional Fire Refugia Pre-Dating European Settlement in the Wenatchee Mountains. USDA PNW, Wenatchee For. Sci. Lab., Univ. of Washington, Seattle. Elsevier Science Publishers B.V. *Forest Ecology and Management* 95:63–77.

Castelle, A. J., A. W. Johnson, and C. Conolly. 1994. Wetland and Stream Buffer Size Requirements—A Review. *Journal of Environmental Quality* 23(5):878–882.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997b. Response of Juvenile Coho Salmon and Steelhead to the Placement of Large Woody Debris in a Coastal Washington Stream. *Transactions of the American Fisheries Society*. 118:368–378.

Cederholm, C. J., W. J. Scarlett, N. P. and Peterson. 1988. Low-Cost Enhancement Technique for Winter Habitat of Juvenile Coho Salmon. *North American Journal of Fisheries Management* 8:438–441.

Chambers, J. Q., J. I. Fisher, H. Zeng, E. L. Chapman, D. B. Baker, and G. C. Hurtt. 2007. Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. *Science* 318 (5853):1107.

Chen, J., J. F. Franklin, and T. A. Spies. 1995. Growing-Season Microclimatic Gradients from Clearcut Edges into Old-Growth Douglas-Fir Forests. *Ecological Applications* 5(1):74–86.

Chesney, C. 2000. *Functions of Wood in Small, Steep Streams in Eastern Washington: Summary of Results for Project Activity in the Ahtanum, Cowiche, and Tieton Basins*. Washington Department of Natural Resources. Prepared for the Timber/Fish/Wildlife Monitoring Advisory Group and the Northwest Indian Fisheries Commission. TFW Effectiveness Monitoring Report: TFW-MAGl-00-002.

Chin, A., M. D. Daniels, M. A. Urban, H. Piegay, K. J. Gregory, W. Bigler, A. Z. Butt, J. L. Grable, S. V. Gregory, M. Lafrenz, L. R. Laurencio, and E. Wohl. 2008. Perceptions of Wood in Rivers and Challenges for Stream Restoration in the United States. *Environmental Management* 41:893–903.

Clay, C. 1949. The Colorado River Raft. *The Southwestern Historical Quarterly* 102 (4):400–426.

Coe, H. J., P. M. Kiffney, G. R. Press, K. K. Kloehn, and M. L. McHenry. 2009. Periphyton and Invertebrate Response to Wood Placement in Large Pacific Coastal Rivers. *River Research and Applications* 25(8):1025–1035.

Coho, C., and S. J. Burges. 1993. Dam-Break Floods in Low Order Mountain Channels of the PNW. *Water Resources Series Tech Rep no. 138*. Dept. Civil Engineering, Univ. of Washington, Seattle. 68 pp.

Coho, C., and S. J. Burges. 1994. Dam Break Floods in Low Order Mountain Channels of the Pacific Northwest. TFW SH9 93 001. Timber Fish and Wildlife, Department of Natural Resources, Olympia. 70 pp.

Collins, B. D., and A. J. Sheikh. 2005. *Historical Reconstruction, Classification, and Change Analysis of Puget Sound Tidal Marshes*. University of Washington (Seattle, WA) and the Nearshore Habitat Program, Washington State Dept. of Natural Resources, Olympia, WA. See more at: http://www.eopugetsound.org/science-review/3-tidal-wetlands#sthash. T4OyhfFd.dpuf

Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical Changes in the Distribution and Functions of Large Wood in Puget Lowland Rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59:66–76.

Collins, B. D., D. R. Montgomery, and A. J. Sheikh. 2003. Reconstructing the Historical Riverine Landscape of the Puget Lowland. Pages 79–128 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press, Seattle.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett. 2003. Nitrogen Export from Forested Watersheds in the Oregon Coast Range: The Role of N_2-Fixing Red Alder. *Ecosystems* 6(8):773–785.

Cordova, J. M., E. J. Rosi-Marshall, A. M. Yamamuro, and G. A. Lamberti. 2007. Quantity, Controls, and Functions of Large Woody Debris in Midwestern USA Streams. *River Research and Applications* 23:21–23.

Crook, D., and A. Robertson. 1999. Relationships between Riverine Fish and Woody Debris: Implications for Lowland Rivers*. Marine and Freshwater Research* 50:941–953.

Cushman, M. J. 1981. *The Influence of Recurrent Snow Avalanches on Vegetation Patterns in the Washington Cascades*. Ph.D. dissertation. University of Washington, Seattle, Washington.

Dacy, G. H. 1921. Pulling the Mississippi's Teeth. *Scientific American* 75(4):60, 70.

Danehy, R. J., and B. J. Kirpes. 2000. Relative Humidity Gradients across Riparian Areas in Eastern Oregon and Washington Forests. *Northwest Science* 74(3):224–233.

Davis, W. M. 1901. *Physical Geography*. Boston, MA: Ginn and Company.

Dickman, A., and S. Cook. 1989. Fire and Fungus in a Mountain Hemlock Forest. *Canadian Journal of Botany* 67:2005–2016.

Doloff, C. A., and M. L. Warren, Jr. 2003. Fish Relationships With Large Wood in Small Streams. *American Fisheries Symposium* 37:179–193.

Dominguez, L. G., and C. J. Cederholm. 2000. Rehabilitating Stream Channels Using Large Woody Debris with Considerations for Salmonid Life History and Fluvial Geomorphic Processes. Pages 545–563 in E. E. Knudsen. C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser (eds.), *Sustainable Fisheries Management: Pacific Salmon*. Lewis Publishers, New York.

Edmonds, R. L., T. B. Thomas, and K. P. Maybury. 1993. Tree Population Dynamics, Growth, and Mortality in old-Growth Forests in the Western Olympic Mountains, Washington. *Canadian Journal of Forest Research* 23:512–519.

Elmore, W., and R. L. Beschta. 1988. The Fallacy of Structures and the Fortitude of Vegetation. *Proc. of Calif. Riparian Systems Conference*. Davis, Calif.

Environmental Agency. 2009. *The Hyporheic Handbook. a Handbook of the Groundwater-Surface Water Interface and Hyporheic Zone for Environmental Managers.* Science Report SC050070. 264 pp. Available: http://www.hyporheic.net/SCHO1009BRDX-e-e.pdf. Accessed: June 13, 2014.

Fahnestock, G. R. 1976. Fires, Fuel, and Flora as Factors in Wilderness Management: The Pasayten Case. *Tall Timbers Fire Ecology Conf*. 15:33–70.

Fahnestock, G. R., and J. K. Agee. 1983. Biomass Consumption and Smoke Production by Prehistoric and Modern Forest Fires in Western Washington. *Journal of Forestry* 81:653–657.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large Woody Debris, Physical Process, and Riparian Forest Development in Montane River Networks of the Pacific Northwest. *Geomorphology* 13:133–144. Elsevier Science B.V.

Findlay, S., J. Tank, S. Dye, H. M. Valett, P. J. Mulholland, W. H. McDowell, S. L. Johnson, S. K. Hamilton, J. Edmonds, W. K. Dodds, and W. B. Bowden. 2002. A Cross System Comparison of Bacterial and Fungal Biomass in Detritus Pools of Headwater Streams. *Microbial Ecology* 43(1):55–66.

Flebbe, P. A. 1999. Trout Use of Wood Debris and Habitat in Wine Spring Creek, North Carolina. *Forest Ecology and Management* 114:367–376.

Forest Ecosystem Management Assessment Team (FEMAT). 1993. *Forest Ecosystem Management: An Ecological, Economic, and Social Assessmen*t. Report of the Forest Ecosystem Management Assessment Team. July.

Foster, D. R., and E. R. Boose. 1992. Patterns of Forest Damage Resulting from Catastrophic Wind in Central New England, USA. *Journal of Ecology* 80:79–98.

Fox, M. J. 2001. *A New Look at the Quantities and Volumes of Instream Wood in Forested Basins within Washington State. Master of Science thesis.* College of Forest Resources, University of Washington.

Fox, M. J. 2003. *Spatial Organization, Position, and Source Characteristics of Large Woody Debris in Natural Systems*. Ph.D. dissertation. College of Forest Resources, University of Washington. Seattle, Washington.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Frangi, J. L., and A. E. Lugo. 1991. Hurricane Damage to a Flood Plain Forest in the Luquillo Mountains of Puerto Rico. *Biotropica* 23(4a):324–335.

Franklin, J. F., and C. T. Dyrness. 1973. *Natural Vegetation of Oregon and Washington*. USDA Forest Service. Gen. Tech. Rep. PNW-8.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. *North American Journal of Fisheries Management* 12 182–197.

Gandy, C. J., and A. P. Jarvis. 2006. *Attenuation of Nine Pollutants in the Hyporheic Zone.* Environment Agency, Bristol, England, June. 33 pp.

Gastaldo, R. A., and C. W. Degges. 2007. Sedimentology and Paleontology of a Carboniferous Log Jam. *International Journal of Coal Geology* 69:103–113.

Gastaldo, R. A., and T. M. Demko. 2011. The Relationship Between Continental Landscape Evolution and the plant-Fossil Record: Long Term Hydrologic Controls on Preservation. Pages 249–285 in P. A. Allison and D. J. Bottjer (eds.)*, Taphonomy: Process and Bias Through Time*. *Aims & Scope Topics in Geobiology Volume 32*. Springer Netherlands.

Gibling, M. R., and N. S. Davies. 2012. Palaeozoic Landscapes Shaped by Plant Evolution. *Nature Geoscience* 5(2):99–105.

Gibling, M. R., A. R. Bashforth, H. J. Falcon-Lang, J. P. Allen, and C. R. Fielding. 2010. Log Jams and Flood Sediment Buildup Caused Channel Abandonment and Avulsion in the Pennsylvanian of Atlantic Canada. *Journal of Sedimentary Research* 80:268–287.

Gillespie, Major G. L. 1881. Report of the Chief of Engineers, U.S. Army. Appendix OO 10, 2603–2605.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1996. Distribution and Hydraulic Significance of Large Woody Debris in a Lowland Australian River. *Hydrobiologia* 318:179–194.

Graham, R., and K. Cromack. 1982. Mass, Nutrient Content, and Decay Rate of Dead Boles in Rain Forests of Olympic National Park. *Canadian Journal of Forest Research* 12(3):511–521.

Grant, G. E., and F. J. Swanson. 1995. Morphology and Processes of Valley Floors in Mountain Streams, western Cascades, Oregon. Pages 83–101 in J. D. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock (eds.). *Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph 89*. American Geophysical Union, Washington DC.

Grant, G. E., M. J. Crozier, and F. J. Swanson. 1984. An Approach to Evaluating Off-Site Effects of Timber Harvest Activities on Channel Morphology. *Proceedings of the Symposium on the Effects of Forest and Land Use on Erosion and Slope Stability. Environment and Policy Institute, E-West Center, University of Hawaii, Honolulu* 177–186.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An Ecosystem Perspective of Riparian Zones. *BioScience* 41(8):540–551.

Gregory, S. V., K. L. Boyer, and A. M. Gurnell (eds.). 2003. *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Grette, G. B. 1985. The role of Large Organic Debris in Juvenile Salmonid Rearing Habitat in Small Streams. MS thesis, University of Washington, Seattle, WA.

Grizzel, J. D., and N. Wolff. 1998. Occurrence of Windthrow in Forest Buffer Strips and its Effect on Small Streams in Northwest Washington. *Northwest Science* 72:214–223.

Grizzel, J., M. McGowan, D. Smith, and T. Beechie. 2000. Streamside Buffers and Large Woody Debris Recruitment: Evaluating the Effectiveness of Watershed Analysis Prescriptions in the North Cascades Region. TFW-MAGI-00-003. Washington State Timber, Fish & Wildlife.

Guardia, J. E. 1933. Some Results of the Log Jams in the Red River. *The Bulletin of the Geographical Society of Philadelphia* 31(3):103–114.

Guyette, R. P., D. C. Dey, and M. C. Stambaugh 2008. The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits. *Ecosystems* 11:643–653.

Hafs, A. W., L. R. Harrison, R. M. Utz, and T. Dunneda. 2014. Quantifying the Role of Woody Debris in Providing Bioenergetically Favorable Habitat for Juvenile Salmon. *Ecological Modelling* 286:30–38.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

Hartopo, 1991. The *Effect of Raft Removal and Dam Construction on the Lower Colorado River, Texas*. Unpublished M.S. Thesis, Texas A & M University.

Hauer, F. R. 1989. Organic Matter Transport and Retention in a Blackwater Stream Recovering from Flow Augmentation and Thermal Discharge. *Regulated Rivers: Research and Management* 4:371–380.

Hedman, C. W., D. H. Van Lear, and W. T. Swank. 1996. In-Stream Large Woody Debris Loading and Riparian Forest Seral Stage Associations in the Southern Appalachian Mountains. *Canadian Journal of Forest Research* 26:1218–1227.

Heede, B. H. 1972. Influences of a Forest on the Hydraulic Geometry of Two Mountain Streams. *Water Resources Bulletin* 8:523–530.

Henderson, J. 1996. Unpublished Data Regarding Tree Height vs. Age for Two Common Plant Association Groups. USDA Forest Service, Pacific Northwest Region, Mount Lake Terrace, WA.

Henderson, J. A., R. D. Lesher, D. H. Peter and D. C. Shaw. 1992. *Field Guide to the Forested Plant Associations of the Mt. Baker-Snoqualmie National Forest*. USDA Forest Service, Pacific Northwest Region. Tech paper R6 ECOL TP 028-91.

Hershey, K. 1995. *Characteristics of Forests at Spotted Owl Nest Sites in the Pacific Northwest.* M.S. thesis, Oregon State University, Corvallis.Hewitt, E. R. 1934. *Hewitt's Handbook of Stream Improvement.* The Marchbanks Press, New York.

Hester, E. T., and M. N. Gooseff. 2010. Moving Beyond the Banks: Hyporheic Restoration is Fundamental to Restoring Ecological Services and Functions of Streams. *Environmental Science and Technology* 44:1521–1525.

Hester, E. T., M. W. Doyle, and G. C. Poole. 2009. The Influence of in-Stream Structures on Summer Water Temperatures via Induced Hyporheic Exchange. *Limnology and Oceanography* 54:355–367.

Hewitt, E. R. 1934. *Hewitt's Handbook of Stream Improvement.* New York: The Marchbanks Press.

Hickin E. J. 1984. Vegetation and River Channel Dynamics. *Canadian Geographer* 28(2):111–126.

Hinkle, S. R., J. H. Duff, F. J. Triska, A. Laenen, E. B. Gates, K. E. Bencala, D. A. Wentz, and S. R. Silva. 2001. Linking Hyporheic Flow and Nitrogen Cycling near the Willamette River – A Large River In Oregon, USA. *Journal of Hydrology* 244:157–180.

Hogan, D. L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. Pages 343–353 in R. L. Beschta, T. Blinn, G. E. Grant, F. J. Swanson, and G. G. Ice (eds.), *Erosion and Sedimentation in the Pacific Rim*. IAHS Publication No.165.

Hollis, G. E. 1975. The Effects of Urbanization on Floods of Different Recurrence Intervals. *Water Resources Research* 11:431–435.

Holstine, C. 1992. *An Historical Overview of the Wenatchee National Forest, Washington*. Rep. 100-80. Archaeological and historical Services. Eastern Washington University, Cheney.

Horner, R. R., D. B. Booth, A. Azous, and C. W. 1997. Watershed Determinants of Ecosystem Functioning. Pages 251–274 in L. A. Roesner (ed.), *Effects of Watershed Development and Management on Aquatic Ecosystems*, American Society of Civil Engineers, New York, NY.

House, R. A., and P. L. Boehne. 1985. Evaluation of Instream Enhancement Structures for Salmonid Spawning and Rearing in a Coastal Oregon Stream. *North American Journal of Fish Management* 5:283–295.

House, R. A., and P. L. Boehne. 1986. Effects of Instream Structures on Salmonid Habitat and Populations in Tobe Creek, Oregon. *North American Journal of Fisheries Management* 6:283–295.

Hyatt, T. L., and R. J. Naiman. 2001. The Residence Time of Large Woody Debris in the Queets River, Washington, USA. *Ecological Applications* 11(1):191–202.

Ikeya, H. 1981. A Method for Designation Forested Areas in Danger of Debris Flows. In *Erosion and Sediment Transport in Pacific Rim Steeplands.* Edited by T. R. H. Davies and A. J. Pearce. *International Association of Hydrological Sciences, Publication* 132:576–588.

Johnson, L. B., D. H. Breneman, and C. Richards. 2003. Macroinvertebrate Community Structure and Function Associated with Large Wood in Low Gradient Streams. *River Research and Applications* 19:199–218.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian Forest Disturbances by a Mountain Flood—The Influence of Floated Wood. *Hydrological Processes* 14:3031–3050.

Kauffman, J. B., R. L. Beschta, N. Otting, and D. Lytjen. 1997. An Ecological Perspective of Riparian and Stream Restoration in the Western United States. *Fisheries (Bethesda)* 22:12–24.

Keeton, W. S., C. E. Kraft, and D. R. Warren. 2007. Mature and Old-Growth Riparian Forests: Structure, Dynamics and Effects on Adirondack Stream Habitats. *Ecological Applications* 17:852–868.

Keller, E. A. and A. MacDonald. 1995. River Channel Change: The Role of Large Woody Debris. Pages 217–236 in A. Gurnell and G. Petts (eds.), *Changing River Channels*. John Wiley and Sons, Chichester. 217-235.

Keller, E. A., and F. J. Swanson. 1979. Effects of Large Organic Material on Channel Form and Fluvial Processes. *Earth Surface Processes* 4:361–380.

Keller, E. A., and T. Tally. 1979. Effects of Large Organic Debris on Channel Form and Fluvial Processes in the Coastal Redwood Environment. Pages 169–197 in D. D. Rhodes and G. P. Williams (eds.), *Adjustments of the Fluvial System.* Proceedings of the 10th Annual Binghamton Geomorphology Symposium. Kendal-Hunt. Dubuque, IA.

Kennard, P., G. Pess, T. Beechie, B. Bilby, and D. Berg. 1998. Riparian-in-a-Box: A Manager's Tool to Predict the Impacts of Riparian Management on Fish Habitat. Pages 483-490. in M. K. Brewin and D. M. A. Monita (eds.), *Forest-Fish Conference: Land Management Practices Affecting Aquatic Ecosystems*. Proceedings of Forest-fish conference, May 1-4, 1996, Calgary, Alberta. Natural Resources Canada. North For. Cent., Edmonton, Alberta Inf. Rep. NOR-X-356.

Koehn, J. D., W. G. O'Connor, P. D. Jackson. 1994. Seasonal and size-Related Variation in Microhabitat Use of a Small Victorian Stream Fish Assemblage. *Australian Journal of Marine and Freshwater Research* 45:1353–1366.

Krause, C., and C. Roghair. 2014. *Inventory of Large Wood in the Upper Chattooga River Watershed, 2007–2013*. U.S. Forest Service Southern Research Station, Center for Aquatic Technology Transfer. Blacksburg, VA.

Krause, S., M. J. Klaar, D. M. Hannah, J. Mant, J. Bridgeman, M. Trimmer, and S. Manning-Jones. 2014. The Potential of Large Woody Debris to Alter Biogeochemical Processes and Ecosystem Services in Lowland Rivers. *Wiley Interdisciplinary Reviews (WIREs): Water* 1:263–275.

Lancaster, S. T., S. K. Hayes, and G. E. Grant. 2001. Modeling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds. *Geomorphic Processes and Riverine Habitat, Water Science and Application Volume 4*:85–102. American Geophysical Union.

Lautz, L. K., D. I. Siegel, and R. L. Bauer. 2006. Impact of Debris Dams on Hyporheic Interaction along a Semi-Arid Stream. *Hydrological Processes* 20:183–196.

Lee, P. C., C. Smyth, and S. Boutin. 2004. Quantitative Review of Riparian Buffer Width Guidelines from Canada and the United States. *Journal of Environmental Management* 70:165–189.

Lemly, A. D., and R. H. Hilderbrand. 2000. Influence of Large Woody Debris on Stream Insect Communities and Benthic Detritus. *Hydrobiologia* 421:179–185.

Leopold, L. B. 1973. River Channel Change with Time: An Example. *Geological Society of America*

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of Large Woody Debris in Streams in Old-Growth Douglas-Fir Forests. *Canadian Journal of Forest Research* 17:150–156.

Lisle, T. 1995. Effects of Coarse Woody Debris and its Removal on a Channel Affected by the 1980 Eruption of Mount St. Helens, Washington. *Water Resources Research* 31:1797–1808.

Lockaby, B. G., J. A. Stanturf, and M. G. Messina. 1997. Effects of Silvicultural Activity on Ecological Processes in the Floodplain Forests of the Southern United States: A Review of Existing Reports. *Forest Ecology and Management* 90:93–100.

Lyell, C. 1830. *Principles of Geology*, Volume I. London, UK: John Murray. Published in 1990 by University of Chicago Press. Chicago, IL.

Magilligan, F. J., K. H. Nislov, G. B. Fisher, J. Wright, G. Mackey, and M. Laser 2008. The Geomorphic Function and Characteristics of Large Woody Debris in Low Gradient Rivers, Coastal Maine, USA. *Geomorphology* 97:467–482.Makaske, B., D. G. Smith, and H. J. Berendsen. 2002. Avulsions, Channel Evolution and Floodplain Sedimentation Rates of the Anastomosing Upper Columbia River, British Columbia, Canada. *Sedimentology* 49(5):1049–1071.

Makaske, B., D. G. Smith, and H. J. Berendsen. 2002. Avulsions, Channel Evolution and Floodplain Sedimentation Rates of the Anastomosing Upper Columbia River, British Columbia, Canada. *Sedimentology* 49(5):1049–1071.

Marston, R. A. 1982. The Geomorphic Significance of Log Steps in Forested Streams. *Annals of the Association of American Geographers* 72:99–108.

Martin, D. J., and L. E. Benda. 2001. Patterns of Instream Wood Recruitment and Transport at the Watershed Scale. *Transactions of the American Fisheries Society* 130:940–958.

Maser, C., and J. M. Trappe (eds.). 1984. *The Seen and Unseen World of the Fallen Tree*. Gen. Tech. Rep. PNW-164. Portland, OR: U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (eds.). 1988. *From the Forest to the Sea: A Story of Fallen Trees*. General Tech. Report PNW-GTR-229. USFS. 153 pp.

McCall, E. 1984. *Conquering the Rivers*. Louisiana State University Press. Baton Rouge, LA.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source Distances for Coarse Woody Debris Entering Small Streams in Western Oregon and Washington. *Canadian Journal of Forest Research* 20:326–330.

McHenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the Quantity and Characteristics of LWD in Streams of the Olympic Peninsula, Washington, USA (1982-1993). *Canadian Journal of Fisheries and Aquatic Sciences* 55(6):1395–1407.

Means, J. E., K. Cromack Jr., and P. C. MacMillan, 1986, Comparison of Decomposition Models Using Wood Density of Douglas-Fir Logs. *Canadian Journal of Forestry Research* 15:1092–1098.

Melillo, J. M., R. J. Naiman, J. D. Aber, and K. N. Eshleman. 1983. The Influence of Substrate Quality and Stream Size on Wood Decomposition Dynamics. *Oecolgia (Berlin)* 58:281–285.

Mellina, E. and S. G. Hinch. 2009. Influences of Riparian Logging and in-Stream Large Wood Removal on Pool Habitat and Salmonid Density and Biomass: A Meta-Analysis. *Canadian Journal of Forest Research* 39:1280–1301.

Miller, D., C. Luce, and L. Benda. 2003. Time, Space, and Episodicity of Physical Disturbance in Streams. *Forest Ecology and Management* 178(1):121–140.

Miller, S. W., P. Budy, and J. C. Schmidt. 2010. Quantifying Macroinvertebrate Responses to In-Stream Habitat Restoration. *Applications of Restoration Ecology* 18:8–19.

Millward, A. A., C. E. Kraft, and D. R. Warren. 2010. Ice Storm Damage Greater Along the Terrestrial-Aquatic Interface in Forested Landscapes. *Ecosystems* 13:249–260.

Montgomery, D. R., and T. B. Abbe. 2006. Influence of Logjam-Formed Hard Points on the Formation of Valley-Bottom Landforms in an Old-Growth Forest Valley, Queets River, Washington, USA. *Quaternary Research* 65:147–155.

Montgomery, D. R., and J. M. Buffington. 1993. *Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition*. TFW-SH10-93-002. Washington State Timber, Fish & Wildlife.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-Reach Morphology in Mountain Drainage Basins. *Geological Society of America Bulletin* 109:596–611.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1995a. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995b. Pool Spacing in Forest Channels. *Water Resources Research* 31:1097–1105.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Moore, M. K. 1977. Factors Contributing to Blowdown in Streamside Leave Strips on Vancouver Island. *Land Management Report No. 3.* Victoria, BC: Province of British Columbia Ministry of Forests, Information Division.

Moulin, B., E. R. Schenk, and C. R. Hupp. 2011. Distribution and Characterization of In-channel Large Wood in Relation to Geomorphic Patterns on a Low-gradient River. *Earth Surface Processes and Landforms* 36:1137–1151.

Muir, J. 1878. Forests of California, the New Sequoia. *Harper's New Monthly Magazine* LVII (CCCXLII):813–827.

Mulholland, P. J., and J. R. Webster. 2010. Nutrient Dynamics in Streams and the Role of J-NABS. *Journal of the North American Benthological Society* 29:100–117.

Mulholland, P. J., and 33 others. 2009. Nitrate Removal in Stream Ecosystems Measured by 15N Addition Experiments: Denitrification. *Limnology and Oceanography* 54:666–680.

Murphy, M. L. 1995. Forestry Impacts on Freshwater Habitat of Anadromous Salmonids in the Pacific Northwest and Alaska—Requirements for Protection and Restoration. *U.S. Department of Commerce Coastal Ocean Program, NOAA. Decision Analysis Series No. 7*, 156 pp.

Murphy, M. L., and K. V. Koski. 1989. Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. *North American Journal of Fisheries Management* 9(4):427–436.

Mutz, M., E. Kalbus, and S. Meinecke. 2007. Effect of Instream Wood on Vertical Water Flux in Low-Energy Sand Bed Flume Experiments. *Water Resources Research* 43:W10424.

Nagayama, S. and F. Nakamura. 2010. Fish Habitat Rehabilitation Using Wood in the World. *Landscape and Ecologic Engineering* 6:289–305.

Naiman, R. J., T. J. Beechie, L. E. Benda, P. A. Bisson, L. H. MacDonald, M. D. O'Conner, P. L. Olsen, and E. A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. Pages 127–188 in R. J. Naiman (ed.), *Watershed Management: Balancing Sustainability and Environmental Change*. Springer: New York.

Naiman, R. J., K. L. Fetherston, S. McKay, and J. Chen. 1998. Riparian Forests. Pages 289-323 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag: New York.

Naiman, R. J., E. V. Balian, K. K. Bartz, R. E. Bilby, and J. J. Latterell. 2002. Dead Wood Dynamics in Stream Ecosystems. Pages 23–48 in W. F. Laudenslayer Jr., P. J. Shea, B. E. Valentine, C. P. Weatherspoon, and T. E. Lisle (eds.), *Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests*. Gen. Tech. Rep. PSW-GTR-181. US Forest Service, Pacific Southwest Forest and Range Experiment Station.

National Marine Fisheries Service. 1996. *Making Endangered Species Act Determinations of Effect for Individual or Grouped Actions at the Watershed Scale*. Environmental and Technical Services Division, Habitat Conservation Branch.

Neumann, R. M., and T. L. Wildman. 2002. Relationships Between Trout Habitat Use and Woody Debris in Two Southern New England Streams. *Ecology of Freshwater Fish* 11:240–250.

Nickelson, T. E., M. F. Solazzi, S. L. Johnson, and J. D. Rodgers. 1992. Effectiveness of Selected Stream Improvement Techniques to Created Suitable Summer and Winter Rearing Habitat for Juvenile Coho Salmon (*Oncorhynchus kisutch*) in Oregon Coastal Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 49:790–794.

North American Forest Commission. 2011. *Forests of North America*. Vector Digital Data. Food and Agriculture Organization of the United Nations. Commission for Environmental Cooperation. Montreal, Quebec, CA.

Oliver, C. D. 1980/1981. Forest Development in North America Following Major Disturbances. *Forest Ecology and Management* 3:153–168.

Oregon Department of Forestry. 1995. *A Guide to Placing Large Wood in Streams*. Salem, OR, Forest Practices Section. 13 pp.

Palik, B., S. W. Golladay, P. C. Goebel, and B. W. Taylor. 1998. Geomorphic Variation in Riparian Tree Mortality and Stream Coarse Woody Debris Recruitment from Record Flooding in a Coastal Plain Stream. *Ecoscience* 5:551–560.Pariset, E., R. Hausser, and A. Gagnon. 1966. Formation of Ice Covers and Ice Jams in Rivers. *Journal of the Hydraulics Division* 92(6):1–24.

Pariset, E., R. Hausser, and A. Gagnon. 1966. Formation of Ice Covers and Ice Jams in Rivers. *Journal of the Hydraulics Division* 92(6):1–24.

Parrish, R. M. and P. B. Jenkins. 2012. *Natural Log Jams in the White River: Lessons for Geomimetic Design of Engineered Log Jams*. U.S. Fish and Wildlife Service, Leavenworth, WA.

Pearsons, T. D., and H. W. Li. 1992. Influence of Habitat Complexity on Resistance to Flooding and Resilience of Stream Fish Assemblages. *Transactions of the American Fisheries Society* 121:427–436.

Peters, P. 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, North Pacific Coast Ecoregion. Western Washington Office, Aquatic Resources Division. Lacey, WA. 34 pp.

Petts, G. E., A. L. Roux, and H. Moller (eds.). 1989. *Historical Changes of Large Alluvial Rivers, Western Europe*. Chichester: John Wiley.

Phillips, J. D. 2012. Log-jams and Avulsions in the San Antonio River Delta, Texas. *Earth Surface Processes and Landforms* 37:936–950.

Phillips, J. D., and L. Park. 2009. Forest Blowdown Impacts of Hurricane Rita on Fluvial Systems. *Earth Surface Processes and Landforms* 34:1069–1081.

Piégay, H., A. and R. A. Marston. 1998. Distribution of Coarse Woody Debris Along the Concave Bank of a Meandering River (the Ain River, France). *Physical Geography* 19(4):318–340.

Piégay, H., A. Thevenet, and A. Citterio. 1999. Input, Storage and Distribution of LWD Along a Mountain River Continuum, the Drôme River, France. *Catena* 35:19–39.

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and Hydraulic Effects of Riparian Root Networks on Streambank Stability: Is Mechanical Root-Reinforcement the Whole Story? *Geomorphology* 116(3):353–362.

Pollock, M. M., and T. J. Beechie. 2014. Does Riparian Forest Restoration Thinning Enhance Biodiversity? The Ecological Importance of Large Wood. *JAWRA Journal of the American Water Resources Association* 50(3):543–559. Online publication date: June 1, 2014.

Pollock, M. M., R. J. Naiman, and T. A. Hanley. 1998. Plant Species Richness in Riparian Wetlands—A Test of Biodiversity Theory. *Ecology* 79:94–105.

Pollock, M. M., T. J. Beechie., M. Liermann, and R. E. Bigley. 2009. Stream Temperature Relationships to Forest Harvest in Western Washington. *Journal of the American Water Resources Association* 45(1):141–156.

Prowse, T. D. 2001. River Ice Ecology. 1: Hydrologic, Geomorphic, and Water Quality Aspects. *Journal of Cold Regions Engineering* 15(1):1–16.

Ralph, S. C., G. C. Poole, L. L. Conquest, and R. J. Naiman. 1991. Stream Channel Morphology and Woody Debris in Logged and Unlogged Basins of Western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51:37–51.

Raup, H. M. 1957. Vegetation Adjustment to the Instability of Sites. *Proceedings and Papers of the 6th Technical Meeting of the International Union for Conservation of Nature and Natural Resources*. Edinburgh. Pages 36–48.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991. Rehabilitating and Modifying Stream Habitats. Pages 519–557 in *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication* 19.

Reid, L. M., and S. Hilton. 1998. Buffering the Buffer. Pages 71–80 in R. R. Ziemer (ed.), *Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story*; held May 6, 1998, in Ukiah, California. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-168.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and Function of Large Woody Debris in Subalpine Rocky Mountain Streams in Northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Riley, S. C. and K. D. Fausch. 1995. Trout Population Response to Habitat Enhancement in Six Northern Colorado Streams. *Canadian Journal of Fisheries and Aquatic Sciences*. 52:34–53.

Robison, E. G. and R. L. Beschta. 1990. Identifying Trees in Riparian Areas that can Provide Coarse Woody Debris to Streams. *Forest Science* 36:790–801.

Roni, P., M. Liermann, and A. Steel. 2003. Monitoring and Evaluating Fish Response to Instream Restoration. In D. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies. University of Washington Press: Seattle.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2014a. Wood Placement in River Restoration: Fact, Fiction, and Future Direction. *Canadian Journal of Fisheries and Aquatic Sciences* 72(3):466–478.

Rosenfeld, J. S., and L. Huato. 2003. Relationship Between Large Woody Debris Characteristics and Pool Formation in Small Coastal British Columbia Streams. *North American Journal of Fisheries Management* 23:928–938.

Rosgen, D., and H. L. Silvey. 1996. *Applied River Morphology. Wildland Hydrology*. Pagosa Springs, CO.

Rot, B. 1993. *Windthrow in Stream Buffers on Coastal Washington Streams*. ITT-Rayonier Inc. 49 pp.

Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream Channel Configuration, Landform, and Riparian Forest Structure in the Cascade Mountains, Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 57:699–707.

Ruffner, E. H. 1886. *The Practice of the Improvement of the Non-Tidal Rivers of the United States, with an Examination of the Results Thereof*. New York, NY: John Wiley and Sons.

Ruiz-Villanueva, V., A. Díez-Herrero, J. M. Bodoque, and E. Bladé. 2014. Large Wood in Rivers and its Influence on Flood Hazard. *Cuadernos de Investigación Geográfica* 40:229–246.

Russell, I.C. 1909. *Rivers of North America*. New York, NY: G.P. Putnam and Sons.

Saunders, J. W. and M. W. Smith. 1955. Physical Alteration of Stream Habitat to Improve Brook Trout Production. *Canadian Fish Culturist* 16:185–188.

Saunders, J. W. and M. W. Smith. 1962. Physical Alteration o f Stream Habitat to Improve Brook Trout Production. *Transactions of the American Fisheries Society* 82:185–188.

Schenk, E. R., J. W. McCargo, B. Moulin, C. R. Hupp, and J. M. Richter. 2014a. The Influence of Logjams on Largemouth Bass (*Micropterus salmoides*) Concentrations on the Lower Roanoke River, a Large Sand-bed River. *River Research and Applications*. www.wileyonlinelibrary.com, DOI: 10.1002/rra.2779

Schenk, E. R., B. Moulin, C. R. Hupp, J. M. Richter. 2014b. Large Wood Budget and Transport Dynamics on a Large River Using Radio Telemetry. *Earth Surface Processes and Landforms* 39:487–498.

Scherer, R. 2004. Decomposition and Longevity of In-Stream Woody Debris: A Review of Literature from North America. Pages 127–133 in *Forest Land–Fish Conference–Ecosystem Stewardship through Collaboration*. Proceedings of Forest-Land-Fish Conference II.

Schuett-Hames, D., A. E. Pleus, J. Ward, M. Fox, and J. Light. 1999. *TFW Monitoring Program Methods Manual for the Large Woody Debris Survey*. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-004. DNR #106. March.

Sedell, J. R., and J. L. Frogatt. 1984. Importance of Streamside Forests to Large Rivers: The Isolation of the Willamette River, Oregon, U.S.A., from its Floodplain by Snagging and Streamside Forest Removal. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1828–1834.

Sedell, J. R., and K. J. Luchessa. 1981. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. Symposium *on Acquisition and Utilization of Aquatic Habitat Inventory Information*. October 23–28, Portland, OR.

Sedell, J. R., and K. J. Luchessa. 1982. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. Pages 222–245 in N. B. Armantrout (ed.). *Acquisition and Utilization of Aquatic Habitat Inventory Information.* Proceedings of a Symposium October 28–30, 1981. Billings, MT: The Hague Publishing.

Sedell, J. R., and F. J. Swanson. 1984. Ecological Characteristics of Streams in Old-Growth Forests of the Pacific Northwest. Pages 9–16 in W. R. Meehan, T. R. Merrell Jr., and T. A. Hanley (eds.), *Fish and Wildlife Relationships in Old-Growth Forests*. Juneau, AK: American Institute of Fisheries Research Biologists.

Sedell, J. R., F. H. Everest, and F. J. Swanson. 1982. Fish Habitat and Streamside Management: Past and Present. Pages 244–255 in *Proceedings of the 1981 Convention of the Society of American*

Foresters, September 27–30, 1981. Society of American Foresters, Publication 82–01, Bethesda, Maryland.

Sedell, J. R., F. J. Swanson, and S. V. Gregory. 1984. Evaluating Fish Response to Woody Debris. Pages 191–221 in T. J. Hassler (ed.). *Proceedings of the Pacific Northwest Streams Habitat Management Workshop*. American Fisheries Society. Humboldt State University. Arcata, CA.

Seehorn, M. E. 1985. *Fish Habitat Improvement Handbook: Atlanta, Georgia*. U.S. Forest Service, Southern Region. Technical Publication R8-TP-16. 30 pp.

Senter, A. E., and G. B. Pasternack. 2010. Large Wood Aids Spawning Chinook Salmon (*Oncorhynchus Tshawytscha*) in Marginal Habitat on a Regulated River in California. *River Research and Applications* 27:550–565.

Shields, F. D., Jr., and R. H. Smith. 1992. Effects of Large Woody Debris Removal on Physical Characteristics of a Sand Bedded River. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:145–163.

Singer, S., and M. L. Swanson. 1983. *The Soquel Creek Storm Damage Recovery Plan with Recommendations for Reduction of Geologic Hazards in Soquel Village, Santa Cruz County, California.* Unpublished USDA Soil Conservation Service report to the Santa Cruz County Board of Supervisors.

Smith, D. G. 1979. Effects of Channel Enlargement by River Ice Processes on Bankfull Discharge in Alberta, Canada. *Water Resources Research*, 15(2):469–475.

Smith, D. G., and C. M. Pearce. 2000. River Ice and its Role in Limiting Woodland Development on a Sandy Braid-Plain, Milk River, Montana. *Wetlands,* 20(2):232–250.

Smith, D. G., and D. M. Reynolds. 1983. Tree Scars to Determine the Frequency and Stage of High Magnitude River Ice Drives and Jams, Red Deer, Alberta. *Canadian Water Resources Journal* 8(3):77–94.

Smock, L. A., G. M. Metzler and J. E. Gladden. 1989. Role of Debris Dams in the Structure and Functioning of Low Gradient Headwater Streams. *Ecology* 70:764–775.

Society for Ecological Restoration. 2004. *The SER International Primer on Ecological Restoration*. Available: <http://www.ser.org>.

Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of Increasing Winter Rearing Habitat on Abundance of Salmonids in Two Coastal Oregon Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 57:906–914.

Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of Log Decay in Old-Growth Douglas-Fir Forests, *Canadian Journal of Forest Research* 17:1585–1595.

Spänhoff, B., and E. Cleven. 2010. Wood in Different Stream Types: Epixylic Biofilm and Wood-Inhabiting Invertebrates in a Lowland Versus an Upland Stream. *Annales De Limnologie-International Journal of Limnology* 46(3):169–179.

Spänhoff, B., and E. I. Meyer. 2004. Breakdown Rates of Wood in Streams. *Journal of the North American Benthological Society* 23(2):189–197.

Spänhoff, B., C. Alecke, and E. Irmgard Meyer. 2001. Simple Method for Rating the Decay Stages of Submerged Woody Debris. *Journal of the North American Benthological Society* 20(3):385–394.

Spies, T. A., J. F. Franklin, and T. B. Thomas. 1988. Coarse Woody Debris in Douglas-Fir Forests of Western Washington and Oregon. *Ecology* 69:1689–1702.

Spies, T. A., and J. F. Franklin. 1991. The Structure of Natural Young, Mature, and Old-Growth Douglas Fir Forests in Oregon and Washington. Pages 91–109 in L. F. Ruggiero, K. B. Aubrey, A. B. Carey, and M. H. Huff (technical coordinators), *Wildlife and Vegetation of Unmanaged Douglas Fir Forests*. USDA Forest Service. General Technical Report PNW-GTR-285.

Stanford, J. A. and J. V. Ward. 1988. The Hyporheic Habitat of River Ecosystems. *Nature* 335:64–66.

Steinhart, G. S., G. E. Likens, and P. M. Groffman. 2000. Denitrification in Stream Sediments in Five Northeastern (USA) Streams. *Verhandlungen Internationale Vereinigung für Theorertische und Angewandte Limnologie* 27:1331–1336.

Stock, J. D., D. R. Montgomery, B. D. Collins, W. E. Dietrich, and L. Sklar. 2005. Field Measurements of Incision Rates Following Bedrock Exposure: Implications for Process Controls on the Long Profiles of Valleys Cut by Rivers and Debris Flows. *Geological Society of America Bulletin* 117(11/12):174–194.

Sullivan, K. J., J. Tooley, K. Doughty, J. E. Caldwell, and P.A. Knudsen. 1990. *Evaluation of Prediction Models and Characterization of Stream Temperature Regimes in Washington*. TFW-WQ3-90-006, Timber Fish & Wildlife, Department of Natural Resources, Olympia, WA.

Sundbaum, K. and I. Naslund. 1998. Effects of Woody Debris on the Growth and Behavior of Brown Trout in Experimental Stream Channels. *Canadian Journal of Zoology* 76:56–61.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land-Water Interactions: The Riparian Zone. Pages 267–291 on R. L. Edmonds (ed.), *Analysis of Coniferous Forest Ecosystems in the Western United States*. US/IBP Synthesis Series, Hutchinson Ross Publishing Company: Stroudsburg, PA.

Swanson, F. J., T. K. Kranz, N. Caine, and R. G. Woodmansee. 1988. Landform Effects on Ecosystem Patterns and Processes. *BioScience* 38:92–98.

Tappeiner, J. C., D. Huffman, D. Marshall, T. A. Spies, and J. D. Bailey. 1997. *Density, Ages, and Growth Rates in Old-Growth and Young-Growth Forests in Coastal Oregon*. Paper 3166 of the Forest Research Laboratory, Oregon State University, Corvallis.

Tarzwell, C. M. 1934. *The Purpose and Value of Stream Improvement Method. Stream Improvement.* Bulletin R-4. Presented at the Annual Meeting of the American Fisheries Society. Ogden, UT.

Tarzwell, C. M. 1936. Experimental Evidence of the Value of Trout Stream Improvements. *Transactions of the American Fisheries Society* 66:177–187.

Thompson, D. M. 2002. Long-term Effect of Instream Habitat-improvement Structures on Channel Morphology along the Blackledge and Salmon Rivers, Connecticut, USA. *Environmental Management* 29(1):250–265.

Thompson, D. M. 2005. The History of the Use and Effectiveness of Instream Structures in the United States. *Geological Society of America Reviews in Engineering Geology* XVI:35–50.

Tonina, D., and J. M. Buffington. 2009. Hyporheic Exchange In Mountain Rivers I: Mechanics and Environmental Effects. *Geography Compass* 3:1063–1086.

Triska, F. J. 1984. Role of Large Wood in Modifying Channel Morphology and Riparian Areas of a Large Lowland River under Pristine Conditions: A Historical Case Study. *Verhandlungen-InternationaleVereinigung für Theorelifche und Angewandte Limnologie* 22:1876–1892.

Triska, F. J., and K. Cromack, Jr. 1979. The Role of Wood Debris in Forests and Streams. In R.H. Waring, Forests: Fresh Perspectives from Ecosystem Analysis*.* Pages 171–190 in *Proceedings of the 40th Annual Biology Colloquium*. Corvallis, OR: Oregon State University Press. Corvallis, OR.

Tufekcioglu, A., J. W. Raich, T. M. Isenhart, and R. C. Schultz. 2003. Biomass, Carbon and Nitrogen Dynamics of Multi-Species Riparian Buffers within an Agricultural Watershed in Iowa, USA. *Agroforestry Systems* 57(3):187–198.

U.S. Department of Agriculture (USDA). 1980. *Ecoregions of the United States*. U.S. Forest Service, Washington, D.C. Miscellaneous Publication No. 1391

Valett, H. M., C. L. Crenshaw, and P. F. Wagner. 2002. Stream Nutrient Uptake, Forest Succession, and Biogeochemical Theory. *Ecology* 83:2888–2901.

Van Cleef, J. S. 1885. How to Restore Our Trout Streams. *Transactions of the American Fisheries Society* 14:50–55.

Van Sickle, J., and S. V. Gregory. 1990. Modeling Inputs of Large Woody Debris to Streams from Falling Trees. *Canadian Journal of Forest Research* 20(10):1593–1601.

Veatch, A. C. 1906. Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas. Washington D.C. *United States Geological Survey Professional Paper* 46.

Wadsworth, A. H., Jr. 1966. Historical Deltation of the Colorado River, Texas. Pages 99–105 in *Deltas in Their Geologic Framework.* American Association of Petroleum Geologists.

Wallace, J. B., and A. C. Benke. 1984. Quantification of Wood Habitat in Subtropical Coastal Plain Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 41:1643–1652.

Wallace, J. B., J. R. Webster, and J. L. Meyer. 1995. Influence of Log Additions on Physical and Biotic Characteristics of a Mountain Stream. *Canadian Journal of Fisheries and Aquatic Sciences* 52:2120–2137.

Wallerstein, N., C. R. Thorne, and M. W. Doyle. 1997. Spatial Distribution and Impact of Large Woody Debris in Northern Mississippi. Pages 145–150 in C. C. Wang, E. J. Langendoen, and F. D. Shields (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision.* University of Mississippi. Oxford, MI.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of Floodplain River Ecosystems: Ecotones and Connectivity. *Regulated Rivers Research and Management* 15:125–139.

Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. 2002. Riverine Landscape Diversity. *Freshwater Biology* 47:517–539.

Warren, D. R., E. S. Bernhardt, R. O. Hall Jr., and G. E. Likens. 2007. Forest Age, Wood and Nutrient Dynamics in Headwater Streams of the Hubbard Brook Experimental Forest. *N.H. Earth Surface Processes & Landforms* 32(8):1154–1163.

Webster, J. R., and E. F. Benfield. 1986. Vascular Plant Breakdown in Freshwater Ecosystems. *Annual Review of Ecology and Systematics* 17(1):567–594.

White, R. J., and O. M. Brynildson. 1967. *Guidelines for Management of Trout Stream Habitat in Wisconsin*. Wisconsin Department of Natural Resources Technical Bulletin 39. Madison, WI.

Whiteway, S. L., P. M. Biron, A. Zimmermann, O. Venter, and J. W. A. Grant. 2010. Do In-Stream Restoration Structures Enhance Salmonid Abundance? A Meta-Analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 67:831–841.

Whitney, G. G. 1996. *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present.* Cambridge University Press: Cambridge, UK.

Wilford, D., Maloney, D., Schwab, J., and Geertsema, M. 1998. Tributary Alluvial Fans. *B.C. Ministry of Forests Extension Note* 30.

Wiltshire, P. E. J., and P. D. Moore. 1983, Paleovegetation and Paleohydrology in Upland Britain. Pages 433–451 in K. J. Gregory (ed.), *Background to Paleohydrology*. John Wiley: Chichester, UK.

Wohl E., D. A. Cenderelli, K. A. Dwire, S. E. Ryan-Burkett, M. K. Young, and K. D. Fausch. 2010. Large in-Stream Wood Studies: A Call for Common Metrics. *Earth Surface Processes and Landforms* 35:618–625.

Wohl, E. 2013. Floodplains and Wood. *Earth-Science Reviews* 123:194–212.

Wolff, H. H. 1916. The Design of a Drift Barrier Across the White River, near Auburn, Washington. *Transactions of the American Society of Civil Engineers* 16:2061–2085.

Wondzell, S. M. 2011. The Role of the Hyporheic Zone across Stream Networks. *Hydrological Processes* 25:3525–3532.

Wondzell, S.M., and P. A. Bisson. 2003. Influence of Wood on Aquatic Biodiversity. Pages 249–263 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37*. Bethesda, MD: American Fisheries Society.

Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards. 2009. Changes in Hyporheic Flow Following Experimental Removal of a Small, Low-Gradient Stream. *Water Resources Research* 45:W05406, 13 pp.

Wuehlisch, G. Von. 2011. Evidence for nitrogen-Fixation in the Salicaceae Family. *Tree Planters' Notes* 54(2):38–41.

Zeng, H., J. Q. Chambers, R. I. Negron-Juarez, G. C. Hurtt, D. B. Baker, and M. D Powell. 2009. Impacts of Tropical Cyclones on U.S. Forest Tree Mortality and Carbon Flux from 1851 to 2000. *Proceedings of the National Academy of Sciences* 106(19), 7888–7892.

Zimmerman, R. C., J. C. Goodlett, and G. H. Comer. 1967. The Influence of Vegetation on Channel Form of Small Streams, Symposium on River Morphology. *International Association of Science Hydrology Publication, Gentbrugge, Belgium* 75:255–275.

Zobel, D. B., A. McKee, G. M. Hawk, and C. T. Dyrness. 1976. Relationships of Environment to Composition, Structure, and Diversity of Forest Communities of the Central Western Cascades of Oregon. *Ecological Monographs* 46:135–156.

Chapter 2

LARGE WOOD AND THE FLUVIAL ECOSYSTEM RESTORATION PROCESS

Placement of large wood in the Lower Elwha River, Elwha River Ecosystem Restoration Project, Lower Elwha Klallam Tribe, Port Angeles, Washington. Source: Tim Abbe.

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2.1 Introduction

This chapter provides a general overview of the ecological restoration planning and decision-making process and how it applies to the overall planning and implementation of projects that use large wood to restore process and function to fluvial aquatic ecosystems. It describes the important components to consider by proposing a 12-element planning framework that leads to successful restoration projects. Inherent to the restoration process is the recognition that suitable solutions may include a wide range of design elements, from simple changes in resource management practices to major structural alterations, the selection of which depends on the nature of each individual project. To this end, an integrated approach to the planning and decision-making process provides the foundation for selecting and using appropriate tools and procedures for placing wood in streams.

Anthropogenic activities have degraded aquatic ecosystems around the world. As a result, large efforts to restore function to these ecosystems have occurred for a variety of economic, cultural, and environmental reasons (Roni 2005; NRC 1992). In North America, hundreds of millions of dollars are invested annually by federal, state, and local agencies for restoring or improving fish habitat alone. Millions more are invested by local programs to restore function to aquatic ecosystems for other social and economic values such as flood control. For these efforts to be successful, an understanding as well as consideration of the immutable controls (e.g., geology, climate) and processes (e.g., delivery of wood, water, and sediment) that affect and create fluvial aquatic ecosystems needs to be incorporated into the restoration planning process.

Land use and other anthropogenic activities can affect ecosystem functions by disrupting the processes that form and/or sustain them, such as the supply and movement of sediment from hillslopes, large wood recruitment, shading of the channel, and the volume of water (Roni 2005; Roni et al. 2002). Many processes that create in-channel features operate on time scales of decades or longer (e.g., channel migration). Interrupting these processes (e.g., by stabilizing banks or by constructing roads and levees) can lead to loss of ecosystem functions for decades or even centuries (Beechie and Bolton 1999). As such, most anthropogenic activities tend to disrupt natural processes that form habitat (e.g., delivery of wood, water, sediment, and nutrients).

It is important to note that most habitat enhancement efforts by themselves tend to be relatively short lived (less than a decade) if the underlying ecological process that has been disrupted is not corrected (Roni 2005). To this end, restoration of watershed processes should occur in conjunction with site-specific habitat enhancement.

GUIDANCE

Restoration actions, intended to offset the effects of anthropogenic activities, can affect species habitat through two major pathways:

1. Some habitat restoration approaches focus on restoring natural processes (e.g., road removal, riparian replanting) and thus affect ecosystem functions by influencing the underlying watershed processes (e.g., sediment supply, delivery of organic material).
2. Other techniques focus on manipulating or enhancing habitats for organisms at specific sites (e.g., wood placement for cover). Restoration actions should be at a scale commensurate with environmental problems. (Roni 2005)

Resource managers and restoration practitioners should be mindful of the broader watershed context and recognize that coupling site-specific enhancement efforts with restoration of basic watershed processes will be the most efficient course for habitat restoration.

It is also important to recognize that there are many scientific, societal, and economic factors to consider when planning a restoration project. For example, cost, cost–benefit (e.g., fish/dollar, area restored/dollar), habitat quality, location, access, land ownership, endangered species, and other factors often must be considered when planning restoration projects. Focusing on restoring watershed and ecosystem processes rather than focusing solely on site-specific habitat enhancement activities ensures that the naturally diverse and dynamic conditions to which a variety of species are adapted are maintained, and, in the long run, may be the most efficient and cost-effective course of action.

This manual, and specifically this chapter, is not intended to replace any existing planning guidelines previously adopted by federal agencies, such as the Natural Resource Conservation Service's *Stream Restoration Design Handbook* (NEH 654); U.S. Army Corps of Engineers' (USACE's) *Engineer Regulations (ERs) 1105-2-100*, *1165-2-501*, and *1165-2-100*; and U.S. Environmental Protection Agency's *Handbook for Developing Watershed Plans to Restore and Protect our Water* (2008) and *A Quick Guide to Developing Watershed Plans to Restore and Protect Our Waters* (2013). Rather, this manual addresses how the use of large wood can be considered in concert with these restoration planning processes. Furthermore, the use of additional tools is discussed—such as the Project Screening Matrix and River Restoration Analysis Tool (RiverRAT) (Skidmore et al. 2011), Structured Decision Making (SDM), and Multi-Criteria Decision Analysis (MCDA)—along with how these tools can be applied to alluvial ecological restoration projects.

2.2 Ecological Restoration Process

The need for a holistic approach for conducting restoration activities is well established (Heede and Rinne 1990; NRC 1992; Kauffman et al. 1997; Beechie and Bolton 1999).

CROSS-REFERENCE

As discussed in Chapter 1, *Large Wood Introduction*, ecological restoration is an "intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (Society for Ecological Restoration 2002).

Ecological restoration planning is commonly an iterative process where initial design concepts must be carefully assessed, adjusted, and reevaluated through consideration of a variety of planning elements (Figure 2-1). The planning process not only can result in design changes, but in modified goals and objectives based on the site information and constraints encountered.

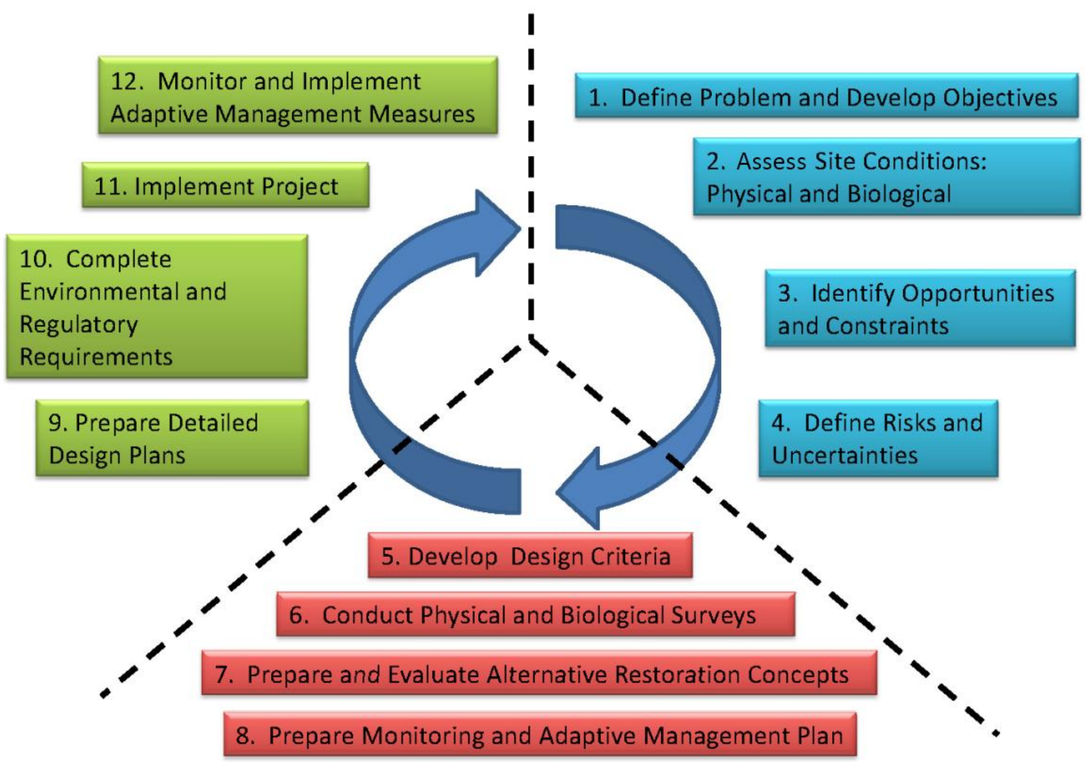
In general, ecological restoration is based on the particular site—its location, upstream watershed conditions, and downstream development. However, one of the key planning elements will be describing the historical changes a site has undergone—documenting the role of both natural and human disturbance. If possible, a *reference reach* should be identified, one that has a similar drainage area and valley confinement but has not been subjected to human disturbance. Documenting the reference reach's ecology will help the planning team evaluate the extent of the subject reach's problems and establish reasonable objectives. However, because reference reaches are difficult to identify and quantitatively describe, often conditions reflecting pre-human disturbance have to be modeled based on historic records of channel planforms, riparian floodplain vegetation, flow records, and changes to the watershed. Depending on the magnitude and complexity of impacts and project constraints, considerable effort could be required for data gathering and analysis.

Issues such as land ownership, local knowledge of river restoration, available restoration funding, politics, recreation, flow regulation, uncertainty in upstream watershed disturbances, and permitting can all influence ecological restoration planning. How rivers are supposed to look and function are ideals that vary from one person to another. Philosophies and approaches to river restoration vary within the restoration profession starting with the state to which a site should be restored and the conditions needed to achieve the desired goals.

Project designs must also address environmental and ecological factors, as well as satisfy the immediate river restoration need. Rivers in urban areas present unique challenges for restoration, particularly how existing infrastructure is protected, either through improvements or how wood is used.

Within the scientific community, there is general agreement on the fundamental ecological restoration planning elements that should be considered in restoring streams (Society for Ecological Restoration 2004; EPA 2000). For the purposes of this manual, we describe 12 principal elements that are typically sequenced within three general phases of an ecological restoration planning framework (Figure 2-1). The Project Screening Matrix and River Restoration Analysis Tool provides a good example of the practical application of these concepts to river restoration projects (Skidmore et al. 2011). Consideration of these elements will help guide aquatic ecological restoration projects using large wood.

Figure 2-1. Phases and Considerations Associated With Ecological Restoration Projects Using Large Wood



2.2.1 Define the Problem and Develop Goals

2.2.1.1 Defining the Problem

Roni (2005) pointed out that most aquatic ecosystem restoration efforts are largely in response to a whole host of impacts (i.e., problems caused) on aquatic ecosystems that occurred following European settlement of North America. Improving the navigation in aquatic environments through dredging and snagging (removal of wood) has simplified many rivers (Sedell and Froggatt 1984; Collins et al. 2003).

CROSS-REFERENCE

As described in Chapter 1, *Large Wood Introduction*, forest practices have negatively affected many streams by increasing fine and coarse sediment, altering stream hydrology, disrupting delivery of woody and organic debris, and simplifying habitat (Salo and Cundy 1987; Murphy 1995).

Agricultural activities have had detrimental effects on aquatic ecosystems through dredging, draining, filling, pollution, and channelization of waterways (NRC 1992). Water diversions for a large variety of uses have led to altered hydrologic patterns, reduced stream flows, higher water temperatures, reduced ability to transport sediment, and other deleterious effects (Orth 1987; Hill et al. 1991). Mining has resulted in the removal of substrates as well as releases of toxic substances (Nelson et al. 1991). Residential development, industrialization, and urbanization have led to a suite of problems for aquatic ecosystems such as filling and channelization, changes in hydrology from increased impervious surface area, pollutants from point and nonpoint sources, elimination of riparian zones, and simplification of habitat (Booth 1990). All of these factors have contributed to the degradation of aquatic ecosystems that are the basis for most of the comprehensive restoration efforts that are currently underway.

Many perceived or actual river problems are associated with the three fundamental types of matter conveyed by streams: water, sediment, and wood. Changes in flow regimes, or the supply of sediment and wood, can result in major changes to a river. Changes can be a result of localized river modifications such as a new culvert or bridge crossing, or floodplain modification, or a more system-wide alteration. They might be due to urbanization that increased impermeable surface area that increased runoff, leading to more frequent high flows, which, in turn, increased sediment transport capacity and led to channel incision. Biological and ecological impacts are sometimes associated with other factors such as changes in water chemistry; low-flow regimes; or vegetation on the banks, floodplain, and riparian zones.

CROSS-REFERENCE

Chapter 3, *Ecological and Biological Considerations*, and Chapter 4, *Geomorphology and Hydrology Considerations*, assess these factors in detail.

Bank and meander migration, scour, and deposition are natural river processes that are not necessarily negative themselves and actually contribute to healthy ecosystems. For example, cottonwood regeneration in Midwestern rivers is very much dependent on channel migration and new formation of sand bars. Natural meander migration rates vary across hydrophysiographic areas, so that a particular rate may or may not constitute a problem. In some areas, very small rates, perhaps a fraction of a meter per year, might signal a problem, while in other areas many meters of movement in a single event might be normal.

Often, any adjustment is viewed as a problem because it causes an unwanted impact on anthropogenic land use or structures. People tend to view static conditions as desirable when in reality such situations are rare. This perception is magnified in systems constrained by development, and there are economic incentives for a static state. Although there are changes that can signal problems, the problems may have as much to do with the constraints on the system as the processes that created the problem.

Understanding the characteristics and variability of natural processes and how human changes affect these processes is critical in all river restoration endeavors. Thousands of miles of streambanks have been artificially hardened to create a static condition that is very unnatural and can lead to local impacts that are compounded downstream. This is especially true regarding wood. Having the right expertise to describe and diagnose a system is essential to restoring and managing streams.

It is important to recognize that short-term changes in sediment storage, channel shape, and planform are both inevitable and acceptable in natural channels with unprotected banks. A key to preventing problems or developing self-sustaining solutions is to provide the channel system with adequate space and time for adjustment. Define the "geomorphic response corridor" and build your restoration plan around this. The area encompassing both the 500-year flood inundation zone and channel migration zone provides a good proxy for defining the geomorphic response corridor (Rapp and Abbe 2003; Abbe and Brooks 2011).

The term *stability* with respect to channels or wood should only be used when clearly defined. Is it *morphologic* stability in a channel that regularly moves its position? Is it *spatial* stability where a channel rarely moves? Numerous factors contribute to channel stability, such as variability of flow regime, fluctuations in wood and sediment loading, bank materials, and the influence of riparian vegetation. Effective restoration projects build a robust system that can experience variations in flow, sediment, and wood, and will change through time while continuing to provide the desired habitat conditions that sustain a healthy ecosystem. Many mistakes have been made in the past due to the lack of recognition and understanding of natural disturbance and the consequences of human actions (Wohl 2013; Reid and Dunne 1996).

2.2.1.2 Develop Goals

The perceived success or failure of many river restoration projects can be heavily dependent upon describing the problem and defining project goals and objectives. Achieving project objectives depends on understanding the problem and why restoration is needed. Once established, the defined parameters can help delineate key metrics for success, data collection, assessment methodologies, and finally the design itself. Having vague and ambiguous objectives for the project can lead to problems. Narrowing the objectives reduces ambiguity for the team members. Objectives should be specific, realistic, achievable, and measurable.

Clear ecological objectives that are achievable and that identify the constraints and capabilities of the river and its associated riparian area will lead to better designs that perform as intended. Some objectives may, at first glance, appear to be realistic, but may need to be redefined if preliminary design information indicates that the costs will be too high, that intended results may not be achievable, or that site constraints may significantly alter or preclude implementation of the final design. Ecological objectives should address the maintenance or rehabilitation of environmental quality by designing and constructing river restoration projects that have the following traits:

- Focus on ecosystem function and how wood placement will influence hydraulics and habitat formation to achieve restoration goals.
- Address the needs of endangered and/or imperiled species and their habitats.

- Incorporate wood placements designed to sustain and accommodate natural processes such as channel migration and still achieve restoration goals if the channel moves.
- Incorporate engineered structures that look like natural structures.
- Provide desirable river and riparian habitat, including overhanging root cover and large woody material.
- Maintain or improve water quality.
- Are economical to design and build.

The restoration of riparian areas is a critical component of restoring natural basin processes that will establish and maintain natural delivery of large wood to the watershed. The following riparian management recommendations for Puget Sound streams are based on the findings of Fox (2003) and serve as solid examples of attainable ecological objectives for riparian areas.

- Riparian areas should be managed for a diversity of tree species. Managing stand attributes to the potentials of each forest zone will promote riparian characteristics and wood loads assumed to provide favorable habitat.
- Maintaining stem densities and species diversity along a gradient from the stream channel will provide heterogeneity in riparian stand characteristics and resemble natural structure.
- Stream buffer widths should consider the potential for disturbances such as debris flows and snow avalanches, which often influence stand attributes for at least 20 meters (66 feet) on each side of the channel but can alter trees beyond 65 meters (213 feet).
- To provide stream channels with the full potential of large wood that riparian areas can deliver, riparian stands should use management trajectories to at least 550 years in order to not limit potential wood recruitment opportunity.
- Intensive thinning of stands through riparian management will likely reduce the short-term amount of wood delivered to the stream.
- Riparian management objectives developed for the purpose of maintaining instream wood loads should not focus merely on stands adjacent to stream reaches in need of wood, but on basin-wide riparian areas. Restoration project objectives should also address and/or consider infrastructure constraints such as the following:
    - Infrastructure that has adversely affected the river should be replaced in a manner that sustains natural processes characteristic of a restored state (e.g., undersized culverts replaced with larger crossings to accommodate sediment and wood transport; levees set back to re-establish natural unconfined condition).
    - Infrastructure that does not adversely affect river morphology and processes should be protected (e.g., road or levee at margin of channel migration zone).
- Restoration actions should provide downstream flood benefits by
    - Trapping sediment and wood in acceptable reaches of the river.
    - Limiting or reversing channel incision to maintain floodplain connectivity.
    - Raising the water levels where possible to increase flood storage.
    - Not increasing flood risks to infrastructure or developed areas ("no rise" to the 100-year flood stage).
    - Not increasing erosion risk to infrastructure or developed areas.
    - Having a desired factor of safety for structural stability and demonstrating a low risk of failure.
    - Not increasing the quantity of woody material moving downstream that could pose a threat to culverts or bridges.

GUIDANCE

Examples of Where Project Objectives and Constraints Are Typically Incompatible

Objective: Allow natural channel migration over time.

Challenge: Road crossing must be maintained where current bridge constricts the river.

Potential Solution: This situation would likely require a wider bridge span that accommodates channel migration and changes in river planform.

Objective: Add wood material to river channel downstream of a dam to restore supply cut off by an upstream impoundment.

Challenge: Will wood simply pass through the system or will it benefit habitat restoration? Will mobile wood threaten downstream bridges?

Potential Solution: This situation could be solved by knowing where added wood will move and ensuring there are stable wood structures, natural or engineered, in the river downstream of the dam that will trap mobile wood, create habitat (pools, bars, islands), and not threaten bridges.

Examples of Where Project Objectives Are Mutually Supportive

Objective: Provide instream structure, increase pool frequency and aquatic cover, and protect riparian areas while they are reforested.

Challenge: Local landowners are concerned about eroding banks.

Potential Solution: In addition to habitat-focused wood placements, include ELJs or complex timber revetments that protect landowners while also creating instream structure, pools, and cover.

Objective: Protect a buried pipeline exposed by channel incision.

Challenge: Pipeline engineers unfamiliar with fluvial geomorphology are considering reburying the pipeline, but that will only allow the incision to proceed upstream and further degrade the stream. Engineers are also concerned about the integrity and longevity of wood. Regulatory agencies require fish passage for any grade control.

Potential Solution: Use engineered wood placement downstream of the pipeline to restore channel grade and rebury the pipeline to the desired depth. Wood placements should not be simple weirs, but rather complex broad structures well buried into the streambed that ensure fish passage and cannot be scoured or flanked by the stream. Wood burial ensures structural integrity and longevity. The complexity and quantity of wood adds structural redundancy, increasing the factor of safety. Restoration design can incorporate rock within the buried wood matrix to further increase the factor of safety if needed.

2.2.2 Assess Site Conditions

An initial watershed or ecosystem assessment of current and historical conditions as well as disrupted processes is necessary to identify restoration opportunities that are consistent with reestablishing the natural watershed processes and functions that create habitat (Beechie and Bolton 1999; Roni et al. 2002). This also provides information on opportunities for habitat enhancement. The assessment of watershed conditions and processes is a critical, obligatory step in developing an effective restoration plan.

An initial assessment is needed to provide the process-based framework to define past and present watershed dynamics, develop integrated solutions, and assess the consequences and success of past restoration activities. Data collection and assessment creates the foundation for analysis and design and is an essential step in the design process, whether planning the treatment of a single reach or attempting to develop a comprehensive plan for an entire watershed. This assessment generally includes compiling historical photos, records, and data; conducting preliminary topographic and bathymetric surveys; conducting preliminary field investigations of habitat, hydraulic, and geomorphic conditions; and determining how the system has changed and the nature of both natural and anthropogenic disturbances.

In the case of wood, the assessment should address such questions as: how did wood loading and functions change over time, what was the cause of the change, and how have the changes in wood affected the conditions and processes that create and sustain habitat?

Once the underlying problem is defined, opportunities and constraints can be identified at the site. Once the objectives have been established, measureable metrics for determining project success should be defined, such as increasing the number of pools or decreasing the D50. A basic understanding of the watershed and site-specific conditions is necessary prior to identifying opportunities and constraints and defining risks and uncertainties. This information requires an initial assessment of existing information on site conditions.

GUIDANCE

An Assessment Allows You To

- Document the baseline biological conditions.
- Identify the dominant fluvial processes (channel morphology, sediment flux), riparian conditions, and geologic characteristics of the river system.
- Identify the natural state of the stream and the character, frequency, and magnitude of natural disturbances and how they influenced the system (e.g., beaver dams, fires, channel avulsions, and large floods).
- Determine the types of human disturbances and how they may have affected the system (e.g., deforestation, channel straightening, channel clearing, flow impoundment or regulation, and changes in flow and sediment regimes).
- Determine if there is a problem. If so, is it an anthropogenic problem; a problem associated with the system; an existing or potential problem associated with past, current, or future land use, floodplain, or riparian zone changes; or a combination of factors?
- Identify the factors that influence the issues of concern, as well as potential mitigation strategies.

CROSS-REFERENCE

As described in Chapter 4, *Geomorphology and Hydrology Considerations*, and Chapter 3, *Ecological and Biological Considerations*, fluvial ecological restoration is an interdisciplinary, comprehensive effort that focuses not only on reversing past damages but also on establishing a self-sustaining ecosystem with conditions that support the fluvial ecosystem processes, function, and structure—including the species that depend on them. As such, it is important to understand the existing environmental baseline conditions on the site, as well as natural or human-made perturbations that may have caused them (e.g., altered flow regimes and infrastructure).

Knowledge of dominant processes and how human activity has changed them allows the prediction of a system's response to particular alternatives and how to best achieve project goals within site and stakeholder constraints. It is imperative to accurately determine the natural characteristics of the system, which can be very difficult given not only the magnitude of historical changes, but that the system has responded to cumulative impacts for over 100 years.

The initial assessment provides the foundation for understanding how future changes—including alternative management, design, or mitigation strategies—would affect the system. Solutions can be developed once the assessment has been completed and will address the goals and objectives of the project. The solutions might be self-sustaining, or may require periodic maintenance, or only be temporary. In some cases, the best solution might be a *river rules* concept that simply provides adequate space for the river to adjust to change.

Stream evaluations can be performed at varying levels of detail. The appropriate level depends on the status of the study, the perceived significance of potential problems, the scale of the project, associated risks, and available resources.

2.2.3 Identify Opportunities and Constraints

One of the most important tasks in any restoration project is identifying opportunities and constraints. In general, *opportunities* represent situations where the project can best achieve its goals and deliver additional benefits in terms of improving habitat or alleviating stakeholder concerns. *Constraints* involve limitations the project must accommodate. They may be spatial (e.g., the need for temporary water crossings, ensuring the project has no adverse impact on local property or infrastructure) or temporal (regulatory work windows limiting in-water construction). However, with a thorough understanding of a site's history and the geomorphic processes influencing the reach, constraints can be turned into opportunities. For example, restoring pool frequency, cover, and channel length and providing better riparian conditions in an over-widened river often involve placement of ELJs to create stable forested islands and pools with complex cover, and increase channel length by creating anabranching channel patterns. If placement of ELJs can be arranged to protect an eroding bank threatening a road or property, the project can achieve its goals while also benefiting the local stakeholder. This type of opportunity can build community relationships, speed up implementation, and demonstrate how wood is not just for fish but also can solve infrastructure problems.

2.2.3.1 Site Limitations

Constraints are often associated with limitations at the site. Access, staging of materials, and water crossings are all critical issues to contend with during the design process. Work sites may be limited by a variety of constraints such as property ownership, state and federal regulations, and habitat.

GUIDANCE

Examples of How Wood Influences Fluvial Systems

1. *Channel grade:* wood can naturally account for much of the head loss in channels and bed material storage; loss of wood can trigger channel incision, loss of alluvium, and conversion of step-pool and pool-riffle channels to bedrock and plane-bed channels (e.g., Buffington and Montgomery 1999a–c).
2. *Water surface profile:* wood can increase water surface elevations at local (< channel width) to reach (>10 channel widths) scales that increase the spatial extent and duration of inundation, enhancing aquatic habitat and floodplain connectivity (e.g., Brummer et al. 2006).
3. *Grain size:* stress-partitioning by wood reduces the median grain size (D50) of bed material; reductions in the quantities of functional wood will increase the D50 (e.g., Manga and Kirchner 2002).
4. *Channel complexity*: functional wood increases morphologic and textural variability; reductions in wood lead to channel simplification (e.g., Lisle 1995.); Buffington and Montgomery 1999a–c; Abbe and Montgomery 2003).
5. *Hyporheic flow:* functions 1–4 above all contribute to hyporheic groundwater exchange, which enhances aquatic ecosystem and water quality (e.g., Poole et al. 2006; Hester et al. 2009).
6. *Aquatic cover*: wood accumulations (i.e., logjams) provide complex aquatic cover not created by any other material (e.g., Abbe and Brooks 2011).
7. *Pool frequency:* functional wood increases pool frequency and size distributions (e.g., Montgomery et al. 1995).
8. *Aquatic and riparian species habitat:* see Chapter 3, *Ecological and Biological Considerations*.

Depth of Alluvium

Many types of wood placements involve partial burial or placement of piles, posts, or cribbing, all of which require an understanding of geotechnical conditions and the depth of alluvium. The characteristics and depth of alluvium influence scour depth estimates. Changes in subsurface conditions, such as the presence of fine sediments or shallow bedrock, can directly influence design and construction methods. Bedrock canyons are an example of natural channels where wood doesn't tend to accumulate because they act like a log flume. But there are many examples in more unconfined systems where wood created stable obstructions on bedrock that trapped bed material to form an alluvial channel. These cases depended on large trees capable of crossing the channel and withstanding flows until alluvium built up. Once the alluvial channel formed it stabilized more wood, which contributed to trapping more sediment. When wood is removed from these systems they quickly revert to bedrock (Figure 2-2). Without large timber, restoring an alluvial channel on bedrock can require substantial engineering to replace the function wood once had in trapping bed material. This underscores the importance of function, not material. If materials other than wood offer the most secure and inexpensive means of restoring the function of wood that is no longer available or affordable (i.e., large trees) and it will facilitate the accumulation of wood that would not otherwise form, then that is the most reasonable alternative. A no-action alternative that leaves an unnatural bedrock channel untreated represents a long-term loss of habitat with consequences upstream and downstream; therefore, if your goal is to restore wood, keep an open mind to using a variety of materials, focusing on restoring function that wood once provided and creating the conditions that can sustain wood.

Figure 2-2. Gravel Patch on Incising Bedrock Channel, Rickreall Creek, Oregon

Infrastructure

Roads, bridges, culverts, power lines, cable crossings, and buried pipelines all may be found within a project reach. Wood has historically been viewed as a threat to infrastructure. Mobile wood certainly can accumulate at bridges and culverts where blockages can increase risks of flooding and channel avulsions. But these issues are primarily due to infrastructure design that fails to assess and accommodate wood transport. The supply of mobile wood or flotsam has almost always been altered by human actions. The removal of large riparian trees, removal of snags and logjams, and channel straightening increase the supply of small mobile wood and the river's capacity to transport wood. Thus, in many watersheds throughout the country, instream storage of wood has decreased, reducing the system's ability to moderate downstream delivery and increase the risks to inadequately designed infrastructure. This underscores an important point of understanding the function of wood in restoration: stable wood structures that control hydraulics create habitat, trap wood, and thus reduce risks to downstream infrastructure. For these same reasons, stable wood can trigger local channel response and increase water elevations that could affect infrastructure within or upstream of the project reach, highlighting the importance of the location and size of wood placements. Wood placements have been successfully used to protect infrastructure in ways that enhance, not degrade, aquatic and riparian habitat (Figure 2-3).

GUIDANCE

Engineered Logjams Have Been Successfully Used to…

- Improve channel alignment and reduce wood loading at bridge crossings (e.g., Abbe et al. 2003c).
- Raise a streambed and protect buried pipelines (Abbe et al. 2009).
- Protect roads (Abbe et al. 1997, 2003a, 2003b; Abbe and Brooks 2011)

Figure 2-3. Woodward Creek Pipeline Crossing Wood Placement, Washington

Flood Regulations

Many streams are covered under flood regulations, most commonly the federal flood insurance program overseen by the Federal Emergency Management Agency (FEMA) and administered by local and county public works departments. In areas without flood insurance rate maps (FIRMs), there may not be any regulatory requirements, but in areas with flood insurance, the project may need to provide a "zero rise" analysis, demonstrating the project will not raise the elevation of the 100-year flood event. Typically, this analysis requires the approval of a licensed professional with expertise in flood modeling and the FEMA process (i.e., Certified Floodplain Manager). In systems affected by channel incision since the last FEMA mapping, water elevations may be raised, but a rise in the regulatory flood surface would not take place. If restoration results in unavoidable increases in flood elevations but not in any damages, it is possible to remap regulatory flood zones through a Letter Of Map Change (LOMC), Letter Of Map Amendment (LOMA), or Letter of Map Revision (LOMR).

Acceptable Level of Channel Dynamics

Streams are subject to horizontal and vertical changes in channel position. It is important to understand how dynamic a channel is prior to installing wood. A channel can move away from wood placements, thereby diminishing the beneficial effects of the wood. The most serious type of channel movement is at-grade control structures. If the channel moves around the wood, it can quickly cut back down and fail to achieve the desired goals (Figure 2-4). In large rivers, channel migration may require numerous wood placements to achieve the desired goals.

Figure 2-4. Eroding River Bank, Nisqually River, Washington

Community Safety

Wood placements should not introduce any significant risks to community safety, such as elevating flood levels or creating erosion hazards. The best way to improve community safety is through education and by demonstrating the importance and value of wood placements. Complex wood placements have been installed in urban streams, community parks, and many other settings without compromising safety. Early on in the project it is advisable to bring in a recognized professional with expertise and experience in wood placement and assessment to present information to the public about historical impacts and how wood can have positive effects on and benefits for the community (Figure 2-5).

Figure 2-5. Public Meeting

Recreational User Safety

Boating, swimming, and inner tubing are common recreational activities in many streams. Wood placements typically impose little risk to safety during recreational flows but the design should account for recreational use and should carefully consider potential hazards the wood may pose. It is important to document the current presence and role of wood in the system as part of assessing recreational safety. Recreational use in no way precludes the placement of wood, but designers should be forthcoming with how particular wood placements will influence conditions in the river. Some states or local governments may have specific guidelines or requirements pertaining to recreational safety, such as placing warning signs in locations that can be easily seen by boaters floating downstream (Figure 2-6).

Figure 2-6. A Warning Sign on Wood Placement, South Fork Nooksack River, Washington

2.2.3.2 Understanding Regulatory Perspectives in Design

Local, state, and federal regulatory requirements can influence design, cost, and scheduling of any restoration project. In many cases, agencies that permit instream work do not directly regulate the design of large wood placements, their role is typically limited to determining the influence the proposed actions may have on the stream's condition if allowed to proceed. As such, in addition to knowing which permits are required and typical processing time (some permits take months), it is also valuable to understand the perspectives of individual regulatory personnel who would be issuing the permits. For example, in some districts USACE does not consider wood as fill, while in others it does. Permission to perform in-water construction can also vary significantly depending on local regulations. Construction may require temporary channel crossings, temporary dams to isolate project area, and dewatering (Figure 2-7).

2.2.3.3 Considering Climate Change

Restoration projects are increasingly required to consider the potential effects of climate change in the design of large wood installations (Figure 2-8). The warming climate could result in a variety of changes influencing a project. Changes in the magnitude and timing of peak flows, changes in riparian vegetation, shorter winters (less snowpack, later onset of snowfall, and earlier snow melt), and changes in rainfall intensity are all important considerations. Evaluating climate change is similar to considering changes in a watershed that could influence flow, sediment, and natural wood on land development, land clearing, road construction, flow regulation, dams, or dam removal. It is important to evaluate key project goals and how those may change under predicted climate change impacts. However, in general, adding large wood to streams may be one of the most important actions available for building resilience to the impacts of a warming climate. For example, much of the western United States will be subjected to more severe flood peaks and lower summer base flows as a result of climate change.

Figure 2-7. Excavation and Dewatering During Construction of an Engineered Logjam in Elwha River, Washington

Pit is 5 meters (16 feet) deep and pumped to dewater. The river is flowing from bottom to top at the left side of the photo.

Meanwhile, beaver dams have been recognized as a significant means of buffering the impact of increasing peak flow magnitudes and diminishing base flows (Beechie et al. 2012). Therefore, higher wood loading helps attenuate higher peak flows (decreasing magnitude and increasing duration of hydrograph) and retain more water in floodplain areas that can better supplement base flow conditions. Wood restoration can be a critical part of protecting infrastructure that will be subjected to increasing peak flows by securing unstable wood (i.e., flotsam) found in many watersheds due to immature riparian vegetation.

Figure 2-8. Recession of Honeycomb Glacier in North Cascades of Washington Is an Example of How Warming Climate Affects Hydrology (less snow, more rain, and more variable flows)

From Mauri S. Pelto, North Cascade Glacier Retreat: http://www.nichols.edu/departments/glacier/bill.htm.

Increasing the extent of forest cover is typically a component of using wood in river restoration, particularly for cases in which wood is being used to restore anabranching channel systems. Increasing summer shade and floodplain wetland together with reducing channel widths helps reduce water losses due to bed infiltration and evaporation. Wood also helps attenuate the adverse impacts of increased sediment supply resulting from larger magnitude storm events. Therefore, wood is one of most efficient and direct means of preparing watersheds for the adverse impacts that have already begun to occur as a result of climate change.

2.2.4 Define Risks and Uncertainties

CROSS-REFERENCE

As described in Chapter 7, *Risk Considerations*, restoration work has inherent risks and uncertainty, and it is the responsibility of the design team to define those aspects of the project that carry uncertainty and risk. For example, there will be uncertainty regarding the weather and the timing and magnitude of flows that affect a project after construction.

Aspects of design such as revegetation may be particularly susceptible to floods shortly after construction before the plants have had the time to become established.

2.2.4.1 Habitat Recovery

The primary goal of restoration is the recovery of habitat that has been degraded over time. Every project involves some uncertainty in achieving habitat recovery goals. Therefore, designs should clearly define how they might change the system to achieve restoration goals and include quantitative metrics for measuring success. As an example, how will increasing the number of pools or channel length within a project reach help in achieving recovery goals? Defining how the project goals and outcomes will achieve specific goals helps to understand the risks.

2.2.4.2 Infrastructure

To reduce risk to infrastructure, existing infrastructure should be clearly mapped, both overwater structures and subsurface infrastructure such as pipelines and other utilities. Ideally, defining the risk to infrastructure would be straightforward; for example, “the proposed project will not cause flooding or erosion that threatens structures.” As stated earlier, well designed wood placements can not only diminish risks but can be designed to protect infrastructure while also restoring habitat. Additional effort may be needed in the design phase to ensure existing infrastructure will not be exposed to increased risk. The design team should identify the presence of infrastructure and work closely with public agencies and utility companies that have existing facilities or rights-of-way. As an example, bridge crossings in the project reach may benefit from improved flow and wood conveyance (Figure 2-9).

Figure 2-9. Bridge Improvements Done to Improve Wood Conveyance as Part of a Stream Restoration Project (State Route 7 over Ohop Creek, near Eatonville, Washington)

2.2.4.3 Private Property

Many projects involve multiple land owners, including private property owners. The restoration design should demonstrate that the proposed project would have no adverse impacts on private property.

Property boundaries can influence work areas and access routes. Ownership of stream- and riverbeds can depend on local, state, and federal laws. Most large channels fall under state or federal jurisdiction, but it is important to identify ownership ahead of time, particularly in systems where stream or river channels move over time. Restoration, especially in the case of wood placement, will benefit from support of the local community and landowners. Any project will gain community support when local residents feel involved, respected, and invested in project success. For this reason, public meetings and community education are well worth the time and investment.

> *CROSS-REFERENCE*
>
> Chapter 8, *Regulatory Compliance, Public Involvement, and Implementation* provides an indepth examination of public meetings and community education.

2.2.4.4 Public Safety

Streams are inherently dangerous environments. Accidents happen even in standing water bodies. Restoration involving wood placements should clearly describe the context in which the wood is being placed. For example, many streams naturally have accumulations of wood and varying degrees of bank erosion. Trees fall into rivers during storms, while naturally occurring bank erosion can create potential safety hazards that are simply part of the river ecosystem. Complex wood placements have been used successfully to protect public facilities (Abbe et al. 2003a; Abbe and Brooks 2011). Wood placements should emulate the placement and conditions that the public would encounter in a natural environment. Challenges tend to occur in highly altered or managed systems where the public has grown accustomed to unobstructed and simplified channels such as those confined by levees and revetments. The best strategy to educate the public on the potential dangers associated with restoration is through a public education campaign. This can be accomplished by working with boating and fishing clubs and school programs, and by placing interpretative signage at boat ramps, parks, and other facilities.

2.2.5 Develop Design Considerations

CROSS-REFERENCE

As described in Chapter 6, *Engineering Considerations*, there are numerous and excellent publications available regarding design criteria.

While every project will have its own unique site conditions, each project should evaluate the stability of the proposed structures relative to flow conditions, sediment transport, and bed scour at the site. Designing wood structures should include the same design criteria and engineering principles as designing a rock revetment or groin, a bridge pier, or a floodwall. Timber has been successfully used for centuries to construct spur dikes, flood walls, bulkheads, bridge abutments, and even dams. Additional analysis would be needed for creating more complex structures, assessing geomorphic and ecological response, and using more variable natural materials (e.g., range of wood material shapes, sizes, and conditions).

2.2.5.1 Wood Structures

The general public has had negative preconceptions about wood in streams or rivers: that it floats away or quickly rots. However, wood is a very diverse and extremely versatile material. There are upward of 90,000 species of trees and woods, with specific gravities ranging from 0.15 to 1.4 (anything over 1.0 will sink). Some woods are extremely resistant and can last for centuries while others will break down in a few years. Trees vary widely in sizes and shapes, which defines the type of snag they will form once in a stream or river channel. Designing wood structures can be as simple as placing "key" pieces into a channel to create functional wood, or it can be as complex as creating structures composed of tens to hundreds of logs arranged in interlocking patterns.

A *key* piece is one that is likely to create a stable snag and typically has a basal diameter equal to or greater than half the bankfull depth of the river. The presence of a rootwad significantly increases the stability of a snag as will multiple stems. The most common challenge is the acquisition and transport of large trees with attached rootwads. When limited to trees smaller than the desired key piece size, stable structures can be designed using a variety of approaches, such as piles (driven or vibrated into streambed), posts (placed in excavated or drilled holes and backfilled), cribbing with ballast, and rock ballast collars. Wood can also be stabilized with other materials such as rock, steel piles, and concrete jacks. Regardless of the materials used or structural configuration, the design should always try to emulate the function and appearance of natural wood structures.

2.2.5.2 Wood Structure Stability

For wood to be functional and safe, the designer must create a structure capable of controlling hydraulics and channel morphology. The size and shape of natural and engineered wood structures may change over time with the accumulation or export of mobile debris, but the core of the structure must remain stable.

CROSS-REFERENCE

Chapter 6, *Engineering Considerations*, addresses wood stability in detail.

A log weir that forms a plunge pool is only functional if it remains in place. Stability of wood is simply based on the premise that the forces resisting motion must be greater than those acting to move the wood. The forces acting on the wood are drag and buoyancy, both of which can either move or break the wood. *Drag* is proportional to the square of the flow velocity and cross-sectional area of the wood normal to the flow, and a drag coefficient related to the structure's permeability, shape, and size relative to the flow area. *Buoyancy* is proportional to the volume of water the wood displaces, which will be a function of the wood's specific gravity and volume. Resistance is provided by gravitational forces acting on the wood. In the case of a large snag that is only partially submerged, the gravitational forces can far exceed the buoyant forces, thus holding the snag in place (Abbe and Montgomery 1996). Once a snag begins to become embedded in alluvium its stability increases quickly (Abbe et al. 2003b; Abbe and Brooks 2011). Dense or saturated wood with a specific gravity greater than 1.0 (i.e., density greater than 1,000 kilograms per cubic meter) will sink, and with a net downward normal force it will encounter some frictional resistance from the streambed. Understanding the physical attributes of snags (shape, stem, and rootwad size; relative density) that define stability in a particular channel can be used to develop specifications for key pieces needed for restoration in relatively undeveloped areas. For many locations it will not be possible to secure key pieces, or circumstances simply require more certainty. In these cases engineered solutions are available to stabilize wood, such as using ballast or piling. The greater the gravitational force, the more stable the wood, just as in the case of a simple gravity dam. This is the basic approach to using rock or alluvial surcharge to stabilize wood.

Scour is one of the principle reasons for wood placement failures and occurs when constricting or deflecting flow, and with plunging flow for structures acting as weirs. Proper embedment is the best strategy for preventing scour damage, but this can be expensive if it requires extensive excavation.

GUIDANCE

Structural Elements Providing Stability

As previously described, there are key factors contributing to the stability of wood placements:

- Size, shape (large rootwad, multiple stems), effective density, and strength of log(s).
- Displacement (submerged volume) of wood.
- Buried surface area of wood and skin friction.
- Surcharge (gravitational load acting on wood).
- Frictional resistance of surface where the wood is situated.
- Longevity/preservation of the wood.

Specific structural elements providing stability include:

- Key pieces.
- Piles and posts.
- Ballast (e.g., alluvium or rock).
- Interlocking architecture of the structure.
- Mechanical attachments (e.g., cable lashing or steel pins securing logs to one another).
- Racked logs and debris that reduce permeability and drag coefficient of the structure and prevent scour from undermining the core of the structure.

Pile embedment should be well below estimates of maximum probable scour. Artificial armor layers such as scour aprons consisting of immobile clasts (more than D90) can be used to limit scour depths. For ELJs, the racked logs that accumulate on the upstream side of the structure can be an important element contributing to stability. The drag imposed on a logjam is dependent on the structure's shape, size and permeability. When permeability is reduced to a point that the flow going thru the structure approaches zero, the structure behaves as a bluff body, and the drag associated with interstitial flow (skin friction and wake interference) is reduced (e.g., Li and Shen 1973; Shields and

Alonso 2012). The racked material also defines the location of scour around the structure. Racked material creates a buffer around the stabilizing core of a structure (e.g., location of piles or timber cribbing). The larger the pile of racked material, the farther the scour hole is from the core. Vegetation is another factor contributing to long-term stability, adding root cohesion to alluvium in burying the wood and increasing surcharge as trees grow. Trees growing on a large wood structure also can increase retention of debris and other racked material delivered during floods. Eventually the trees protected by the large wood structure will mature to create a sustainable source of large stable wood within the system.

2.2.6 Conduct Site Surveys

CROSS-REFERENCE

As described in Chapter 3, *Ecological and Biological Considerations*, Chapter 4, *Geomorphology and Hydrology Considerations*, and Chapter 9, *Assessing Ecological Performance*, a detailed analysis of site-specific conditions is needed to develop the final design features of an ecological restoration project.

Comprehensive evaluations of river systems can require both extensive resources and expertise across a wide range of disciplines. It is important to have adequate expertise and to identify and address the most important issues. For example, it is not uncommon for assessments to focus on hydrology, hydraulics, and biological characteristics. While these might be vitally important in developing an appropriate solution, the most critical basic information is first-hand knowledge of the river system and an assessment of the past, current, and future equilibrium state of the river system.

2.2.6.1 Assess Site-Specific History

A site condition analysis typically begins with an investigation of the historical changes that have occurred to the system. The objective of the historical analysis is to understand how previous modifications continue to guide current process and form. Historical analysis identifies the attributes that may be permanently lost from those that could and should be recreated, thus narrowing the focus for identifying realistic restoration options. Historical analysis for wood placement projects includes assessing the role wood might have had in the river system, including wood sources, rates of delivery, and accumulation and movement of wood in the river. The historical wood-loading analysis is compared to current conditions and used to develop appropriate strategies for wood placement. Sources of information include air photographs, maps, surveys, and ground photographs. Geographic information system (GIS) software is used to assess data at multiple spatial scales to determine historical landscape change. The historical data sources provide input for the assessment of historical planform dynamics and mapping of channel migration zones to determine the role of wood that influenced geomorphic processes, and examines the extent to which wood was available for habitat.

2.2.6.2 Assess Current Site Conditions

Although wood placement projects are typically site specific, a site assessment begins at the watershed level to determine how existing or future land use changes could affect the wood placement, helping to ensure long-term sustainability. Because wood placement projects often occur in disturbed river systems, a watershed assessment is necessary to understand if channel adjustments at the site are a response to local disturbances or indicative of broader watershed-scale alterations. Watershed supplies of sediment, wood, and runoff should be assessed, at least qualitatively, to determine if the assumptions used in the planning process will be sustainable or if the changes in the watershed are likely to result in a new condition that is incompatible with planning assumptions.

Assessing the magnitude, frequency, and duration of physical processes gives context to the temporal and spatial scales of system adjustment, the system's direction of change, and the predicted timeframe for the system to regain an energy balance and stability. GIS is a powerful tool for a watershed-scale assessment. It allows for a thorough analysis of physical processes through subbasin delineation, slope calculation, relating sediment load and caliber with lithology, identification of mass wasting rates, and other analyses.

The focus of the current conditions assessment can then be scaled down from the watershed to the river reach and local site. Streams are open systems and are continually adjusting their form to altering energy inputs and materials. It is important to understand how adjustments in flow, sediment supply, boundary sediment texture and cohesion, large wood inputs, and riparian vegetation interrelate; and how they collectively determine channel form and habitat. This understanding is critical for predicting channel response and developing sustainable wood placement designs.

A solid understanding of river hydrology is critical because knowledge of the streamflow regime is integral to nearly every aspect of wood placement objectives. Because hydrologic information is needed to determine base flow conditions and provide input for hydraulic modeling, design calculations, habitat modeling, and flood risk assessment, hydrologic analysis should be one of the first studies performed.

Ideally, an active river gage exists with many years of data from which statistical analyses of flow records can be performed. This information helps calculate flood-frequency return intervals and flow duration curves, and provides an understanding of the timing and movement of water through the watershed and trends in runoff related to land use changes. If a nearby river gage is not available, then gages elsewhere in the watershed can be analyzed and scaled accordingly to provide a surrogate flow record for the site. Often times, however, no gage data are available, and the project team must decide whether to develop a streamflow gaging network or use hydrologic modeling to develop synthetic runoff curves for use in developing design flows. For projects where knowledge of groundwater and hyporheic flow is important, piezometers can be installed to measure groundwater flux and the interaction of surface and sub-surface flow.

Reach assessments are performed in the field at an appropriate scale to describe the physical and ecological conditions of the channel and floodplain. The physical reach assessments typically include field mapping and topographic surveying components focused on collecting information related to channel morphology, sediment transport, and geotechnical issues that could affect the project. The texture of alluvium and substrate forming the channel bed, bars, banks, and floodplain is mapped as part of facies units or quantitatively measured and then interpreted to understand sediment transport dynamics. Channel bed and bank parameters that contribute to habitat or that can be evidence of stability or instability are assessed, and field estimates of appropriate roughness coefficients needed for future hydraulic modeling are made. Geologic controls are observed, and the geotechnical properties of streambanks and other landforms can be rapidly assessed in the field or studied more quantitatively using bank stability modeling and other tools. Features that indicate previous or potential channel dynamics, such as levees, side channels, crevasse channels, and riparian buffer widths, are measured. Reach data is also collected on any evidence of disturbances, perturbations, or hazards, such as bridges, diversions, beaver dams, landslides, and nearby infrastructure or property potentially at risk. The field mapping of infrastructure is compared with available infrastructure maps to verify the presence and location of utilities, pipes, and property lines. Measurements and observations made during the reach analysis are used to refine channel migration zone mapping and identify zones where the channel could and should be allowed to migrate, versus areas where migration, erosion, and inundation are not likely or desired.

Detailed topographic surveys are performed to provide the elevations needed for hydraulic and sediment transport modeling. The field-surveyed elevations are often combined with Light Detection and Ranging (LiDAR) or photogrammetry-acquired elevations to create a composite elevation surface for the site with continuous coverage of ground and bathymetric surfaces.

Many wood placement projects occur in river reaches where the channel has become hydrologically disconnected from its floodplain (such as from incision, leveeing, or channel pattern simplification from an anabranching pattern into single thread channel), and a project objective may be using wood to increase the frequency of floodplain inundation. A current conditions assessment usually includes studies to determine the presence of a floodplain and how current floodplain connectivity compares to prior conditions. Height above the water surface analysis is often performed to map all elevations at the site relative to the river's water surface elevation to show landform elevations in relation to the river channel. Hydraulic modeling is performed to quantify the flow magnitude required for water to spill out onto the floodplain. Both analyses are important for identifying opportunities and constraints for increasing floodplain inundation.

In addition to calculating water surface elevations needed for evaluating floodplain inundation and current flood risk, one-dimensional (1D) or two-dimensional (2D) hydraulic modeling is performed to simulate velocity vectors, shear stresses, and flow depths in the channel prior to proposed wood placement. The hydraulic models can be coupled with sediment transport calculations, either within the model itself in a mobile bed analysis or in user-created spreadsheets, to evaluate sediment flux in the reach. This type of evaluation is not commonly done because of time and budget constraints. Typically field measurements of sediment transport are made to calibrate and verify model calculations.

Riparian restoration and management are critical to the success of any wood project, particularly in the long term. Trees help stabilize banks and provide a future source of wood to the channel. For systems with migrating channels or that are subject to avulsions, future channel response would largely depend on riparian conditions. Planting plans should incorporate multispecies combinations that provide short- and long-term benefits. Willow and cottonwood can provide short-term benefits because they are fast growing, but plans should include successional climax species that provide the large, long-lived trees needed along the streambanks.

Wood placement projects are designed to be compatible with and augment the prevailing processes that sustain the current channel morphology, or are designed to substantially alter processes that will lead to new desired channel morphology, typically with increased complexity and habitat structure. Therefore, the data sources and analyses described above are used to better understand the site's alluvial channel behavior and dynamic equilibrium energy states. Before designing a wood placement project, it is necessary to know if the observed channel morphology reflects natural scour and fill events or if there has been more long-term aggradation and degradation indicative of channel adjustment response to disturbance. These assessments determine if the observed channel pattern (e.g., straight, sinuous, anabranching, braided) will be sustained by prevailing processes and the extent to which wood placement could accomplish desired morphologic change.

2.2.6.3 Assess Future Site Conditions

Assessing future conditions is necessary if the wood placement project is expected to be self-sustaining and resilient. Many of the analyses undertaken in the historical and current conditions analysis provide the information needed to assess the trajectory of the system and determine if future conditions will support the project goals. The evaluation of watershed land use trends and associated channel morphologic response is used to predict future change using appropriate channel evolution models and knowledge of alluvial channel response to perturbation. Numerical physical and habitat modeling tools can also be used to evaluate certain scenarios and test how the wood placement would perform. Considerations should be made on how riparian conditions would change and how they may influence the project, in both positive and negative ways. This is especially true in the restoration of urban creek corridors where restoration of riparian areas leads to future wood recruitment that could raise water levels or create concerns for downstream culverts. Beavers and their influence on the channel should also be considered in riparian planting plans. Beavers are coming back to many areas in the United States, including urban streams.

Climate change predictions also must be factored into the design. Although the exact implications of climate change on streamflow characteristics are not certain, existing climate change models that predict regional watershed response are available for review. This information provides estimates about runoff patterns and sediment loads and helps determine adjustments that may be needed to adequately design the structures.

2.2.7 Prepare and Evaluate Alternative Restoration Concepts

Every restoration project should include a set of alternatives, the first of which is a “no-action” scenario. Typically there would be at least two additional alternatives that vary in magnitude or in the manner in which they address the problem; these additional alternatives also would achieve the desired goals within the constraints of the project. Alternatives are presented graphically and descriptively, explaining how they would achieve project goals and their associated risks and costs. Clear metrics for success should be established for evaluating alternatives that are agreed upon by decision makers and stakeholders so that alternatives are assessed as objectively as possible. Traditional metrics include project cost, stability factor of safety, and design life. In addition to these, wood projects should consider metrics that measure habitat enhancement, such as increases in channel length, increases in pool frequency and cover, or increases in inundated area. Other metrics could include channel response associated with each alternative, or the relative uncertainty in each alternative. Project maintenance is another important consideration: will the project require maintenance and, if so, what kind and to what extent? Other metrics should cover how well the alternative works within the project constraints, such as flooding risks or risks to infrastructure. For more complex and costly projects, it may be valuable to weight assessment metrics and conduct a quantitative benefit-cost assessment.

2.2.8 Prepare Monitoring and Adaptive Management Plan

Monitoring of wood placement project metrics is necessary for assessing whether project goals and objectives are being achieved and to determine which adaptive management actions must be implemented.

CROSS-REFERENCE

Chapter 9, *Assessing Ecological Performance*, provides a detailed discussion about adaptive management.

Monitoring not only evaluates project successes or failures, it also enables appropriate post-project adjustments to be made, and is critical for expanding scientific knowledge of physical processes that allow future restoration projects to be more advanced and successful. The monitoring elements should be developed from the project's objectives and evaluation criteria. As discussed in the last section, clear metrics should be established with stakeholders that can be measured through time to assess how well a project is performing. Metrics should be realistic and affordable. Simple presence or absence monitoring can be valuable for wood placements that simply require noting global positioning system (GPS) coordinates through time and tracking flow events.

A monitoring plan is typically prepared after the alternatives development and evaluation stage, and must incorporate the previously defined risks and uncertainties.

Physical attribute monitoring for wood placement projects typically includes measurements to assess structural integrity and the level to which a feature is providing desired functionality. Measurements can include identifying the number of wood pieces from the original structure that are still intact, accumulated debris, scour and fill associated with the structure, sediment sorting and diversification, channel planform change, and hydraulic attributes. Natural wood accumulation is common for large wood placements and can provide an idea of how structures change through time; it can also provide information on the amount of wood that is naturally moving through the system. Ecological monitoring often includes surveys of adult and juvenile fish; temperature monitoring; and assessment of depths, cover, shading, and other important habitat elements.

The frequency of monitoring and total period over which monitoring occurs is largely dependent on project budgets and availability of staff or volunteers to perform the monitoring work. Immediately following construction, an as-built survey with established photo points should be established to document that the wood placements were built as designed and to provide a comparison condition for future monitoring surveys. Monitoring is recommended at least once per year for the first 5 years, with reduced monitoring frequency thereafter (e.g., once every 2 to 3 years until year 10).

During the design phase and prior to construction, the project team and stakeholders should develop criteria for adaptive management. Clear threshold criteria should be agreed upon so that necessary remedial actions can be taken quickly if monitoring shows that anticipated performance of the wood placement features is not meeting expectations. For example, threshold criteria could document that additional wood will be added or additional anchoring implemented if a certain percentage of the structure is lost, or additional plantings will be added if survival rates of revegetation are too low. Additionally, flood risk criteria can document that any racked debris will be removed once a certain volume is accumulated. The adaptive management plan must document how decisions will be made regarding whether or not maintenance work is needed, how the work will be paid for, and who will perform the work. The adaptive management plan must also specify how monitoring and maintenance work will be reported and the timing for delivering reports to the stakeholders.

2.2.9 Prepare Detailed Design Plans

Detailed design drawings serve multiple purposes for a large wood project. Initially concept design plans are developed to convey the major elements of one or more alternatives that would achieve the project objectives. Often design plans are put forth as a percentage of completion to give stakeholders a general idea of design development status. When the design team is ready to lay out basic concept ideas on paper they are typically referred to as a *10% design*. Concept plans include enough detail to show the general layout the project would have on the landscape and principal construction activities such as excavation or grading, instream construction, relative size of structures, and how the site would look after construction. A *30% design* refers to the stage when a preferred concept alternative is selected and incorporated into the engineering plan sheets design set, referring to the relative percentage of a complete design package. This initial design set is often presented to stakeholders, landowners, and regulatory agencies to get initial approval and begin the permitting process. Final permits typically require a more detailed design set, such as 60% that includes all construction aspects of the project such as water crossings, erosion control, access and staging, structure details (e.g., pile driving, pumping), traffic management, and other actions that could affect fish and wildlife and local communities. In the final stages of the project, designs serve as the basis for cost estimates and material acquisition, and they provide contractors the necessary information to construct the project. A final design package not only includes detailed spatial plans (map or plan view, cross-sections, and profiles) but details of subsurface conditions, water, and specifications. The design engineer prepares a cost estimate based on the plans. The completed package is referred to as plans, specifications, and estimates (PS&E). A *90% design* usually represents a completed design package ready for final review.

Given the variability of fluvial environments, flow and groundwater conditions, nonuniform characteristics of large wood, and other common materials, the detailed design plans should build in flexibility for field adjustments during the construction process. The level of detail provided should be tailored to the specific design phase and intent of that phase.

2.2.10 Complete Environmental and Regulatory Requirements

Environmental compliance and documentation is performed in tandem with the development of the detailed design plans. Although writing of environmental documents and permit applications usually begins at the 30 to 60% design level, early and continual involvement of the regulatory agencies in the review and advancement of the entire planning and design process will greatly increase the likelihood of the wood placement project receiving timely environmental clearance with necessary permits. Generally, design is not regulated by environmental review agencies but rather indirectly regulated by professional licensure requirements of due diligence. As such, representatives from the regulatory agencies are often invited to be part of the project stakeholder team or technical advisory group to allow them to give feedback on project opportunities and constraints, and have a vested interest in the project's success. Their early input will help identify future obstacles that could derail the project entirely or necessitate costly design changes. During the design stage, an open dialogue must be maintained with all regulatory agencies.

Project schedules must allow ample time for agency review and comments, and be flexible to allow for design changes that will arise based on agency feedback and permitting needs. The design and permitting process should be considered an iterative stage of the project because neither component can be successfully completed without direct interaction with the other. Many wood placement projects have encountered serious challenges by advancing the design too far before introducing it to the regulatory agencies and asking for their approval.

GUIDANCE

Common Design Phases and Additional Information Provided

- *30% Conceptual Design Level.* The primary purpose of the 30% design is to convey the concept and objectives to key stakeholders. It includes enough information to convey the general intent.
- *60% Preliminary Design Level.* The primary purpose of the 60% design level is to support project permits and develop a planning-level cost estimate. It includes key design information (number of structures, sections, profiles, typical details) to evaluate construction impacts from the project. Many large wood projects proceed to construction at this stage using engineer-led field construction. The viability of this method is dependent on the experience of the owner, designer, and contractor and findings from the risk assessment. The 60% plans are typically used for permitting because no significant changes in design are expected from this point forward.
- *90% Final Design Level.* The primary purpose of the 90% design set is to develop an accurate engineer's cost estimate and finalize design details and specifications to ensure constructability and compliance with project permits. Technical specifications are often included in this phase to accompany the design plans and provide additional details to project sponsors.
- *100% Bid-Ready Package*. This design level includes all pertinent information for a contractor to develop an accurate construction estimate and construct the project elements.

Technical specifications from the 90% design level are expanded into full contractual documents. Through the design process additional information is often provided to the project sponsor and stakeholders:.

- *Selection Criteria*. Selection criteria for the contractors (e.g., restoration experience and required equipment).
- *Quality Control/Quality Assurance (QA/QC) and Liability.* Beginning with initial concepts, it is expected that experts are reviewing and signing off on designs, including licensed professionals who stamp the designs. Any plans focused on restoration of ecological communities should include reviews by appropriate fisheries, wildlife, and plant experts prior to submitting design plans for permitting. Most construction design plans require the stamp of a civil engineer with expertise in stream restoration. A licensed geologist with expertise in fluvial or coastal geomorphology should also stamp any plans that involve alteration of the landscape and natural processes such as surface and subsurface flow, erosion, and sedimentation. Some plan sheets may also require stamping by a land surveyor, landscape architect, or structural engineer.
  Construction Checklists and Inspection Reports. Preparing construction checklists helps ensure projects are successfully completed:
  - Proper safety equipment is used and procedures are followed.
  - Permit conditions are met throughout construction.
  - Structure locations are accurately staked.
  - Builder meets specifications in the plans for materials and completed structures.
  - Contractor invoices reflect materials and work completed.
  - Photo points documenting before and after conditions are established.

Most wood placement projects will require instream work and the need for dewatering or site isolation to contain turbidity and limit disruption to fish, wildlife, and vegetation communities. Detailed plans will likely be required by the regulatory agencies that identify the best management practices (BMPs) that will be implemented, construction techniques, and fish and wildlife exclusion and avoidance measures taken before permits are issued. Environmental compliance will often require a risk level assessment and a site-specific stormwater pollution prevention plan (SWPPP) that identifies an effective combination of erosion control, sediment control, and nonstormwater BMPs that must be implemented to reduce construction effects on receiving water quality. The SWPPP must define a program of regular inspections of the BMPs and in some cases sampling of water quality parameters. The SWPPP also should demonstrate compliance with all applicable local and regional erosion and sediment control standards, identification of responsible parties, a detailed construction timeline, and a BMP monitoring and maintenance schedule.

Wood placement projects are often designed with the intention of altering channel hydraulics to promote beneficial physical processes and enhance habitat conditions. The extent to which the wood placement project creates a large enough flow obstruction to appreciably increase water surface elevations, and thus potentially increase flood risk, depends on the scale of the project and wood placement locations. Larger projects with the potential to elevate water surface elevations and increase flood risk in the regulatory floodway may be required by the local jurisdiction and FEMA to document with a hydraulic modeling study, approved by a licensed engineer, that the project will not create a net-rise in the 100-year flood base elevations. If modeling shows the wood placement project will create a net-rise, then the project team must advocate with agencies and neighbors to approve the net-rise because the base level elevations used to assess flood risk will increase. This will typically require completion of Conditional LOMR and LOMR documents.

2.2.11 Implement the Project

The project implementation stage is the most critical component to a successful large wood project and achieving the desired project outcomes. Despite all the planning and design efforts to get to this stage, if a project encounters challenges during construction that compromise the design intent or intended outcomes, the project may be viewed as a failure, making it difficult to pursue future large wood projects in that watershed. Critical implementation consideration should include construction management and oversight.

2.2.11.1 Construction Management

Prebid Meeting

This meeting should be required for all potential bidders to increase the odds of receiving qualified bids and reduce the potential for change orders.

Contractor Selection

Due to the inherent complexity and uncertainty of site conditions and wood materials in many restoration projects, it is highly advised that contractor selection not be limited to low bids, but be based on contractor experience, qualifications, and construction approach. This will increase the odds of receiving qualified bids and reduce the potential for quality control issues and change orders.

2.2.11.2 Construction Oversight

Large wood is not uniform and is available in a variety of quality grades. An initial task for project sponsors and designers should always be to inspect the large wood delivered to the site to ensure it meets the species, size, and quality specifications provided in the bid documents. Any pieces not meeting the specifications should be tagged and removed from the site immediately. Extreme care should also be taken in working around wood placements as the size of pieces and ability of heavy equipment to move wood can create safety hazards for unaware laborers and observers. Safety protocols should be clearly established and followed on job sites.

Daily Logs

Daily logs should be kept by the sponsor and/or designated field engineer/scientist when on site to document field conditions, construction progress, compliance with design plans, and conversations with the contractor. Daily logs should include photos and plan mark-ups documenting whether the project is being constructed as designed or if changes are needed. These logs can serve as key information to the sponsor and/or designer during any disputes and can limit the potential for unnecessary change orders that increase costs.

Change

Some amount of change from the design plans during the construction process should be expected on every large wood project for the reasons previously mentioned. Projects where some amount of uncertainty is anticipated should build that expectation into the design plans and contract documents, and discussions should be held with contractors to reduce the potential for costly change orders during the construction process. Common strategies to add flexibility in contract documents include bidding items lump sum and creating force account items for miscellaneous items (e.g., setting up bid item for contractor to lock into cost of machine and operator time).

2.2.12 Monitor and Implement Adaptive Management Measures

Once environmental documentation is approved, permits are received, and construction is completed, the monitoring and adaptive management phase of the project begins.

CROSS-REFERENCE

Chapter 9, *Assessing Ecological Performance*, provides a detailed discussion about monitoring and implementing adaptive management measures.

Although completion of the environmental documentation and permitting process may introduce new requirements that necessitate modification of the monitoring and adaptive management plan, by this stage in the project, all of the key project elements should be approved and in place as preparation of the plan has already been completed. As discussed above, the monitoring and adaptive management plan will have clear criteria stating which elements will be monitored, the frequency of monitoring, and whether performance standards have been met. As the monitoring is implemented and reports are written, the stakeholders will use the approved adaptive management plan to determine any remedial work that must be performed. The length of monitoring and adaptive management will vary between projects based on budget constraints, but the longer the monitoring periods the greater the probability the project will achieve its objectives.

2.3 Restoration Decision Making

At each step in the ecological restoration planning process critical decisions need to be made that will influence the outcome of the project. Historically, even well-intentioned resource management has resulted in degraded ecosystems across the United States (Noss and Peters 1995). To address the past impacts as well as prevent potential future degradation of ecosystems, habitat enhancement or improvement projects have become the mitigation action of choice to offset many habitat deficiencies. Unfortunately, restoration projects are often planned and implemented without proper consideration of their landscape context as well as the ecosystem processes and structure (Beechie et al. 2010). Failure to recognize these broader scale concerns may lead to poor project selection and increased potential for failure.

The integration of socioeconomic factors into restoration plans has been a critical component of successful programs. To this end, over the last 20 years, researchers and resource managers have emphasized the use of decision support tools for implementing ecosystem restoration efforts (Wyant et al. 1995; EPA 1995; Pastoroka et al. 1997; Linkov et al. 2005; Linkov and

Moberg 2012; Suding and Hobbs 2009; Beechie et al. 2010; USACE IWR 2010; Gregory et al. 2012; Convertino et al. 2013; IUCN 2014). This section describes the importance of the project planning team and scaling project size, along with a number of the tools that have been developed to assist in quantifying and understanding the resource as well as the socioeconomic tradeoffs associated with those decisions. Specifically, it highlights the value of taking an SDM approach that considers MCDA tools in ecological restoration planning for improving the manner in which restoration decisions are made as well as the success of restoration projects.

2.3.1 Planning Team Composition

A strong multidisciplinary team is necessary given the amount and range of infrastructure, public and private stakeholder involvement, regulatory issues, and potential liability. Professional engineers should be aware that foundational due diligence includes obtaining substantial information from other professional disciplines. Designs compiled by an individual or a limited team may represent a breach of the ethical canon, "Engineers shall perform services only in areas of their competence." The project team should comprise more than those just working on technical aspects of the design. As appropriate, it should also include representatives from key regulatory agencies, landowners, or local municipalities. Understanding local knowledge and politics provides value in defining project constraints, speeding up stakeholder approval, and ultimately reducing costs.

While the exact makeup of the project team can vary, it should typically include engineering professionals, geomorphological professionals, landscape architects, and experts as well as individuals with a variety of ecological expertise.

As such, the design team should consider the experts listed in the *Guidance* box that follows, many of whom should have experience and expertise in the use of wood in restoration projects.

GUIDANCE

Professionals and Experts to Involve

- Geologists with specific expertise in fluvial geomorphology, hydrology, sediment transport, and wood.
- Engineers with expertise in river system design and construction of wood structures.
- Hydrologists with specific expertise in flow characterization and fluvial geomorphology.
- Fisheries biologists and/or aquatic ecologists with regional expertise.
- Riparian plant ecologists or foresters with regional expertise.
- Regulatory specialists with local and regional expertise.
- Wetland scientists.
- Landscape architects.
- Resource economists.
- Community facilitators, planners, or watershed coordinators.

It is crucial to include the stakeholders throughout the ecological restoration planning efforts. Stakeholders are often the individuals or groups who may fund the project, affect the river directly, or be affected by actions taken on the river. A trained facilitator may be needed to guide the development of goals and objectives and to ensure that all stakeholders, challenges, other opportunities, and constraints are fully recognized. Once agreement is reached on the goals and objectives, the team can start on the design process and develop design alternatives.

2.3.2 Scaling the Process

The scale of ecological restoration projects can range from simply stabilizing a streambank at a specific location to restoring self-sustaining ecological functions to an entire watershed. Restoration projects vary in scale from an entire watershed to a valley reach to a small section of channel. Regardless of size and focus, every restoration undertaking should consider the cumulative impacts of every project element and how the project would not only achieve the desired goals, but sustain those conditions.

The larger and more complex the project, the greater the effort will be required for design and permitting. Projects with greater visibility typically require more detailed design and review. A project design can be directly affected by a wide range of site conditions such as infrastructure (above and below ground), earth materials, threatened and endangered species, archaeological and cultural resources, land ownership, or wetland delineations. Site conditions should be assessed early on in the project to guide how the greatest ecological uplift can be accomplished within site constraints—or how the project can redefine or eliminate constraints by improving infrastructure, securing easements, or avoiding sensitive areas.

The scale of restoration also pertains to how much intervention is needed. Passive restoration focuses on allowing natural processes to proceed without human intervention. This strategy would focus on making sure a system is capable of re-establishing the desired conditions in a reasonable timeframe if left alone, and “design” would focus on new management guidelines that encourage and protect natural recovery. Examples include systems with mature riparian vegetation where wood is naturally being recruited. Many other sites will require direct intervention. As such, scaling the process to fit the size and complexity of the project is essential.

2.3.3 Integrating Socioeconomics into the Restoration Process

Large wood projects result in both costs and benefits to private resources owners and to the wider public. Consideration of these costs and benefits is therefore a crucial component of restoration planning and will influence large wood project decision making. Comparing the costs and benefits of large wood projects is challenging because of the differing manner in which costs and benefits of projects are realized. Costs are mostly centralized and incur to those implementing the project. Benefits, on the other hand, are more diffuse in nature for several reasons. First, benefits of large wood projects accrue to a much larger segment of society than the project costs. Second, while some benefits of large wood projects, such as increased fish populations and increased recreational opportunities, may be measured by market activity, other benefits of large wood projects, such as many ecosystem services, are less directly tied to or have no ties to market activity. These benefits require methods other than analyzing market data to estimate their value. This section provides a brief introduction to the costs and benefits of restoration planning. In relation to restoration planning costs, this section describes the major factors that influence project costs. In considering restoration planning benefits, the section describes a framework for estimating the benefits of restoration projects, the types of values that result from projects, and common methods used to estimate the monetary value of these benefits.

2.3.3.1 Costs of Restoration

The costs of restoration activities are an important factor that can influence the scale and scope of projects, and help determine which projects are undertaken. It is important to consider project costs in the early stages of planning, as costs drive project decisions. As noted by Evergreen Funding Consultants (EFC

2003), this early consideration of costs helps to ensure that project plans present realistic descriptions of associated costs and thus increases the likelihood that funding will be available for proposed actions. In addition, a careful consideration of costs at the planning stage helps to ensure that the funding sources will be available when they are needed over the course of the project.

The costs of large wood projects can be broken down into several categories, a helpful tool for estimating project costs, because various factors will affect these cost categories in different ways. Understanding the categories likely to affect restoration costs, and how these categories would be affected by the specific aspects of a project, increases the ability of planners to accurately estimate project costs.

GUIDANCE

Major Cost Categories for Restoration Projects

- Construction
- Design
- Permitting
- Appraisal
- Basic monitoring
- Routine maintenance
- Reestablishing the site to prior conditions
- Project management
- General administration and enforcement
- Longer-term monitoring and maintenance

By considering each of these categories separately, one can assess how different factors of a given restoration project would likely affect each cost category. (EFC 2003)

Cost estimates for large wood projects are commonly estimated on a scale of dollars per stream mile. EFC prepared a primer on various types of restoration project costs for the Puget Sound Shared Strategy (2003), including large wood projects. This primer can be used to obtain rough estimates of project costs, based on different factors that could influence costs. As noted by EFC in the primer, the level of predictability of costs for large wood projects is generally good because there is a large amount of certainty as to how the main factors of large wood projects affect costs.

In addition to the factors discussed above, EFC mentioned two other factors that can affect large wood project costs. First, risks associated with the project can increase costs. Second, risks can result from hazards that may be introduced by large wood projects, such as trapping recreational river users, jamming downstream culverts, and changing channel and floodplain characteristics (which can increase erosion and flood risks). Risks of large wood projects are higher in more heavily populated areas, such as projects on streams that traverse urban or suburban areas. Risks related to large wood projects can be mitigated through design and planning, but usually at an additional cost. The remoteness of a project site can be a good indication of risk-related costs, with more remote sites posing fewer risks.

CAVEAT

Factors Likely to Affect Restoration Planning Costs

Project scope influences project costs in that larger projects tend to have smaller costs on a per-stream-mile basis. This is due to economies of scale that come into play when a larger stream area is the focus of the restoration activity. In other words, the fixed costs of restoration projects can be spread out for larger projects, reducing the implementation costs as compared to fixed costs incurred by a project.

Treatment intensity of the large wood project also affects costs, with more intensive levels of restoration having higher costs. This is because higher levels of treatment intensity generally require more materials, equipment, and labor than projects with a lower level of treatment intensity. One way that treatment intensity can be measured is by the density of wood used in the project. Large wood projects with less wood density have smaller materials costs than projects with greater levels of wood density.

Stream size is one of the biggest factors affecting restoration project costs, with larger streams generally having higher project costs than smaller streams. The reason for this positive correlation between stream size and project costs is that large wood projects on larger streams generally require more planning, design, materials, permitting, equipment, and labor than projects on smaller streams.

Access can have a significant influence on restoration project costs because the ease of access will determine the type of equipment and the amount of labor needed. For example, some large wood projects may require the use of helicopters to get the material to the project site, which increases costs over projects where material can be directly hauled to the site by ground transport.

Material availability can affect costs based on whether materials are purchased or obtained through some other means. If the materials are purchased, the quantity and quality of timber that is acquired for the project would have a direct impact on the resulting project costs.

Contract type can influence project costs based on whether labor and equipment are rented by the hour or based on some other type of arrangement. Other variations in contract type include whether the contract is for construction or for equipment rental. Construction contracts are generally more expensive than equipment rental contracts, but the arrangements for liability are different between these two contract types, which also affects costs. For construction contracts, the contractor usually assumes the liability, whereas liability is not assumed for equipment rental contracts.

Amount of time needed for the project affects costs because longer projects require more labor hours. Time may also be needed to acquire necessary permits.

2.3.3.2 Economic Benefits of Restoration

Although project costs are often relatively straightforward to estimate, benefits of restoration projects are more challenging and often require specialized estimation techniques. Estimating the benefits of restoration projects usually starts with a process of quantifying the change in ecosystems, and the services provided by them, that would result from a project. Next, monetary values are ascribed to these changes. Missing or incomplete data and uncertainties about the cause-and-effect relationships between restoration and improvements create challenges when quantifying changes to ecosystem services. Additionally, the process of monetizing these changes is often challenging because it is difficult to identify the actual values that society places on ecosystem services.

The following discussion identifies an overall framework and specific steps for estimating the benefits of restoration projects. This is followed by descriptions of the potential benefits of restoration planning. Lastly, the methods and approaches used to value the ecosystem service benefits of restoration projects are discussed.

Framework for Valuing the Benefits of Restoration Projects

A framework for valuing the benefits of restoration planning involves a systematic and scientific process of quantifying ecological impacts and ascribing monetary values to them. The U.S. Environmental Protection Agency's Science Advisory Board (2009) developed such a framework in a report titled *Valuing the Protection of Ecological Systems and Services*. This framework consists of three steps, as shown in the *Guidance* box that follows.

In Step 1 of the framework, the scope of the benefit estimation process is narrowed down to only focus on ecosystem services that would be affected by the proposed restoration project. Restricting this focus should not be interpreted as deducing that other unaffected ecosystem services do not have value or are less important. Because these other services will not be affected by the restoration project, their value will not be changed by the restoration project, and knowing their value will thus not affect decision making related to the restoration project. Identifying key ecosystem services can be accomplished by making a list of the restoration activities that a project will entail, and then making a list of the ecosystem services affected by these activities.

Step 2 of the framework involves quantifying the final ecosystem services that were developed in Step 1. This set of ecosystem services is called "final" because the framework makes a distinction between the ecosystem services that are directly valued by people and those that provide an input to another good or service, and are thus valued only indirectly. Another way to think of this distinction is to focus only on ecosystem services that are directly enjoyed, consumed, or used by human beings. The focus only on the end products of ecosystem services helps to avoid the double-counting of ecosystem services and thus artificially inflating their value.

GUIDANCE

EPA's Framework Steps for Valuing the Benefits of Restoration Projects

1. Identify management actions and ecosystem services of strategic importance.
    a. Identify ecosystem production functions and restoration activities that affect ecosystem services.
    b. Of the affected ecosystem services, identify the ones that directly affect the well-being of society and are of the greatest importance to society.
2. Quantify final ecosystem services.
    a. Develop ecological production functions that specify the cause and effect relationships among restoration activities and ecosystem services.
    b. Quantify changes in ecosystem services in units of measurement that can be linked to societal well-being.
3. Value final ecosystem services.
    a. For each ecosystem service, determine whether it provides value to the resource owner, the wider public, or both.
    b. Focus valuation efforts on the types of benefits from each ecosystem service that are the most important to the private resource owner and the public.
    c. Use a range of economic valuation methods to capture the different types of values of ecosystem services.

Lastly, Step 3 of the framework involves ascribing a monetary value to the quantified changes in ecosystem services identified in Step 1 and quantified in Step 2. The steps of quantifying and monetizing ecosystem services are challenging, and require changes in ecosystem services to be expressed in measurable units that are meaningful to people and reflect the sense of the well-being people receive from ecosystem services. For the purpose of valuation, it is often important to make a distinction between benefits that accrue to private owners of a resource and those that accrue to the general public. Ecosystem services can then be valued by estimating the well-being people receive from their use, by the reduced costs to society for not having to provide these services by other means, or by the avoided damages that could result if these ecosystem services were lost (U.S. Environmental Protection Agency, 2010).

Values of Ecosystem Services

Ecosystem services that are enhanced or improved by restoration projects provide value to private resource owners and the public in different ways. At the highest level, such values can be broken down into *use* values and *non-use* values, with total economic value representing the sum of these two components.

CROSS-REFERENCE

Chapter 3, *Ecological and Biological Considerations*, provides an indepth examination of using models to quantify the biological benefits of restoration.

Use values are the most straightforward manner in which ecosystem services provide value to society. Direct use refers to when humans directly use the end product of an ecosystem service, such as consuming fish and animals, harvesting timber, or utilizing other forest products. Humans also use ecosystem services indirectly, such as when an ecosystem service is an input into something else that human beings directly use. For example, ecosystems provide habitat for plants and animal species that are then used by people, either consumptively or non-consumptively (such as through wildlife viewing). Habitat provision is thus an indirect use value provided by ecosystem services. Other examples of indirect use values of ecosystem services include flood protection, waste assimilation, and carbon sequestration.

In addition to the current use of ecosystem services, another type of value is that which people place on the option to use ecosystem services in the future. This type of value is called *option value,* an example of which is a wilderness area that one hopes to visit one day, or a species of bird one hopes to someday see.

Another type of value, non-use, does not involve any actual direct or indirect use by people. One type of non-use value, *existence value*, is the value people place on knowing an environmental amenity exists, even if they have no plans to personally use it. Existence values are commonly identified with rare landscapes or with threatened or endangered species. *Bequest value*, another non-use value, refers to the value people place on knowing that resources will be available for use by their children or future generations.

Methods for Estimating Economic Values of Ecosystem Services

A variety of methods exist for estimating the value of ecosystem services, with different methods being more suited to estimating the benefits of different ecosystem services. The objective of all of these methods is to estimate the net benefits that ecosystem services provide, or their benefits to society over and above the cost required to obtain them. The measure of net benefit is also called *consumer surplus* and can be thought of as the difference between what a person is willing to pay to receive a good or service and what they must actually pay for it. Economic valuation methods measure consumer surplus either by estimating willingness to pay and total cost for a good or service and then taking the difference of the two, or by measuring consumer surplus directly.

Economic valuation methods can be classified at the highest level into *revealed preference* methods and *stated preference* methods.

Revealed Preference Methods

Revealed preference methods rely on actual market data to estimate the value of ecosystem services. The most straightforward approach of revealed preference methods is the market price method, which uses market data for a good or service as a means for measuring consumer surplus. The market price method can be used when the products of ecosystem services are directly traded in market, such as the markets for timber, food, or fuel, or for ecosystem services that produce goods and services sold directly in markets. Despite the simplicity of using the market price method, its application for valuing ecosystem services is limited because it can only be used for ecosystem services with a direct tie to market activity. This method also does not provide a direct measure of consumer surplus, which must be inferred or estimated from the existing market data.

Other revealed preference methods can be used to estimate the values of ecosystem services that are less directly tied to market activity. For example, some valuation methods value ecosystem services by estimating the cost of replacing the services provided by ecosystems by other means. This method, the *replacement cost* method, can be used to value ecosystem services such as water quality that could be provided by other means if they were not provided by ecosystems. Another, the *damage cost* method, values ecosystem services by estimating the costs of damages that could result if an ecosystem service were lost. For example, the water retention benefits of a restoration project could be valued by estimating the costs that the project would help to avoid from floods that would be more likely to occur without water retention services. One drawback of these approaches, however, is that they estimate costs of replacing lost services or avoiding damages, which may not represent the full value that societies place on ecosystem services.

Another revealed preference approach is the *hedonic pricing* method. This method uses the value of related market goods to estimate the value of a related non-market ecosystem service. The most common application of this method involves using property market data to estimate the value of ecosystem services associated with private properties. In other words, hedonic pricing involves using statistical techniques to infer the value of ecosystem services by comparing the value of properties that include these services with similar properties that do not include them. Hedonic pricing has been used extensively to value the impact of open space and other environmental amenities such as air and water quality on properties. A drawback of this method is that it can only be used to value ecosystem services that would affect property values.

Another revealed preference approach, the *travel cost* method, is commonly used to value ecosystem services related to recreation and aesthetic enjoyment. This method is based on the premise that the value that people place on a recreational resource is equal to the amount of time and money they had to spend to travel to the resource and to use it. Information on travel costs is most often collected through surveys of visitors to a specific recreation site. The travel cost method has been used extensively to value parks, open space, and other sites used for outdoor recreation. This method, however, is limited in its applicability because it can only be used to measure resources related to recreation and visitation by people.

Stated Preference Methods

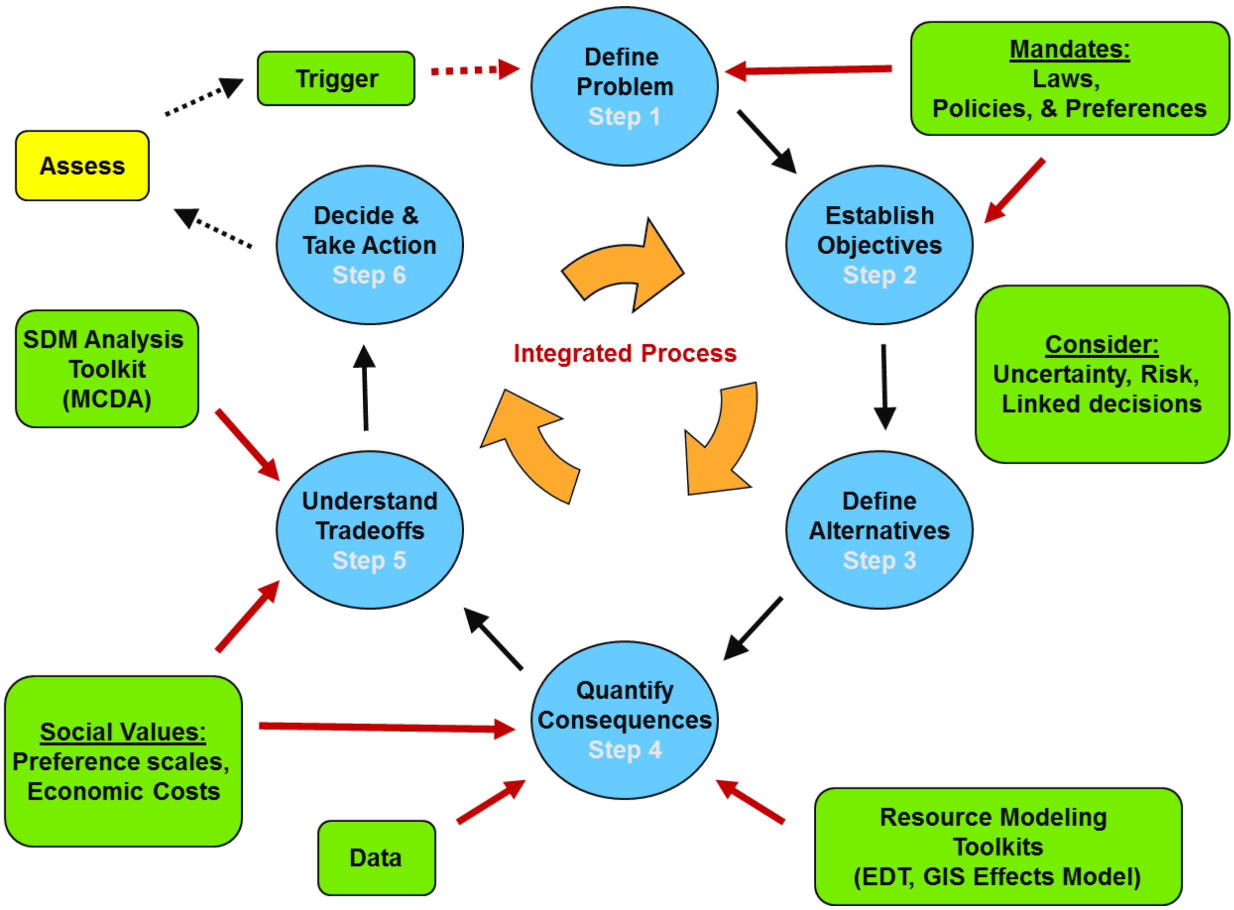
As opposed to revealed preference methods that use actual market data, stated preference methods use public opinion surveys to ask people about their values for ecosystem services. Stated preference methods are commonly used to value ecosystem services that do not have clear ties to market activity. Additionally, stated preference methods are the only valuation method that can capture the non-use component of the value of ecosystem services. One common stated preference method, *contingent valuation*, is conducted by creating a hypothetical market for a good or service, and then asking people to state their willingness to pay for a change in the level of provision of it. Another stated preference method, *choice modeling*, asks people to select their preferred option among repeated choices among alternatives with differing levels of provision of attributes. Both of these approaches can be used to estimate the consumer surplus associated with ecosystem services, and can be used to estimate the value of proposed programs or policies that have not yet occurred. Despite these advantages, however, the hypothetical nature of stated preference methods can be controversial and has led to criticism of these methods and the results obtained by them. Also, due to the need to collect survey data, stated preference methods are time consuming and expensive to conduct.

An alternate approach to conducting original revealed and stated preference studies is to use *benefit transfer* methods, which customize, or adapt, the results of previous studies to fit a new context. Given the time and expense needed to conduct primary studies, benefit transfer methods are widely used by government agencies and other researchers to value ecosystem services. Conducting a benefit transfer initially involves doing a comprehensive literature search to learn if similar ecosystem services have been valued in other studies. Any identified similar studies are then evaluated for their quality and suitability for a benefit transfer exercise. If suitable source data can be found, the next step is to transfer the original value to the new study context. The transfer is accomplished either through a direct transfer of the estimated value, or a transfer of the function used to estimate the original value. Many researchers prefer to transfer the benefit as opposed to the value, because transferring a function allows the researcher to customize the variables in the function to match the current analytical context.

2.3.4 Using Structured Decision Making

Structured decision making is a general concept that applies to a carefully organized analysis of problems used to reach decisions that are focused on achieving clearly defined fundamental objectives (Gregory et al. 2012; Clemen and Reilly 2001; Kirkwood 1997; Keeney and Raiffa 1993). Based in decision theory and risk analysis, SDM encompasses a simple set of concepts and helpful steps, rather than a rigidly prescribed approach, for problem solving (Figure 2-10). Key SDM concepts include making decisions based on clearly articulated objectives, addressing uncertainty, and responding transparently to legal mandates and public preferences or values in decision making. As such, SDM integrates science and policy. Every decision consists of several primary elements: management objectives, decision options, and predictions of decision outcomes (Table 2-1). By analyzing the components within a comprehensive decision framework, it is possible to improve the quality of decision making. The core SDM concepts and steps are applicable to all types of decisions, from those associated with minor restoration projects to complex public sector decisions involving multiple decision makers, scientists, and other stakeholders. The key component for success is the ability to integrate quantifiable information at critical steps in the process.

Figure 2-10. The Structured Decision Making Process



Source: Modified from USFWS 2008.

Table 2-1. Steps in Structured Decision Making

Step	Important Considerations
1. Problem Definition	What specific decision has to be made? What is the spatial and temporal scope of the decision? Will the decision be iterated over time?
2. Establishing Objectives	What are the management objectives? Ideally, these are stated in quantitative terms that relate to metrics that can be measured. Setting objectives falls in the realm of policy, and should be informed by legal and regulatory mandates, as well as stakeholder viewpoints.
3. Defining/Understanding Alternatives	What are the different management actions from which we can choose? This element requires explicit articulation of the alternatives available to the decision maker. The range of permissible options is often constrained by legal or political considerations, but structured assessment may lead to creative new alternatives.
a. Uncertainty	Because we rarely know precisely how management actions will affect natural systems, decisions are frequently made in the face of uncertainty. Uncertainty makes choosing among alternatives far more difficult. A good decision-making process will confront uncertainty explicitly, and evaluate the likelihood of different outcomes and their possible consequences. Scientific uncertainty will exist in the flow alteration–ecological response relationships, in part because of the confounding of hydrologic alteration with other important environmental determinants of river ecosystem condition (e.g., temperature).
b. Risk Tolerance	Identifying the uncertainty that impedes decision making, then analyzing the risk that uncertainty presents to management is an important step in making a sound decision. Understanding the level of risk a decision maker is willing to accept, or the risk response determined by law or policy, will make the decision-making process more objectives-driven, transparent, and defensible.
c. Linked Decisions	Many important decisions are linked over time. The key to effectively addressing issues associated with linked decisions is to isolate and resolve the near-term issues while sequencing the collection of information needed for future decisions.
4. Quantifying Consequences	What are the consequences of different management actions? To what degree would each alternative lead to successfully reaching a given objective? In SDM, we predict the consequences of the alternative actions with an appropriately chosen model. Depending on the information available or the quantification desired for a structured decision process, consequences may be modeled with highly scientific computer applications, or with personal judgment elicited carefully and transparently. Ideally, models are quantitative, but they need not be; what is most important is that they link actions to consequences.

Step	Important Considerations
5. Understanding Tradeoffs	If there are multiple objectives, how do they trade off with each other? In most complex decisions, the best we can do is to choose intelligently between less-than-perfect alternatives. Numerous tools are available to help determine the relative importance or weights among conflicting objectives; this information is used to compare alternatives across multiple attributes to find the best compromise solutions.
6. Decide and Take Action	For those decisions that are iterated over time, actions taken early on may provide a learning opportunity that improves management later, provided that an appropriate monitoring program is in place to provide the feedback. Adaptive management is a special case of structured decision making for decisions that are iterated or linked over time.
Source: Gregory et al. (2012).	

2.3.4.1 Decision Support Tools

Decision making for ecosystem restoration projects can be a complex and challenging process, characterized by trade-offs between socio-political, environmental, and economic impacts. The adherence to appropriate environmental policies, land-use planning, and other regulatory decision-making challenges involves multiple selection criteria such as cost, benefit, environmental impact, safety, and risk. As such, mangers have often used cost-benefit analyses, occasionally in concert with comparative risk assessment, to choose between competing project alternatives. Additionally, some selection criteria cannot easily be condensed into simple values, which complicates the integration of resource and socioeconomic values inherent in making comparisons and trade-offs. Furthermore, environmental concerns often involve ethical and moral principles that may not be related to any economic use or value. To this end, this manual presents two decision support tools that enhance the decision-making process.

Multi-Criteria Decision Analysis

MCDA is a sub-discipline of operations research that explicitly considers multiple criteria in decision-making environments (Clemen and Reilly 2001; Kirkwood 1997; Keeney and Raiffa 1993). Considerable research on MCDA has made available practical methods for applying scientific decision theoretical approaches to multi-criteria problems. For example, in 2010, USACE recognized its value in achieving its environmental mission by considering a broad range of criteria (USACE IWR 2010). MCDA techniques were identified as excellent ways to help USACE planners and project managers balance their decisions based on social equality, environmental soundness, and economic viability. To this end, MCDA techniques are tools USACE can use to improve the transparency of the decision-making process. MCDA provides a proven mathematical means for comparing criteria with differing units such as habitat units, cultural resources, public sentiment, and total cost. The stakeholders, both those in support and against a project, can provide input into the criteria used to evaluate plans. The plans and their effects are plainly described in the decision matrix, allowing the stakeholders and project team an greater understanding of the problems associated with a particular plan. As such, MCDA is a valuable tool that can be applied to many complex decisions. It is most applicable to solving problems that are characterized as a choice among alternatives and has all the characteristics of a useful decision support tool: it helps us focus on what is important, logical and consistent, and is easy to use.

GUIDANCE

The International Society on Multiple Criteria Decision Making (MCDM)

MCDM identifies software packages that can assist with MCDA (http://www.mcdmsociety.org/soft.html):

- 1000Minds software for MCDM, prioritization, and resource allocation. Internet-based and free for academic use.
- BENSOLVE Free MatLab implementation of Benson's algorithm to solve linear vector optimization problems.
- Decisionarium, global space for decision support (for academic use).
- DEXi, program for qualitative multi-attribute decision modeling, developed at the Jožef Stefan Institute, Ljubljana, Slovenia.
- D-Sight, visual and interactive tool for multicriteria decision aid problems based on the PROMETHEE methods and Multi-Attribute Utility Theory.
- GUIMOO, Graphical User Interface for Multi Objective Optimization from INRIA.
- IDS Intelligent Decision System for Multiple Criteria Decision Analysis under Uncertainty (using the Evidential Reasoning Approach).
- IDSS Software: MCDM software of the Laboratory of Intelligent Decision Support Systems (University of Poznan, Poland).
- IND-NIMBUS: implementation of the interactive NIMBUS method that can be connected with different simulation and modeling tools.
- Interalg free solver, which includes global nonlinear multiobjective optimization with user-defined accuracy.
- IRIS and VIP, IRIS: Interactive Robustness analysis and parameters' Inference software for multicriteria Sorting problems and VIP (Variable Interdependent Parameters) Analysis software.
- MACBETH for MCDA, Measuring Attractiveness by a Categorical Based Evaluation TecHnique in MultiCriteria Decision Aid.
- MakeItRational, AHP based decision software.
- modeFRONTIER, commercial software developed by ESTECO Spa dedicated to multi-objective optimization and multi-disciplinary design, providing an easy coupling to almost any Computer Aided Engineering (CAE) tool.
- Collection of Multiple Criteria Decision Support Software by Dr. Roland Weistroffer.
- WWW-NIMBUS for solving nonlinear (and even nondifferentiable) multiobjective optimization problems in an interactive way. Operates via the Internet, free for academic use.
- ParadisEO-MOEO, module specifically devoted to multiobjective optimization in ParadisEO, software framework for the design and implementation of metaheuristics, hybrid methods as well as parallel and distributed models from INRIA.
- Priority Estimation Tool, open-source (free) software for AHP-based decision making.
- PROMETHEE-GAIA software.
- MCDA software by Quartzstar Ltd.: OnBalance for evaluation decisions and HiPriority for resource allocation.
- RGDB, Graphic tool that helps to select preferable rows from relational databases.
- Accord by Robust Decisions implementing the Bayesian Team Support technique.
- TransparentChoice - Strategic decision-making software, MCDM software that allows multi-disciplinary teams to collaborate on complex decisions.
- VISA, Web based Multi-Criteria Decision Making Software.

Within the context of SDM, MCDA helps natural resource decision makers talk about the restoration project in a way that allows them to consider both natural and socioeconomic values. It provides a tool for decision makers to consider and assess the complex trade-offs among project alternatives. In effect, it helps decision makers think, re-think, query, adjust, decide, rethink some more, test, adjust, and finally decide. To this end, the typical elements of the MCDA tool integrate well with SDM.

- Define the Decision
- Identify Decision Criteria
- Build a Decision Framework
- Rate the Alternatives

  Two common rating scales that that are used in MCDA are:

  - Relative Scale:

    Each alternative is rated relative to the others in satisfying a particular interest. For example, among four alternatives, assign each a 1, 2, 3, or 4 depending on which satisfies the interest: the best = 4; second best = 3; third best = 2; and the worst at satisfying the interest = 1.

  - Ordinal Scale:

    Using a scale of your choosing (e.g., a five–point scale, or a ten-point scale) assign each alternative a rating for how well it satisfies a particular interest. For example, a five-point scale might be: 5 = excellent; 4 = good; 3 = satisfactory; 2 = below average; 1 = poor.

- Weight Decision Maker/Stakeholder Interests
- Score the Alternatives
- Discuss Results, Re-Score, Discuss Again, Decide

River Restoration Analysis Tool

RiverRAT was developed to address the failure by resource managers to consider and integrate the appropriate information in making river restoration decisions (Skidmore et al. 2011). RiverRAT includes a suite of resources to guide more efficient, consistent, and comprehensive reviews of stream management and restoration proposals. Such resources help determine the depth of review required, ensure that a project proposal is complete, and guide reviewers through a thorough and scientifically sound project review. The RiverRAT Science Document and its appendices provide a comprehensive synthesis of science behind stream management and restoration project development.

The ultimate, long-term goals of RiverRAT include:

- Enabling consistent, comprehensive, transparent, and documented project reviews.
- Facilitating improved project planning and design.
- Encouraging projects that are attuned to their watershed and geomorphic context.
- Improving the science and technology of stream restoration and management.

The RiverRAT tools, the supporting Science Document, and the detailed technical appendices, are available to the public at www.restorationreview.com. For example, the Project Screening Matrix and River Restoration Analysis Tool is a good example of the practical application of river restoration concepts to individual projects (Skidmore et al. 2011).

CROSS-REFERENCE

Figure 7-3 in Chapter 7, *Risk Considerations*, shows the RiverRAT Project Risk Screening Matrix.

2.4 References

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, and C. Petroff. 1997. Design of Stable In-Channel Wood Debris Structures for Bank Protection and Habitat Restoration: An Example from the Cowlitz River, WA. Pages 809–816 in S. S. Y. Wang, E. J. Langendoen, and F. D. Shields (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi, Oxford, MS.

Abbe, T. B., J. Carrasquero, M. McBride, A. Ritchie, M. McHenry, and K. Dublanica. 2003a. *Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington*. Proceedings of the Georgia Basin/Puget Sound 2003 Research Conference, Vancouver, B.C., March 31–April 1, 2003, T. Droscher (ed.). Puget Sound Action Team, Olympia, WA.

Abbe T. B, A. P. Brooks, and D. R. Montgomery. 2003b. Wood in River Rehabilitation and Management. Pages 367–389 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003c. Integrating Engineered Log Jam Technology into River Rehabilitation. In D. R. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies.

Abbe, T. B., C. Miller, and A. Michael. 2009. *Self-Mitigating Protection for Pipeline Crossings in Degraded Streams: A Case Study from Woodward Creek, Washington.* 9th International Right of Way Symposium. 2009. Portland, OR.

Beechie, T. J., and S. Bolton. 1999. An Approach to Restoring Salmonid Habitat-Forming Processes in Pacific Northwest Watersheds. *Fisheries* 24:6–15.

Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, P. Roni, and M. M. Pollock. 2010. Process-Based Principles for Restoring River Ecosystems. *Bioscience* 60:209–222.

Beechie, T. J., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N Mantua. 2012. Restoring Salmon Habitat for a Changing Climate. *River Research and Applications* 29:939–960.

Booth, D. B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. *Water Resources Bulletin* 26:407–417.

Brummer, C., T. B. Abbe, J. R. Sampson, and D. R. Montgomery. 2006. Influence of Vertical Channel Change Associated with Wood Accumulations on Delineating Channel Migration Zones, Washington State, USA. *Geomorphology* 80:295–309Clemen, R. T., and T. Reilly. 2001. *Making Hard Decisions with Decision Tools*. Pacific Grove, CA: Duxbury Thomson Learning.

Buffington, J. M., and D. R. Montgomery. 1999a. A Procedure for Classifying Textural Facies in Gravel-Bed Rivers. *Water Resources Research* 35(6):1903-1914.

Buffington, J. M., and D. R. Montgomery. 1999b. Effects of Hydraulic Roughness on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3507–3521.

Buffington, J. M., and D. R. Montgomery. 1999c. Effects of Sediment Supply on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3523–3530.

Clemen, R. T., and T. Reilly. 2001. *Making Hard Decisions with Decision Tools.* South-Western Cengage Learning. 733 pp.

Collins, B. D., D. R. Montgomery, and A. J. Sheikh. 2003. Reconstructing the Historical Riverine Landscape of the Puget Lowland. Pages 79–128 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press, Seattle.

Convertino, M., K. M. Baker, J. T. Vogel, C. Lu, B. Suedel, and I. Linkov. 2013. *Multi-Criteria Decision Analysis to Select Metrics for Design and Monitoring of Sustainable Ecosystem Restorations*. U.S. Army Research. Paper 190. Available: <http://digitalcommons.unl.edu/usarmyresearch/1905>.

Evergreen Funding Consultants (EFC). 2003. A Primer on Habitat Project Costs. Available: http://www.evergreenfc.com/section_services/resources/primer.pdf.

Fox, M. J. 2003. *Spatial Organization, Position, and Source Characteristics of Large Woody Debris in Natural Systems*. Ph.D. dissertation. College of Forest Resources, University of Washington. Seattle, Washington.

Gregory, R., L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson. 2012. *Structured Decision Making: A Practical Guide to Environmental Management Choices.* ISBN: 978-1-4443-3341-1. Wiley-Blackwell. 312 pp.

Heede, B. H. and J. N. Rinne, 1990. Hydrodynamic and Fluvial Morphological Processes: Implications for Fisheries Management and Research. *North American Journal of Fisheries Management*, 10:249–268.

Hester, E. T., M. W. Doyle, and G. C. Poole. 2009. The Influence of In-Stream Structures on Summer Water Temperatures via Induced Hyporheic Exchange. *Limonology and Oceanography* 54:355–367.

International Union for Conservation of Nature (IUCN). 2014. I*UCN Releases an Economic Framework for Analyzing Forest Landscape Restoration Decisions*. Available: http://cmsdata.iucn.org/downloads/flr_economic_analysis_tutorial___july_2014_1.pdf.

Kauffman, J. B., R. L. Beschta, N. Otting, and D. Lytjen. 1997. An Ecological Perspective of Riparian and Stream Restoration in the Western United States. *Fisheries (Bethesda)* 22:12–24.

Keeney, R. L., and H. Raiffa. 1993. *Decisions with Multiple Objectives Preferences and Value Tradeoffs*. Cambridge University Press.

Kirkwood, C. W. 1997. *Strategic Decision Making. Multi-Objective Decision Analysis with Spreadsheets.* Wadsworth.

Li, R., and H. W. Shen. 1973. Effect of Tall Vegetation on Flow and Sediment. *Journal of the Hydraulic Division, ASCE* 99(5):793–814.

Linkov. I., and E. Moberg. 2012. *Multi-Criteria Decision Analysis: Environmental Applications and Case Studies*. CRC Press. ISBN: 978-1-4398-5318-4.

Linkov, I., A. Varghese, S. Jamil, T. P. Seager, G. Kiker, and T. Bridges. 2005. Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites. In I. Linkov and A. Bakr Ramadan (eds.), *Comparative Risk Assessment and Environmental Decision Making*. NATO Science Series Volume 38 2005ISBN: 978-1-4020-1895-4 (Print) 978-1-4020-2243-2 (Online).

Lisle, T. 1995. Effects of Coarse Woody Debris and its Removal on a Channel Affected by the 1980 Eruption of Mount St. Helens, Washington*. Water Resources Research* 31:1797–1808.

Manga, M., and J. W. Kirchner. 2002. Stress Partitioning in Streams by Large Woody Debris. *Water Resources Research* 36:2373–2379.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995. Pool Spacing in Forest Channels. *Water Resources Research* 31:1097–1105.

Murphy, M. L. 1995. Forestry Impacts on Freshwater Habitat of Anadromous Salmonids in the Pacific Northwest and Alaska—Requirements for Protection and Restoration. *U.S. Department of Commerce Coastal Ocean Program, NOAA. Decision Analysis Series No. 7*, 156 pp.

Noss, F., and R. L. Peters. 1995. *Endangered Ecosystems – A Status Report on America'sVanishing Habitat and Wildlife*. 133 Pages. Defenders of Wildlife, 1101 Fourteenth Street, NW, Suite 1400, Washington, DC 20005.

Pastoroka, R. A., A. MacDonaldb, J. R. Sampsona, P. Wilberc, D. J Yozzod, and J. P Titred. 1997. An Ecological Decision Framework for Environmental Restoration Projects. *Ecological Engineering* 9 (1–2):89–107.

Pelto, M. S. 2011. *North Cascade Glacier Retreat*. Nichols College, Dudley, MA. Available: http://www.nichols.edu/departments/glacier/bill.htm.

Poole, G. C., J. A. Stanford, S. W. Running, and C. A. Frissell. 2006. Multiscale Geomorphic Drivers of Groundwater Flow Paths: Subsurface Hydrologic Dynamics and Hyporheic Habitat Diversity. *Journal of the North American Benthological Society* 25:288–303.

Rapp, C., and T. Abbe. 2003. A *Framework for Delineating Channel Migration Zones*. Washington State Department of Ecology Publication Number 03-06-027. Final Draft.

Reid, L. M., and T. Dunne. 1996. *Rapid Evaluation of Sediment Budgets*. Reiskirchen, Germany: Catena Verlag (GeoEcology paperback). 164 pp.

Sedell, J. R., and J. L. Frogatt. 1984. Importance of Streamside Forests to Large Rivers: The Isolation of the Willamette River, Oregon, U.S.A., from its Floodplain by Snagging and Streamside Forest Removal. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1828–1834.

Shields, F. D., Jr., and C. V. Alonso. 2012. Assessment of Flow Forces on Large Wood in Rivers. *Water Resources Research* 48(4):W04156.

Skidmore, P. B., C. R. Thorne, B. L. Cluer, G. R. Pess, J. M. Castro, T. J. Beechie, and C. C. Shea. 2011. *Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals*. U.S. Department of Commerce. NOAA Tech. Memo. NMFS-NWFSC-112.

Society for Ecological Restoration. 2002. SER International Primer on Ecological Restoration. Science & Policy Working Group, Version 2, October. Available: http://www.ser.org/resources/resources-detail-view/ser-international-primer-on-ecological-restoration.

Society for Ecological Restoration. 2004. *The SER International Primer on Ecological Restoration*. Available: <http://www.ser.org>.

Suding, K. N., and R. J. Hobbs. 2009. Threshold Models in Restoration and Conservation: A Developing Framework. *Trends in Ecology & Evolution* 24 (5):271–279.

U.S. Army Corp of Engineers Institute for Water Resources (USACE IWR). 2010. *IWR Planning Suite MCDA Module User's Guide*. U.S. Army Corp of Engineers Institute for Water Resources.

U.S. Environmental Protection Agency (EPA). 1995. *A Decision-Making Guide for Restoration in Ecological Restoration*. EPA 841-F-95-007 (November)

U.S. Environmental Protection Agency (EPA). 2000. *Principles for the Ecological Restoration of Aquatic Resources*. EPA841-F-00-003. Available: <http://www.epa.gov/owow/wetlands/restore/.

U.S. Environmental Protection Agency (EPA). 2008. *Handbook for Developing Watershed Plans to Restore and Protect our Water*.

U.S. Environmental Protection Agency. 2009. *Valuing the Protection of Ecological Systems and Services*. May. Available: http://yosemite.epa.gov/sab%5CSABPRODUCT.NSF/F3DB1F5C6EF90EE1852575C500589157/$File/EPA-SAB-09-012-unsigned.pdf. Accessed: October 8, 2014.

U.S. Environmental Protection Agency. 2013. *A Quick Guide to Developing Watershed Plans to Restore and Protect Our Waters*. Available: http://water.epa.gov/polwaste/nps/upload/watershed_mgmnt_quick_guide.pdf.

U.S. Fish and Wildlife Service (USFWS). 2008. *SDM Fact Sheet*. Available: http://www.fws.gov/science/doc/structured_decision_making_factsheet.pdf. Accessed: May 15, 2015.

Wohl, E. 2013. Floodplains and Wood. *Earth-Science Reviews* 123:194–212.

Wyant, J. G., R. A. Meganck, and S. H. Ham. 1995. A Planning and Decision-Making Framework for Ecological Restoration. *Environmental Management* 19(6):789–796.

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Chapter 3
ECOLOGICAL AND BIOLOGICAL CONSIDERATIONS

Photo credit: Ken DeCamp

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3.1 Introduction

Large wood can be found in nearly all streams with forested riparian areas. Large wood has several ecological functions in streams, such as trapping sediment, creating structure, providing shade and cover for aquatic organisms, and diversifying flows. Wood is a key habitat component for many stream organisms, particularly for fish such as salmonids.

Resource managers using wood to restore ecological functions of streams are faced with many questions, such as:

- What are the biological purposes in restoring large wood?
- What ecological functions are enhanced by restoring large wood?
- What is the potential contribution of large wood to achievement of management goals?
- How does wood restoration relate to fish habitat?
- How do we manage riparian forests to maintain wood supply to the channel?

The answers to these questions depend on how the quantity and quality of habitat relates to fish abundance, distribution, and persistence over time and how these are affected by large instream wood. These issues are addressed in this chapter. The chapter discusses the ecological and other biological considerations associated with large wood in streams. The discussion favors the role of wood in salmonid ecosystems, reflecting the preponderance of research and the key role of wood in salmonid ecosystems. However, many of the principles derived from work on salmonid ecosystems are applicable to other systems and species.

GUIDANCE

This chapter provides a basic understanding of the following:

- Ecological functions of large wood in streams.
- Assessing the need for wood placement.
- Natural sources of wood.
- Scale and the River Continuum Concept.
- Hyporheic zone.
- Wood as habitat for invertebrates and terrestrial species.
- Importance of assessing wood placement.

In most cases, restoration of large wood is undertaken to achieve some biological goal. Hence, the inherent assumption of restoration of large wood is that habitat features in streams associated with wood are positively related to the survival, persistence, and abundance of desired species and communities and ecological functions (Whiteway et al. 2010). The relationship between individual habitat attributes and fish survival or abundance can be difficult to prove in a quantifiable and statistically meaningful way (Conquest and Ralph 1998; Bradford et al. 2005). Consequently, some researchers have reasonably questioned the benefits of stream restoration activities (Thompson 2006; Stewart et al. 2009), or called for a better accounting of the costs and benefits of restoration investments (Bernhardt et al. 2007). Benefits are challenging to detect, in part, because of the number of confounding factors affecting fish abundance in any year or over time, especially at a population scale for far-ranging anadromous species such as salmon (Rose 2000).

The observed response of fish and other organisms to wood enhancement also reflects a suite of watershed level conditions that can obscure the effects of site-specific wood restoration. Engineering solutions that do not account for species habitat needs, stream dynamics, disturbance regimes, and watershed characteristics are often unsuccessful (Beschta 1997). Nagayama and Nakamura (2010) reviewed the success of wood enhancement worldwide and observed that wood restoration has localized effects but may not be sufficient to recovery fish populations at the watershed scale. They found ample examples of restoration projects that have failed because of physical failure or sediment accumulation. They conclude that, "restoration projects should be aimed at restoring natural processes of wood recruitment and routing, which can provide fish and other organisms with sustainable wood habitats at the watershed scale over the long term" (Nagayama and Nakamura 2010). In other words, large wood enhancement should be viewed as an interim restoration measure until natural processes of wood recruitment recover to natural levels.

On the whole, however, the bulk of evidence supports the notion that the addition of large wood and large wood structures can, in many cases, provide habitat features believed to be conducive to fish production and that restoration generally (though not always) results in greater abundance and/or biomass of fish at life stage and population scales. For example, Roni et al. (2014b) reviewed 409 published studies evaluating specific restoration actions in terms of fish response and found generally positive, though variable, fish response to restoration actions. Many of these studies (209) focused on placement of logs and instream structures; and the bulk of the studies demonstrated a positive biological response in terms of increased abundance of juvenile or adult salmonids, a minority of studies showed no response, and only a few studies found a negative response to placement of instream structures. In a meta-analysis of published studies of large wood structures in streams, Whiteway et al. (2010) found that wood structure provided key habitat elements including pools and cover; most studies also reported increases in density and biomass of salmonids although there were appreciable differences among species. In should be noted, however, that increases in abundance at project sites by themselves can be misleading. The most relevant metric is the whether or not those increases in abundance cascade to a population level increase.

3.2 Ecological Functions of Large Wood

Large wood is a key structural element in forested stream ecosystems worldwide (Maser and Sedell 1994; Nagayama and Nakamura 2010). Wood serves as a food resource for microbes, fungi, and macroinvertebrates. In addition, a primary ecological role of large wood and accumulations of large wood (wood jams) is associated with its influence on the physical environment of streams and the creation of habitats for aquatic species (Roni et al. 2014a).

The influence of wood on stream habitat and stream ecosystem processes is affected by stream size, wood stability, stream gradient, and the underlying geology. In low-gradient (blackwater) systems typical of the southeastern United States where the bottom of the stream is composed of fine, unconsolidated sediments, large wood and wood jams can provide a stable substrate that can enhance invertebrate abundance, productivity, and diversity (Smock et al. 1989; Johnson et al. 2003; Stewart et al. 2012). As the stream gradient increases, stream power also increases. In alluvial systems, wood becomes increasingly important in pool formation and in the retention of sediments, particulate organic matter, and the inorganic bedload in streams (Wallace et al. 1995a; Roni et al. 2008).

Wood and wood jams also enhance habitat for fish by increasing the complexity of the stream environment, providing habitat for multiple life stages and species. This increase in habitat complexity can occur even when wood has no direct pool forming function (Berg et al. 1998; Flebbe 1999). The physical and visual isolation from competitors and predators that a complex tangle of wood provides may be as or more important in enhancing habitat for fish than pool formation (although these factors often go hand-in-hand). Numerous field studies have attributed increases in fish abundance associated with wood additions to increases in habitat complexity and visual isolation from predators and competitors that accompanies the increase in wood. In experimental channels the presence of even a single piece of wood has been found to dramatically reduce aggressive interactions among individuals and enhance growth of both dominant and subordinate individuals (Sundbaum and Naslund 1998). The potential for wood to create complex habitat that increases local fish abundance extends beyond small streams and salmonids fish (where most research on this topic has focused); wood additions to larger river systems increase habitat diversity at multiple spatial scales and have also been found to elevate local fish abundances (Pess et al. 2012).

3.2.1 Habitat Formation

The flow obstruction created by large wood is effective at increasing the range of physical habitat through diversification in flow depths, velocities, substrate size, and bed morphology. Large wood can transform an otherwise planar morphology reach with relatively uniform hydraulics into a reach where pool scour, sediment sorting, and bar formation can directly create new habitat; given the right conditions, large wood can transform stream morphology into more complex channel and floodplain features that provide reach-scale habitat enhancements.

Habitat consists of elements of the environment that affect the persistence and performance of a species in a specific location (Whittaker et al. 1973; Hall et al. 1997). The quality and quantity of habitat across the life history of the species shape biological performance in terms of abundance, persistence, and fitness (Southwood 1977). Habitats for species can overlap but are usually separated temporally, spatially, or in terms of function. For example, large wood can be an element of habitat for both juvenile salmonids and benthic insect life stages, but the nature of that habitat differs; wood generally provides cover for juvenile salmonids while it provides a substrate on which benthic insects move and feed.

The abundance and persistence of a species in an environment reflect the quality and quantity of habitat and food resources experienced along spatial-temporal pathways defined by the species' life history, as well as predation and competition. Habitat along the life history pathway consists of patches arrayed across space and time that are linked by the life history trajectory of the species (Fausch et al. 2002). In freshwater, these patches are often formed and maintained as a result of instream wood. Habitat patches are distributed across the riverscape, varying in quality and quantity, resulting in the heterogeneous distribution and performance of individuals and the population (Townsend 1989; Pickett and Rogers 1997).

Physical features of the stream that are perceived as habitat by biota form as the result of a hierarchy of controls, ranging from regional to watershed to reaches and channel units (Frissell et al. 1986; Montgomery and Buffington 1998). Large wood contributes to the formation and maintenance of habitat types and survival factors at reach and channel-unit scales. Formation of geomorphic channel units that constitute habitat for salmonid life stages is dependent on flow, channel form, riparian conditions, and structural elements, including large wood (Montgomery and Buffington 1998). Habitat controls operate at the reach or channel unit scale while in turn being constrained by the larger watershed context of controls that affect local environmental conditions.

It is important to view wood in the context of the entire life span experience of a species and conditions encountered across its life history.

Anadromous salmonids, for example, spend only a portion of their life history in freshwater, but the success of the population may be affected by spawning habitat and juvenile survival in streams, which are often closely tied to habitat conditions associated with large wood in streams. The biological value of restoration of large wood in streams depends on the bio-physical context and the array of factors across a range of environments that potentially affect the success of taxa of interest and their associated biological communities.

The ability of large wood to form habitat varies considerably with the specific characteristics of the channel type and of the wood pieces or jams themselves, including their size, position along the bank or within the channel, orientation to flow, and porosity. Some of the ways in which large wood influences physical habitat are discussed below.

3.2.1.1 Wetted Area of the Channel

Large wood creates bedform roughness (resistance to flow, or drag) that effectively slows flow down, consequently raising the water surface level. This may facilitate a hydraulic "backwater effect," whereby the water level immediately upstream of the obstruction is raised, which in turn raises the level of water upstream of it, resulting in an expanse of slower and higher water extending upstream from the obstruction. The backwater effect can result in higher water surface elevations along the banks and, in unconstrained reaches, enhanced floodplain connectivity with an increased volume of water spilling out onto the floodplain. The ability of large wood to alter water levels and influence habitat varies based on local conditions, including the volume of assembled wood and its size relative to channel morphology.

Though not uniform to all systems, research has shown that large wood in the channel has a small to insignificant effect on the duration or frequency of large flood events (approximately events greater than the 20-year flood) because much of the flood water is out on the floodplain. But large wood can increase the duration of smaller floods (i.e., 1 to 2-year events) where most of the flow is still contained within the channel (Rutherford et al. 2007). Large wood of a given size will have a greater effect on a small stream. Rutherford et al. (2007) report large wood generally will not affect small flood events when the projected area of the large wood is less than 10% of the area of the cross-section. The "projected" area is the area of the large wood in a two-dimensional cross-section perpendicular to the channel (direction of flow). A large wood structure needs to be very large to occupy 10% of the cross-section of a third order or higher stream.

3.2.1.2 Hydraulic Diversity

The presence of large wood will create highly three-dimensional flow patterns in surface waters including hydraulic refugia for fish (Daniels and Rhoads 2004). The hydraulics associated with a piece of wood or logjam will vary with the complexity of the wood structure's composition, including its size, position, and orientation to flow. The flow pattern associated with large wood jams is often analogous to the flow pattern encountered at bridge abutments and piers, depending on whether the structure is bank-attached or isolated in the channel. Unlike abutments or piers, however, wood structures typically have a level of porosity that has an important controlling influence on the flow field and the diversity of hydraulics generated (Manners et al. 2007).

The flow obstruction created by the wood creates steep hydraulic gradients in all dimensions where flow depths and velocities can rapidly change from a local maximum to zero over a short area. Pressure gradients created by the structure can generate downwelling, horseshoe vortices, separation zones, wake eddies, and levels of turbulent scour, nutrient mixing, and oxygenation that would not occur in channels with otherwise subcritical reach average conditions. The manner in which the wood structure influences flow also changes with discharge, creating variability in hydraulic patterns over the entirety of the hydrograph.

3.2.1.3 Substrate Composition

Overall, large wood can be quite effective at sorting sediment and channel substrate, creating a diversity in sediment texture available as habitat for aquatic life. Local areas of flow, convergence, and divergence are typically associated with large wood that results in spatially variable shear stress with corresponding variability in sediment texture. Fine sediment can be scoured away to expose coarser substrate suitable for spawning, while in other areas sediment deposition and a reduction in sediment texture can occur.

Research has shown that up to 60% of the total bankfull shear stress in a channel can be spent on form drag caused by large wood (Manga and Kirchner 2000). This means less shear stress is available for transporting sediment, and stream competence declines (Montgomery et al. 2003). Consequently, the median surface grain size of the bed near large wood can be up to 90% finer than what it would be in a wide, planar channel without large wood (Buffington and Montgomery 1999b). Large wood can be effective at promoting deposition of gravel in reaches otherwise too coarse or armored to provide spawning habitat for salmonids.

3.2.1.4 Channel Morphology

The shape and characteristic features of the stream channel (channel morphology) affect the quantity and quality of habitat for fish and other species. The ability of large wood to significantly alter channel morphology at the unit and reach scales is well-documented. Morphologic effects can range from a single rootwad partially embedded in a channel causing enough of a flow obstruction to scour a pool, to a large logjam capable of creating an island that bifurcates flow. Because large wood structures are often fixed in location for long periods, bedforms created are often stable features relative to ones not linked to flow obstructions that are more prone to migration, such as bar-pool morphology in a meandering channel.

CROSS-REFERENCE

Chapter 4, *Geomorphology and Hydrology Considerations*, provides an indepth examination of the ability of large wood to significantly alter channel morphology.

Large wood often creates and maintains pools important to the different life stages of aquatic organisms. Channels located in forested reaches (particularly in old growth forests) have significantly more pools per unit length than in unforested reaches. The specific pool spacing for a given wood frequency can be quite variable due to regional and site-specific differences in channel type and wood characteristics (Montgomery et al. 2003). Research has shown that as wood loading increases there is an increase in pool frequency that begins to level off at wood loadings of about 0.03 piece per square meter (Buffington and Montgomery 1999b; see Figure 4-14a).

Depending largely on its orientation and position above the bed, the type of obstruction formed by wood can create many different pool types, including plunge, underscour, eddy, and dammed pools (Montgomery et al. 2003). The importance of wood size and its ability to create deep pools is illustrated by research that shows the number of stream pools with residual depths >0.5 meter (1.6 feet) increases rapidly with riparian forest stand age, diminishing only after stands reach ages of more than 200 years (Rot et al. 2000; see Figure 4-13a).

Sediment bars typically form in conjunction with the pools created by large wood. Wood can act as a dam that impounds water and forces upstream sediment deposition, similar to the process of sedimentation in a reservoir behind a dam. Bar formation also occurs in flow separation and deposition areas downstream of the zone of flow convergence where pools are scoured. Flow acceleration at large wood accumulations can also create riffle habitats as part of the bar-unit complexes. Much like pool types associated with large wood, the type (e.g., bank-attached, mid-channel) and size of bar formed can be quite variable (*see Chapter 4*). Wood accumulations of sufficient size and stability can create a large enough flow obstruction with subsequent sediment deposition to create new bars or enlarge existing bars. Racking of additional woody material on jams formed at bar apexes can enlarge the jam and enhance its hydraulic influence and stability to a level where enough sediment accretion occurs to ultimately form vegetated channel islands that support new riparian habitat (Abbe and Montgomery 1996).

Large wood has the ability to not only create localized habitat unit features, but to also transform channel morphologic types. In low-order headwater streams, large wood can create step-pool morphology with plunging flow important for oxygenation, and trap enough sediment to develop an alluvial bed in what would otherwise be a bedrock channel. Likewise, large wood can form pool-riffle morphology in reaches that would otherwise be plane bed or bedrock (Montgomery et al. 2003). In fact, it can be rare to observe pools and bars in moderate-gradient (i.e., >0.01) cobble and gravel-bed forest channels not formed or influenced by wood (Montgomery et al. 2003).

3.2.1.5 Planform Change

Planform refers to the shape of the channel as viewed from above, including sinuosity, side channels, oxbows, and other features affecting the type and amount of habitat for species. The flow obstructions created by large wood accumulations can dramatically alter channel planform, increasing channel length and sinuosity. The obstruction created by a wood jam located in the low-flow channel will increase the sinuosity of the low-flow channel as flow is forced around the obstruction. Wood jams of sufficient size that occupy enough of the channel width to significantly constrict flow can deflect flow into the opposite bank and cause bank erosion and undercut bank habitat much the way a point-bar develops in association with outer cut-bank erosion. Strategic placement of multiple wood jams (often on alternating sides of the channel) can promote enough flow redirection, bank erosion, and channel migration to increase the overall channel morphology's sinuosity.

In forested channels, wood can be a primary driver in bifurcating or splitting flow, creating channel avulsions, and creating anabranching rivers that may otherwise be braided or single thread meandering channels (Collins et al. 2012; see Figure 4-8). Using channel bank length as a metric for edge habitat, it is apparent that an unconfined anabranching channel reach has significantly more habitat than incised and leveed reaches of the same river (*Chapter 4*). Large wood is also important for forming and sustaining side channels that can be wetted at low-flow or only during floods (Abbe 2000).

3.2.2 Aquatic Food Webs

A food chain is the linkage between primary resources (plants, detritus) and secondary consumers (e.g., insects and fish) (Pianka 1994). A network of linked food chains forms a *food web*, and stream food webs are among the most complex. Like most ecosystems, aquatic foodwebs begin with the capture of energy from the sun that is fixed by terrestrial and aquatic plants via photosynthesis. This energy is stored in the tissue of the plant where it is available to secondary consumers.

The food chain that supports fish and invertebrate production in streams is based on two photosynthetic energy sources: terrestrial organic matter (leaves, twigs, branches, and large wood) that enters streams from the riparian forest and upstream watershed (Cummins 1974), and algal production in the stream itself (Cummins et al. 1984). Leaves and woody material are largely composed of cellulose that is broken down and made available to other organism by bacteria and fungi (Webster and Benfield 1986). Leaves and detritus are rapidly colonized by bacteria and fungi that begin to break them down. Aquatic invertebrates like mayflies, stoneflies, midge larvae, and scuds (freshwater shrimp) shred leaves and feed on terrestrial detrital inputs. Much of the carbon they assimilate comes from aquatic bacteria and fungi colonizing the detritus rather than the detritus itself. Grazing invertebrates—commonly mayfly and chironomid nymphs—also feed on algae on stream rocks. These algal communities often occur as thin (almost invisible) algal layers on rock or wood, but they may support considerable grazer production because of high algal turnover rates (McNeely and Power 2007; Coe et al. 2009). These aquatic invertebrates (as well as terrestrial insects that fall onto the stream surface) are the primary food source for stream fishes like juvenile salmonids in headwater streams, although many fish feed directly on algae (e.g., stonerollers), detritus (suckers), or other fish (e.g., pike, bass, adult trout).

Production of algae depends largely on light and nutrient (i.e., nitrogen and phosphorous) availability in the stream. These are the two main "bottom-up" factors influencing stream primary production (in contrast to "top-down" effects of grazing invertebrates and fish). In forested headwaters light may be particularly limiting, with nutrient effects on primary production manifesting only after light limitation has been alleviated (Sabater et al. 2005; Bernhardt et al. 2007; Ambrose et al. 2004). In mid-order streams and streams with more limited riparian shading, nutrients are commonly the key factors limiting primary production. And in other systems the availability of stable substrates on which algae can grow may limit the potential production of algae in the stream. While instream wood often has limited direct influence on light or on nutrients, it can be a particularly important substrate on which algae can grow in sand-bed streams or in systems with unconsolidated streambed material. Wood addition can indirectly influence nutrients by changing water transport times, which changes the ability of microorganisms in the stream to remove and regenerate nutrients (Ensign and Doyle 2005). Also, the source of wood in streams can alter light availability in forested streams—either because wood is provided by riparian trees that are cut or pulled down and therefore create canopy gaps or because wood placement requires the removal of riparian vegetation around the placement areas in order to bring in logs from outside the system.

While production of algae depends on light and nutrient availability in stream water (e.g., nitrogen and phosphorous), production of invertebrates that feed on detritus (insect shredders, collector-gatherers, and filter-feeders) depends strongly on retention of detritus in the stream (Cummins 1974; Wallace et al. 1997). Deposition and storage of organic matter takes place in slow-moving backwaters, stream margins, above dammed pools (Wallace et al. 1995b), in openings between rocks, and on the downstream side of obstructions like boulders and large wood. Simplified stream channels with minimal structure tend to act as flumes that transport material downstream with limited local benefit. In contrast, the physical complexity associated with boulders and large wood greatly increases retention of organic detritus, and therefore populations of invertebrates that feed on it (Bilby 1981). Wood in particular can greatly enhance organic matter deposition by trapping fine branches and leaves to form debris dams that enhance invertebrate production (Wallace et al. 1997).

In streams with anadromous species such as salmon, an additional source of energy and nutrients is the carcasses of spawned adult fish.

This is particularly the case in systems with Pacific salmon die soon after their single spawning event (semelparity). Because salmon acquire most of their adult biomass during their ocean residency, salmon carcasses potentially supply many tons of marine-derived nutrients and biomass to otherwise nutrient poor systems (Cederholm et al. 1999; Wipfli et al. 2003) Large wood traps carcasses of spawning salmon, thereby preventing their export and retaining marine-derived nutrients in headwater reaches where it can increase local production of fish and other biota (Cederholm et al. 1999). Marine-derived nutrients have been found to enhance biofilm development, macro-invertebrate production, and overall stream productivity (Wipfli et al. 1998); and may be transferred to wildlife and terrestrial vegetation (Quinn et al. 2009), including even wine grapes (Merz and Moyle 2006). Large instream wood traps carcasses, allowing them to be processed locally by birds, insects, fish, bacteria, and fungi (Cederholm et al. 1999). Nutrients from salmon carcasses can also enhance decomposition of detritus, resulting in a synergistic effect of large wood to trap and hold both forms of organic input (Bretherton et al. 2011).

Atlantic salmon (*Salmo salarin*) in eastern North America and northern Europe may spawn multiple times (iteroparity); therefore, there is less mortality on spawning grounds than there is in Pacific salmon streams. However, transfer of nutrients and energy from marine to freshwater via Atlantic salmon carcasses has been demonstrated (Jonsson and Jonsson 2003; Williams et al. 2009), and it is reasonable to assume that trapping of Atlantic salmon carcasses by large wood could be important for enhancing nutrient transfer from marine to freshwater systems.

Wood also affects predator-prey dynamics. For example, large wood creates cover for prey and provides substrate for algae, microorganisms, and invertebrates. Wood also creates cover for predatory fish that eat invertebrates or other fish (Schenk et al. 2014). The multiple habitats affecting species interactions include backwater pools, side channels, and eddies, and have structural and hydraulic diversity near the stream margins (Naiman et al. 2002c). Sometimes changing the position or removing large wood will decrease the habitats in which predators and prey can hide. Research has found that the volume of large wood in streams can be associated with the density of fish populations (Murphy et al., 1986). Invertebrate predator biomass increases when there is large wood present in streams, and, in general, the invertebrate communities of predators are more productive per unit of biomass following the introduction of woody debris (Naiman et al. 2002c).

3.2.3 Biogeochemical Functions

Large wood plays a key role in nutrient cycling in streams (Bilby and Bisson 1998). In general, wood itself is a poor carbon source. The amount of nitrogen and phosphorous relative to carbon is low, and the lignin in wood is particularly difficult for many organisms to break down (Webster and Benfield 1986). In temperate ecosystems, few macroinvertebrates or fish eat wood directly, but there is a suite of microbes and fungi that break down wood, which, in turn, form food for benthic invertebrates and other biota (Webster and Benfield 1986; Findlay et al. 2002; Spanhoff and Cleven 2010). The stream macroinvertebrates that do eat wood tend to eat smaller particles and/or they ingest wood as a byproduct of feeding on microbial biofilms on wood surfaces (Johnson et al. 2003; Coe et al. 2009). The rate of wood decay by microbes and fungi varies by species. As a rule, trees with more nitrogen per unit of carbon (such as alders maples, and poplars) decay faster that those with lower nitrogen to carbon ratios (such as oaks, firs, and spruce) (Spanhoff and Meyer 2004). As a broad generalization, hardwoods decay faster than softwoods (Webster and Benfield 1986). Slower decay can influence wood persistence, which in turn influences wood function. In many eastern United States streams, for example, large wood from American chestnut (*Castanea dentata*) remains highly functional even though large chestnut trees have been essentially lost from eastern forests for over 80 years (Hedman et al. 1996). Nutrient availability in the stream also influences wood persistence; if nutrients are added to a system biological breakdown of the wood can occur much more rapidly (Spanhoff and Meyer 2004).

Large wood can enhance stream nutrient cycling in multiple ways. First, large wood retains leaf litter and fine particulate organic matter. The breakdown of this organic matter by microbes and fungi creates an elevated demand for nutrients, especially nitrogen and phosphorous. This elevated demand increases the rate at which nutrients are taken up from the water column and increases the retention of nutrients in the stream (Mulholland et al. 2009). Second, when channel-spanning wood and wood jams retain a combination of organic material and fine inorganic material they can create areas of saturated sediment behind and around the wood where oxygen can be locally depleted. Under these anaerobic conditions available nitrogen can be converted to nitrogen gas through a process referred to as *denitrification* (Steinhart et al. 2000). This conversion is highly variable across streams and across regions but it can be an important loss of nitrogen from these systems, especially in areas of the northeastern and Midwestern United States where excess nitrogen pollution is a particular concern. The creation of pools and the modification of stream flow that directs water into subsurface areas also leads to increased uptake and retention of nutrients (Ensign and Doyle 2005). Wood directly supports fungi and bacteria, and wood is often a surface on which algae grow in streams. Collectively the biofilm that lives on wood can be an important area for nutrient uptake as well (Sobota et al. 2007).

Studies removing instream wood have found variable effects on nitrogen processing. Webster et al. (2000) found that wood removal reduced nitrogen processing, while Warren et al. (2014) found that wood removal enhanced nitrogen processing. The authors of the latter study attributed their result to changes in substrate composition and algal production associated with the removal of sediment from rocks around and upstream of the dam. This conclusion was based in part on a study in northern Michigan sand-bed streams that found that modification of stream substrates by scour around added wood can enhance nutrient uptake by exposing stable substrates for algal growth (Holleine et al. 2007). These results highlight how the overall role of wood in stream nutrient dynamics will vary depending upon the physical characteristics of the system and how a given wood structure modifies those (i.e., does it expose via scour large stable substrates where algae can grow or does it cover them by enhancing sediment deposition around the dam?). Studies exploring empirical relationships between natural wood addition processes and phosphorous cycling (rather than experimental manipulations) have found significant associations between wood and phosphorous demand, suggesting that as wood loading increases the capacity of streams to process phosphorous also increases (Valett et al. 2002; Warren et al. 2007).

3.3 Hyporheic Zone

Much of our consideration and scientific study of streams focuses on the visible components of water, channel, wood, and biota. The hyporheic zone extends the river below what we see to include the “sponge” of saturated substrate where water can regularly exchange between surface and subsurface flows (Stanford and Ward 1993). The hyporheic zone is defined as the water-saturated sediment volume below the stream bed and adjacent stream banks where mixing between surface water and groundwater occurs (Bencala 2005). The hyporheic zone has several ecological functions and is the source of summer base flow in many systems. Depending on geological and soil conditions, the hyporheic zone may extend only a few centimeters or 30 meters (100 feet) or more into the adjacent floodplain (Hinkle et al. 2001; Boulton et al. 2010).

Although the hyporheic zone may be shallow, it can also be extensive because it extends from the uppermost headwaters through the lowermost reaches of rivers and into the estuarine zone (Krause et al. 2014). The hyporheic zone is a hydraulic feature but it is also a biological habitat for microbes, invertebrates, insect eggs and pupae, fish eggs, and fish embryos and is therefore a key consideration in the biological and ecological function of streams (Stanford and Ward 1995). In the hyporheic zone, surface water and solutes exchange into and out of the stream bed, having mixed with groundwater to varying extents. Numerous biogeochemical reactions occur in this zone, and it can influence mineralization, major ions, nutrients, and contaminants (Bencala 2005; Gandy and Jarvis 2006; Mulholland and Webster 2010; Krause et al. 2014). Hyporheic flow also has localized influences on stream temperature and dissolved oxygen.

The key ecological role of the hyporheic zone argues for its consideration in stream restoration and large wood placement projects (Hester and Gooseff 2010). Large wood can affect formation and maintenance of the hyporheic zone and the flux of water between the stream and the hyporheic zone, although the effect varies between streams of different geology. Lautz et al. (2006) showed that log dams in a semi-arid stream increased hyporheic interactions by slowing stream velocity, increasing flow complexity, and diverting water to the subsurface. Debris dams slowed water upstream causing localized fine sediment deposition so that sediments immediately downstream contained less fine sediment and had higher capacity to allow water through interstitial spaces of the substrate (Lautz et al. 2007). In a sand-bed flume the introduction of wood produced irregular bedforms, increased flow resistance, and increased vertical water flow across the streambed, which caused surface water to mix deeper into the hyporheic zone (Mutz et al. 2007). However, Stofleth et al. (2007) found that hyporheic storage was an insignificant percentage (less than 0.5%) of total hydraulic retention in sand-bed streams and that it did not increase with the addition of flow obstructions. Their findings suggest that hyporheic zone biogeochemical processing in these lowland streams may not be significant. Lautz and Fanelli (2008) found primarily anoxic zones in pools upstream of log restoration structures and oxic zones downstream in a turbulent riffle.

Hyporheic flow and the exchange with surface water are complex, and wood can enhance that complexity. Hester and Doyle (2008) investigated instream geomorphic structures such as debris dams and wood-associated steps. They found that hyporheic exchange flow was influenced most strongly by structure size, background groundwater discharge, and sediment hydraulic conductivity with lesser influences from geomorphic structure type, depth to bedrock, and channel slope. Debris dams can also exchange seasonal variations in hyporheic flow and associated nutrient processing within this section of the stream (Claussens et al. 2010). Sawyer et al. (2011, 2012) found downwelling water upstream, and upwelling water downstream, of channel-spanning logs with distinctive temperature effects. In a meadow stream Sawyer and Cardenas (2012) found that large wood addition increased hyporheic flow, and that hyporheic return flow locally stabilized stream water diel temperature fluctuations, although only at a local scale (creating refuge habitat rather than whole-stream effects on temperature). But they also found that the nature of hyporheic exchange could limit the influence of wood on flowpaths. The influence of wood on hyporheic exchange (as with assessments of biota) also warrants a long-term perspective. Wondzell et al. (2009), for example, investigated the responses of a small low-gradient stream to large wood removal. They found that hyporheic exchange flow declined in the first few years. Subsequently, however, the decline reversed as pool-riffle patterns developed and enhanced hyporheic exchange flow.

3.4 Regional Differences in Large Wood Ecology

The biological and physical roles of large wood in streams discussed above apply generally to a wide range of geographies and stream types. However, there are important regional differences in wood effects based on differences in geology, climate, and species. Large wood provides different ecological functions in steep gradient and gravel-bed streams typical of the western United States than in low-gradient, sand-bed rivers more typical of the southern United States. Similarly, wood may also provide different ecological functions for warmwater versus coldwater fish communities. Effective application of large wood restoration means understanding the diverse and context-specific functions of large wood across diverse landscapes.

3.4.1 Western United States

The majority of research on stream wood and wood additions has been conducted in the Pacific Northwest of North America. Large wood plays a dominant role in the physical and biological nature of streams of western North America (Bilby and Bisson 1998). In particular, wood provides habitat characteristics that are beneficial to multiple life stages of anadromous and non-anadromous salmonids. As a result, the addition of wood is the predominant habitat restoration action undertaken by federal, state, tribal, and local agencies and stewardship groups intent on enhancing these species in particular (Roni et al. 2014a). Western streams typically have a relatively high gradient and ample alluvium, and, west of the Cascade Range, high precipitation with dense forests. In these streams, wood creates pools and steps, traps sediment and organic debris, and provides cover and protection from predators.

Wood in this region plays an important role in creating and enhancing habitat for salmonids in particular. A number of studies have documented benefits of wood additions for juvenile coho salmon (*Oncorhynchus kisutch*) and juvenile Chinook salmon (*Oncorhynchus tshawytscha*), which may rear in streams for one to two years before migrating to the ocean or estuary to grow and mature (see reviews by (Smokorowski and Pratt 2007; Roni et al. 2008; and Nagayama and Nakamura 2010). Benefits to fish were largely associated with increasing pool habitat or habitat complexity overall (as noted above and elsewhere in this manual). Stream wood in the Pacific Northwest is often quite large because the region has retained a good deal of its old-growth forest relative to other regions of the country. In addition, climate conditions in the coastal and western Cascade mountain ranges are such that tree productivity is often quite high, which leads to relatively rapid development of larger trees. Although a good deal of old-growth forest remains in the Pacific Northwest compared with other regions of the country, much of the region has undergone (and continues to undergo) extensive forest management. Early forest management often used splash dams to move wood downstream. These dams scoured away not only wood but also much of the stream substrate. Wood addition in these areas functions not only to enhance pools and increase habitat complexity, but it is also added in many cases to help promote channel aggradation and the development of spawning habitat for anadromous salmon.

Anadromous salmon are key species in many western streams. They are not only a dominant fish species for management, but, as discussed previously, they also have a key ecological role and provide an important nutrient subsidy to the aquatic ecosystems in which they spawn (Bilby et al. 1998; Stockner 2003; Wipfli and Baxter 2010). Large wood retains salmonid carcasses so that they can be processed locally rather than flushed downstream. In the absence of wood, carcasses may be flushed from a system during high flow, thereby removing the nutrient and carbon subsidies that they provide. Wood is instrumental in keeping carcasses in a stream and thereby maintaining their subsidy function in the ecosystem.

3.4.2 Northeastern United States

In the northeastern United States and uplands of the mid-Atlantic region, studies evaluating wood function have been more variable. Wood can be an important explanatory factor in accounting for variability in stream trout abundance (Kratzer and Warren 2013). When wood was assessed as a habitat feature in Appalachian mountain streams, its use was disproportionate to its availability (Flebbe 1999). However, other studies have found mixed results in assessing the influence of wood jams and large wood structures on stream salmonids in the northeastern United States (Warren and Kraft 2003; Thompson 2006), especially when long-term processes are considered (Warren and Kraft 2002). The variable function of wood in these systems may be attributed in part to the forest management history of this region (Williams et al. 2009). Unlike in the Pacific Northwest, very few areas of old-growth forest remain in the northeastern United States, especially near streams. The large wood in northeastern streams is therefore generally smaller than in other regions. The amount of wood exceeding 30 centimeters (12 inches) in diameter ("large logs") has been tied to stream pool habitat in this region, but wood volume using a smaller size threshold (10–centimeter [4-inch] diameter) has not (Keeton et al. 2007). Assessments of historic wood addition structures by Thompson (2006) found little evidence for a long-term positive effect on habitat—attributed to a limited long-term geomorphic effect. Wood was likely to have been more important in this region in the past when larger trees were adding larger wood. When remnant old-growth forests do remain along streams in the northeastern and central Appalachian mountain regions, wood size and total wood volumes can rival those in old-growth forests from other regions (Keeton et al. 2007; Warren et al. 2009).

Stream wood and wood jams are important in these mountain ecosystems in carbon retention, and a good deal of the early and classic work on the importance of particulate organic matter retained by wood has been conducted in these streams (Fisher and Likens 1972; Bilby 1981; Wallace et al. 1997)

Atlantic salmon have been largely extirpated from the rivers and streams in the northeastern United States where they were historically abundant. Based on work in the Pacific Northwest, wood and wood accumulations were likely to have been important in carcass retention functions for Atlantic salmon and other anadromous stream species in these regions. Although Atlantic salmon are often capable of repeat spawning, stress associated with spawning migration can elevate mortality rates.

3.4.3 Midwestern and Southeastern United States

In the Midwest, stream gradients are lower across much of the region. In addition to its function in creating pools and enhancing habitat complexity, wood also plays a key role as a stable substrate in many low-gradient streams that dominate the coastal plains of the southeast and regions across the Midwest (Smock et al. 1989; Stewart et al. 2012).

Many of the streams in the Midwest and southeast drain relatively low-gradient landscapes and harbor largely warmwater fish communities. The historic reference condition and function of large wood in low-gradient and warmwater streams is generally less well documented here than in higher gradient systems in the northeast and northwest, but tends to indicate a lesser control by wood over channel structure and bedform in very low-gradient streams than in gravel-bed channels (Wohl and Merritts 2007; Walter and Merritts 2008). Sand-bed rivers of the southeastern United States contrast strongly with gravel-bed rivers of the Pacific Northwest; however, large wood in sand-bed rivers was found to be significant as both structure for fish and as a relatively rare stable substrate in a sand-bed environment. Benke et al. (1985) found that filter-feeding invertebrates like caddisfly (Trichoptera spp.) and blackfly (Simuliidae spp.) larvae only occurred on stable substrate and were consequently severely habitat limited, achieving their highest densities on large wood ("snags"); although large wood only accounted for 6% of substrate by area, it accounted for 50% of invertebrate biomass, highlighting the importance of large wood on the productive capacity of sand-bed rivers, above and beyond its role in providing cover for fish.

3.4.4 Mountain West and Southwestern United States

In the Mountain West, the frequency of fires is higher than in the northeastern, midwestern, or Pacific Northwest regions of the country. Wood loading occurs as a result of individual mortality of trees but is also often the result of these large disturbance events. (Richmond and Fausch 1995). Much of the research on wood function and biota in western systems has focused on fish (Schmetterling and Pierce 1999; O'Connor and Rahel 2009; White et al. 2011). One of the longest running assessments of stream wood addition was done in a system in Colorado, where Gowan and Faush (1996) added channel-spanning wood to a series of headwater streams. They assessed the abundance of fish before wood addition and up to 6 years afterward and found significant increases in fish abundance. This work was then followed up by White et al. 2011, who found that the effects of wood loading on fish persisted. Fish abundance at the treatment sites remained well above those in the reference sites 20 years after wood addition. Wood is also important in mountainous regions of the southwestern United States. Wood in these systems functions to create and enhance habitat and as in other regions it can be important for litter retention in streams (Trotter 1990).

3.5 Considering the Need for Wood Placement

When restoration of wood in streams is undertaken to achieve a biological goal, the focus is frequently an increase in the abundance of desired fish species. For instream wood restoration to be effective in achieving this goal, wood, habitat diversity, and cover should be identified as limiting factors for fish and their associated biological communities. An intuitive (if not always practical) measure of success of stream restoration programs in this context is generally a clear and persistent increase in the abundance of desired species over time.

Decisions to invest in restoration of large wood (or indeed any environmental attribute) need to be based on clear assessment of factors limiting a desired species or process. Restoration of large wood at specific sites can have limited biological value if other factors are more limiting at a watershed scale (Nagayama and Nakamura 2010). The factors that limit population productivity need to be understood, at least in a qualitative sense, before designing a restoration project. A number of models are discussed in Section 3.5.2, *Linking Habitat to Fish Population Dynamics*, which can assist in the assessment of needs for wood enhancement relative to other possible limiting factors.

Habitat factors that limit fish production are often described as "bottlenecks" that constrain particular life stages in specific locations (Kennedy et al. 2008). Habitat bottlenecks and limiting factors operate hierarchically. Factors such as temperature operate at watershed or sub-watershed scales and exercise a pervasive impact on growth and survival of biota, while factors such as large wood operate at more localized scales. Consideration of this hierarchy is key to understanding the potential effectiveness of restoration measures, many of which are designed in response to localized conditions that are controlled by larger scale factors.

Water quality parameters represent systemic factors that control the effectiveness of restoration efforts. For example, if stream pH or water temperatures are marginal or unfavorable for a target fish species (i.e., too high or too low for salmonids), then investing in restoration actions may be unwise until the systemic issues are addressed. Similarly, extremely high nutrient loads leading to high levels of primary production and nuisance algal species (eutrophication) and low oxygen could also limit the target species, and may need to be addressed before large wood can effectively enhance habitat.

If water quality in a stream is within the optimal range for a target species, then availability of suitable habitat, including refuges from predation and high flow events, may become the dominant factors limiting population size (Breau et al. 2011; Reeves et al. 1989; Nickleson and Lawson 1998). Limiting bottlenecks will be present when habitat limitation only affects particular life history stages. For instance, lack of adequate spawning habitat may prevent sufficient egg production to saturate available rearing habitat, resulting in juvenile rearing habitat that is under-seeded (below capacity).

Very low densities of juveniles, despite abundant suitable rearing habitat, can be used as a diagnostic to infer spawning habitat (i.e., recruitment) limitation; similarly, very high densities of juveniles with a scarcity of larger subadults and adults may indicate juvenile rearing habitat limitation, even if there is abundant suitable adult habitat (Armstrong and Nislow 2006; Rosenfeld 2014). However, inferences with respect to habitat limitation should be made with care because factors unrelated to habitat—such as low marine survival of adult salmon, leading to low spawner returns—can also lead to under recruitment (low egg deposition and juvenile density), even when spawning habitat is abundant and not limiting the population.

In general, restoration that does not directly address the factors limiting the growth, abundance, or survival of fish will be ineffective in meeting management goals geared toward increasing the overall target fish population. For this reason, management interventions that increase available habitat for multiple life history stages are ideal, particularly if there is uncertainty concerning which life stage is most limiting. This is one of the advantages of large wood addition because the creation of complexity usually increases overall habitat diversity for multiple life stages. For instance, carefully planned large wood additions could enhance spawning habitat by trapping gravel wedges above, or depositing gravel bars below, engineered jams, while simultaneously increasing the availability of low velocity marginal juvenile rearing and overwintering habitat, creating deeper scour holes for larger fish, and increasing organic matter retention that may also benefit overall prey production. Nevertheless, limiting habitat factors should still be assessed to the extent possible because creation of one type of habitat may result in reduced abundance of another habitat type that could negatively impact species with contrasting habitat requirements. For instance, if riffle habitat is very limited, riffle-dependent species could be negatively impacted by back-flooding from large wood jams or other restoration structures, potentially reducing the availability of scarce riffle habitat and any species dependent on it.

Distinguishing between the effects of restoration on habitat *quantity* and *quality* is useful for understanding population responses to habitat change. As discussed in the following section, these habitat measures are related respectively to the biological capacity and productivity of fish populations. Restoration can increase the number of fish by either increasing the *area* of available habitat for a limiting life stage, or by improving the *quality* of available habitat, so that fish will experience higher growth and survival and more will recruit to the next age class.

If a management intervention such as large wood restoration does not increase either the area of habitat limiting a life stage or the habitat quality for a key life stage (leading to better growth and survival), then there will be no population response. In principle, population responses to restoration should be greatest when habitats are present in an optimal ratio where no single habitat becomes a severely limiting bottleneck (Reeves et al. 1989; Rosenfeld 2014). Although the diversity of habitats associated with large wood restoration often has the capacity to help minimize habitat bottlenecks, there are some geomorphic contexts where large wood may not be the most effective restoration intervention (e.g., steep colluvial boulder channels where wood has minimal impact on channel structure).

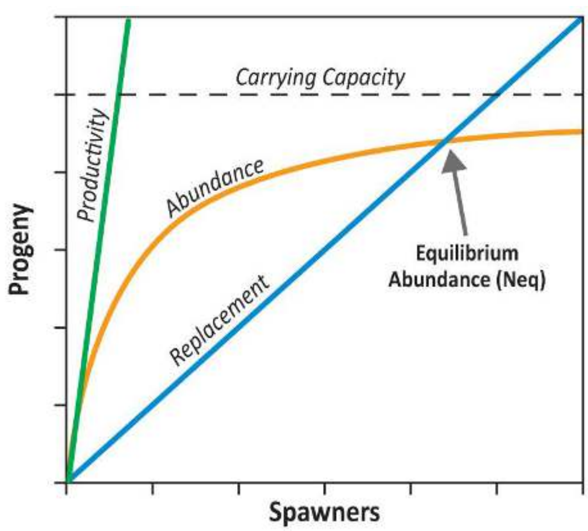
3.5.1 Fish Population Dynamics and Instream Wood

Fluvial environments are a mosaic of channel units with differing conditions that are perceived in unique ways by species and life stages as habitat patches of varying quality area (Winemiller et al. 2010). As discussed above, large wood can play an important role in determining the array of habitat patches across the riverscape. Connectivity between habitat patches in time and space allows a species to complete its life history. Habitat quality, quantity, and connectivity are reflected in the survival and abundance of fish at life stage and population scales (Schlosser and Angermeier 1995; Hayes et al. 1996). Sustained production by a species requires a network of complex and interconnected habitat patches spanning the species' life history (Williams 2006).

The quality of habitat in each patch and competition for limited resources result in an overall survival that reflects both *density-independent* and *density-dependent* survival factors. Density-independent factors refer to attributes, such as temperature, that affect survival regardless of fish abundance (notwithstanding the relationship between pathogens, temperature, and fish density in disease outbreaks). Other survival factors, like food and cover, are consumable and in limited supply, and their per capita availability declines as density increases. The area of habitat and food availability determine the capacity of the environment to sustain a given species (Chapman 1966). As density increases, density-dependent factors limit survival and/or growth, and abundance approaches carrying capacity of a species in a particular habitat (Hayes et al. 1996). Carrying capacity is linked to survival because it relates to the quantity of available resources such as food and space that place an upper bound on density of a life stage in any particular environment (Chapman 1966).

For salmon and other fish, the population dynamics of density dependence are often depicted by stock-recruitment relationships (Hilborn and Walters 1992). There are several forms of these functions, but all portray the relationship between the number of spawners (stock) and resulting progeny (recruits). Figure 3-1 shows the stock-recruitment relationship developed by Beverton and Holt (1957) that is commonly used in salmonid fisheries management. Because of it tractable mathematics, the Beverton-Holt relationship is used in many of the models that relate habitat to potential fish production. The relationship has two parameters: *productivity* or survival (progeny/spawner), at low abundances where density effects are absent, and *carrying capacity*, the maximum abundance of the species possible given the available habitat; density-dependent effects typically limit populations as they approach habitat carrying capacity. Productivity and capacity can be related to the quality and quantity of habitat, respectively (Reisenbichler 1989; Hayes et al. 1996). The diagonal line in Figure 3-1 is the replacement line where the number of spawners equals the number of progeny (productivity = 1.0). At abundances greater than replacement, the population will increase, while it will decrease when abundance falls below replacement. As long as the productivity is greater than 1.0 (replacement), the population abundance will increase, although at a declining rate due to density-dependent survival factors (e.g., increased competition for food and space) that are in limited supply (Figure 3-1). Under steady-state conditions, the abundance of a fish population will equilibrate where the ratio between spawners and progeny is one designated Neq in Figure 3-1. Neq is calculated from the productivity and carrying capacity and thus serves as a useful summary metric of the population response to both habitat quality (productivity) and habitat quantity (capacity).

Figure 3-1. Features of a Beverton-Holt Production Function



Productivity is the density-independent survival, which, along with density-dependent factors of the environment, determines abundance limited by the total capacity of the environment. Replacement is the minimum number of spawners required to maintain a given abundance. Under steady-state environmental conditions, the population abundance equilibrates at Neq, the point where abundance crosses the replacement line.

3.5.2 Linking Habitat to Fish Population Dynamics

Analytical models provide managers the ability to link characteristics of the environment to fish population dynamics in order to assess limiting factors and evaluate alternative restoration strategies. Models serve a role in planning by helping managers address issues such as identifying factors currently limiting species and populations of concern, determining whether restoration of large wood is likely to address these factors, understanding how other factors may augment or limit the value of large wood restoration and quantifying reasonable expectations of the biological benefits of restoring wood. Models can thus help managers invest restoration dollars wisely to meet management objectives. Models also have a key role in adaptive management where they can generate testable hypotheses and synthesize information from monitoring and research programs. However, models are never a substitute for monitoring, assessment, and research and, to be effective, the limitations of each model need to be understood by practitioners and users of model results. Models can structure information from monitoring programs, restoration assessments, and research in a form that is useful to managers and funding agencies and can increase the value added from assessment and monitoring programs. By providing an explicit, logical framework that incorporates available data and knowledge, models can provide accountability for restoration priorities and funding decisions.

Roni et al. (2014b) conclude from their review of the effectiveness of stream restoration actions that models can "help to set realistic expectations for restoration outcomes and help managers choose among alternative restoration scenarios." A key factor in the successful application of models to assess habitat restoration needs is to understand the model's purpose, limitations, and data requirements. The value of the results generated by a model reflects the quality of the data used in the model and the validity of its underlying relationships. To be effective, models need to be continually tested against empirical and experimental data to provide an adaptive platform to guide restoration based on the available science (Boisclair 2001).

In the context of planning and prioritizing habitat restoration actions, including the addition of large wood, the role of models is to evaluate factors potentially limiting fish production in the candidate restoration stream for various stages in a species' life history. For example, observers might examine a portion of stream and conclude that it lacks large wood and recommend investments in large wood structures and other measures with the expectation of improving habitat for salmon or other species. Evaluation of the effects of the action in the context of the entire watershed and species' life history within a modeling framework, however, might indicate that the biological value of investments in large wood would be limited because of other limiting factors such as downstream fish passage impediments, high temperature, or other limiting factors. In this case, the value of the model is to identify factors limiting the population, and suggest the appropriate order for restoration actions based on the available science and conditions within the system.

Habitat models create a set of working hypotheses for limiting physical and biological elements of the environment that can form a basis for evaluation of habitat hypotheses and management actions. Research and monitoring programs test the fundamental assumptions in the models and reflect changes in habitat conditions over time, leading to a refined basis for making decisions regarding investments in restoration of large wood or other measures.

GUIDELINES

Objectives of Species-Habitat Models

1. Formalize our current understanding of the habitat requirements of a species.
2 Understand how environmental factors affect the distribution and abundance of a species.
3. Predict further distributions of a species.
4. Identify weaknesses in our understanding.
5. Generate hypotheses about the species. (Morrison et al. 1998)

Species-habitat models are usually not characterized as statistical models in the sense of a regression model that attempts to find the most parsimonious relationship between variables with no necessary mechanistic relationship (Hilborn and Mangel 1997). Instead, species-habitat models are often mechanistic and reflect a hypothesis concerning attributes of potential importance to fish production based on the available literature ("scientific model" in the sense of Hilborn and Mangel 1997). For instance, these types of models may include relationships between fish abundance (density) and habitat type, or relationships between growth or survival and habitat type (Rosenfeld and Boss 2001; Railsback et al. 2003; Rosenfeld 2003). They can be deterministic or include statistical confidence in attributes and relationships. Models differ in regard to the complexity of hypotheses they can create and their ability to compare restoration alternatives in biologically meaningful terms. However, the reliability of model predictions is only as good as the field data and knowledge that were used to build them, and users should carefully consider potential biases when applying them to different stream or river systems. Several types of species-habitat model are discussed below with application to evaluating restoration measures, including the addition of large wood.

3.5.2.1 Habitat Association Models

The most basic habitat models are based on observed differences in fish density among different habitat types (Nickelson et al. 1993; Rosenfeld 2003), or simple relationships between fish abundance and total habitat area (Sharma et al. 2005; Rosenfeld and Hatfield 2006). For instance, the potential increase in coho smolt production associated with construction of side-channel habitat can be estimated based on average coho smolt production from side-channel habitat reported in the primary literature (i.e., 0.37 smolt m^{-2}) (Roni et al. 2010), if there is confidence that recruitment of juvenile coho is not limited at an earlier stage (i.e., that side-channel habitat is at capacity). Similarly, an average smolt production of 0.39 smolts m^{-2} from pool habitat (Sharma et al. 2005) can be used to estimate the effects of increasing pool habitat through large wood or other restoration. This approach, however, does not take into account the larger context of limiting factors that may affect the value of restoration and must be tempered by recognition of the limitations and uncertainties associated with extrapolating abundance or production estimates from one stream to another. While such estimates based on simple areal production are not a substitute for full assessment of restoration needs, they may be appropriate for basic assessment or project planning.

Habitat suitability models are an additional class of model that have been used to assess habitat conditions for many species, especially wildlife, although models have been developed for fish as well. These models provide flexibility and can range from simple tools for collecting expert knowledge (Railsback and Kadvany 2008) to complex depictions of species distribution across the landscape (Boyce and McDonald 1999; Manly 2002). The Habitat Evaluation Procedure (HEP) is a widely used habitat suitability procedure developed by the U.S. Fish and Wildlife Service to "quantify the impacts of changes made through land and water development projects" (Stiehl 1998). Typically, these models start with development of a habitat suitability index (HSI). This is a dimensionless index of habitat suitability from 0 (entirely unsuitable) to 1 (ideal habitat condition) for life stages or species. Suitability relationships are developed for species occurrence and habitat conditions; for example, the abundance of large wood and the density of coho fry (McMahon 1983). Suitability relationships may be developed for multiple suitability attributes believed to be important to species occurrence and performance and then integrated to create a suitability model that is applied to data for a particular location or scenario. Suitability attributes are analogous to the survival factors of habitat discussed above and relate to habitat quality, growth and survival experienced in different habitats. The quantity of habitat is assessed as Habitat Units.

GUIDELINES

Objectives of Species-Habitat Models

Habitat units are the area of habitat types (e.g., pools or riffles) adjusted for habitat preference (e.g., pools have high preference for coho fry in summer but low preference for coho spawning) and by the suitability of that habitat indexed by the HSI. Habitat Units are thus the quantity (acres or square meters) of habitat adjusted for species preference and suitability.

Like all models, habitat suitability models need to be used with caution because territoriality and other factors can cause habitat selection to generate misleading indices of habitat quality (Van Horne 1983; Garshelis 2000).

The Instream Flow Incremental Methodology (IFIM) uses habitat suitability relationships to assess the effects of incremental changes in discharge on habitat availability (Jowett et al. 2008). IFIM is a set of procedures developed to examine the impacts of alternative flow regulations in streams (Bovee et al. 1998). IFIM typically combines a hydraulic model, like the Physical Habitat Simulation Model (PHABSIM) that predicts changes in velocity and depth with increasing discharge, with a biological model that predicts how habitat quality changes with altered depths and velocities. The biological models are usually habitat suitability curves for velocity, depth, and substrate that rate habitat quality for the target species between 0 and 1 for a range of velocities and depths (equivalent to the HSIs described above). The result of IFIM is an estimation of the amount of available habitat in a stream for a target fish species, expressed as the product of area and habitat suitability termed the Weighted Useable Area (WUA). WUA is analogous to the Habitat Units in HEP. Habitat suitability curves can be generated for different life stages of the target species, allowing assessment of how available habitat changes with discharge for different taxa or life history stages. Similarly, flow can be held constant, and PHABSIM or other hydraulic models can be used for predicting the effects of altered channel structure, such as that associated with restoration, on habitat suitability and availability. Although IFIM and PHABSIM are widely used, they do have limitations and potential biases that must be recognized (Mathur et al. 1985; Rosenfeld and Ptolemy 2012).

3.5.2.2 Habitat Capacity Models

Reeves et al. (1989) developed a knowledge-based key that identifies potential physical limitations on streams and the carrying capacity of the stream for coho salmon. This dichotomous key assists managers in identifying factors limiting coho abundance and capacity and evaluates the need for habitat restoration or augmentation to optimize coho production. The key uses gradient, summer water temperature, and area of key habitat in a stream to identify which life stage habitat limits coho abundance. The procedure is not spatially explicit and analyzes an entire stream or defined area of management interest.

Nickelson et al. (1993) expanded on the key of Reeves et al. (1989) through development of an analytical technique to calculate coho carrying capacity in Oregon streams. They associated the quantity of different stream habitat types with knowledge of life stage habitat needs to calculate the habitat type and season limiting the capacity of the stream for coho production. The habitat bottleneck for a species is identified as the life stage habitat in shortest supply relative to habitat for other life stages. The habitat bottleneck therefore constrains overall production of the species in the environment. Nickelson and Lawson (1998) combined their habitat-based model with fish population modeling to examine the impacts of habitat change on population viability and extinction probabilities of Oregon coho.

Cramer and Ackerman (2009) developed the Unit Characteristic Method to assess limiting factors for steelhead based on life stage carrying capacity. Their method includes consideration of food, addressed as primary productivity, based on alkalinity and turbidity. Alkalinity can be used as a general indicator of stream productivity (Ptolemy 1993) and has been used in other models to address food availability, including the Ecosystem Diagnosis and Treatment model discussed below.

3.5.2.3 Life Cycle Habitat Models

Life cycle models mechanistically link life stages such that fish are moved from one life stage to the next based on life history. Movement between life stages reflects limitations on productivity and capacity using the features of stock recruitment. The Beverton-Holt function (Figure 3-1) is frequently used because of its tractable mathematics, its ability to be disaggregated into life stage functions (Moussalli and Hilborn 1986), and the ability to relate habitat attributes to the productivity and capacity parameters of stock-recruit functions (Bradford et al. 2005; Sharma et al. 2005). Productivity and capacity can be input as values to life cycle models based on hypotheses, empirical measurements, or other models. Productivity and capacity can also be related to quality and quantity of habitat (Hayes et al. 1996), making it possible to model changes in fish populations due to habitat conditions or changes in habitat. Life cycle habitat models discussed here evaluate potential fish performance as a function of habitat in terms of population productivity, capacity, and abundance, which are parameters of the Viable Salmonid Population (VSP) concept (McElhany et al. 2000) used to characterize salmonid populations under the federal Endangered Species Act.

The SHIRAZ model (Scheuerell et al. 2006) is an example of a time series salmonid habitat model. SHIRAZ uses a set of relationships between environmental attributes (temperature, flow, sediment, and habitat area) and productivity and capacity of eggs and fry to evaluate habitat quality at the reach-scale; productivity and capacity for other life stages are input as empirical values derived from the literature (e.g., Bartz et al. 2006), expert hypotheses, or observations. Input to the model is reach-level environmental conditions (temperature, habitat, etc.). SHIRAZ has been used to evaluate habitat restoration alternatives and potential population responses to restoration (Battin et al. 2007). Stochasticity is included in the model by assigning statistical distributions to parameters or by randomly assigning parameter values across model simulations (Monte Carlo approach). The model evaluates potential fish performance over time based on a historic or simulated time series of annual input parameters for flow, temperature, and channel structure.

The Ecosystem Diagnosis and Treatment (EDT) is a population equilibrium model that is commonly used in the Columbia River Basin, Puget Sound, and the California Central Valley to identify habitat-limiting factors and develop restoration strategies (Blair et al. 2009). The mechanism of EDT is the derivation of the population parameters of the Beverton-Holt relationship (Moussalli and Hilborn 1986) as a function of habitat at reach and life stage scales. These life stage estimates of productivity and capacity are integrated across the life history to estimate population-level performance. Input to the model is a reach-scale description of environmental conditions (e.g., temperature, habitat types, and large wood) that is evaluated as habitat for salmonid taxa and life stages using the VSP metrics. The model assesses the potential diversity in fish production by evaluating habitat along thousands of spatial-temporal pathways across the riverscape. Potential fish production along each pathway is estimated and then integrated at the population level; variation in performance across the pathways reflects variation in the environment and the potential life history response of the population. EDT is frequently used in a diagnostic mode to evaluate limiting factors at attribute, reach, and life stage scales. To do this the model compares fish performance under a modeled condition (e.g., the current condition) to performance under a reference condition that could represent historic or future conditions (Lichatowich et al. 1995). The result is a "blue print" for restoration actions and priorities.

There are three general limitations of all habitat models discussed here. First, they are restricted by the availability of life stage-survival relationships for particular taxa and life stages, which may be lacking for important species. This limitation applies to habitat suitability curves used in HEP and IFIM as well as species-habitat relationships used in SHIRAZ and EDT. Second, habitat rating models require information on environmental conditions at a relatively fine scale, such as stream reaches.

Such information is also often lacking (Pess et al. 2002). When suitable fine-scale empirical data on habitat conditions are not available, extrapolations from other areas are made or information is derived from other models. Increasingly, GIS, remote sensing, and other techniques are being used to describe environmental conditions and can be used to parameterize habitat models (e.g., Benda et al. 2007) While, on the one hand, the ability to incorporate a wide range of information is a strength of these models, on the other hand the robustness of the conclusions must be tempered by the uncertainty of input information. Third, habitat rating models are notoriously difficult to validate (Morrison et al. 1998). Habitat suitability relationships used in HEP and IFIM are dimensionless indices reflecting habitat preferences that cannot be measured in the field. Life cycle habitat models such as SHIRAZ and EDT evaluate habitat using the VSP parameters of productivity, abundance, and biological diversity. These are intuitively attractive measures of fish performance that are routinely used in fisheries management but are difficult to measure except in situations where a long series of fish life stage abundance can be generated. Even when such data are available, the VSP parameters are also typically highly variable and reflect variation in survival conditions in the ocean as well as freshwater, and change in a VSP parameter is difficult to ascribe to specific habitat changes (McElhany et al. 2000). While the overall output parameters are difficult to test, the individual components of habitat models, such as the relationship between large wood and fry survival, can and should be tested through evaluation and monitoring programs. Long-term data sets of biomass or production can also form the basis for model validation by comparing model predictions to observed fish abundance and production (e.g., Beecher et al. 2010). Consequently, the effectiveness of conclusions based on habitat models regarding limiting factors and restoration priorities can be evaluated using data collected through assessment programs. Testing of the model components and their predictions should lead to a refinement of the tools over time. This creates a working hypothesis that can guide development of restoration priorities and optimize investment based on the information available. In this way a model becomes a vehicle for navigating restoration through uncertainty and change.

3.5.3 Fish Assemblages and Large Wood

Fish assemblage responses to wood as habitat is evident across the range of ecological regions in the United States. The response of fluvial fish assemblages to wood as habitat, based on the mesohabitat and microhabitat functions outlined above, can be judged in two main ways. First, the fish assemblage in a reach can be compared before and after either wood addition or wood removal, preferably with appropriate control reaches without these treatments, in order to control large-scale variability (e.g., strong year classes for spawning fish at the basin-wide scale). Although there were nearly 1,200 published studies on the functions and dynamics of wood in rivers in the twentieth century (Gregory 2003, as cited by Nagayama and Nakamura 2010), relatively few published studies have dealt with fish assemblage responses to stream rehabilitation involving wood installation. Nagayama and Nakamura (2010) conducted a comprehensive literature search and found 14 published studies involving projects in fluvial habitats in the United States. Six of these studies occurred in the Marine West Coast Forest ecological region, and three each occurred in the Northwestern Forested Mountains and Eastern Temperate Forests ecological regions. Salmonids were the focal species in 11 of the studies, with other fishes being examined in six of the studies (including three at the level of the assemblage). In general, these studies showed positive changes in focal fish abundance following rehabilitation at various scales.

In contrast, removal of large wood from streams has been shown to have negative effects on fish assemblages. In a meta-analysis of riparian logging and wood removal from 37 studies (primarily in the Marine West Coast Forest and Northwestern Forested Mountains ecological regions), Mellina and Hinch (2009) found that thorough removal of instream large wood following logging generally gave negative responses in salmonid density and biomass.

The second means of assessing the response of fish assemblages to wood as habitat is to compare the assemblages in different areas (e.g., reaches of the same river) based on the extent (quality/quantity) of wood. In Ozark headwater streams (Great Plains ecological region), Mitchell et al. (2012) found that large wood volume was uncorrelated with overall fish abundance, biomass, or functional feeding guilds, but also found that creek chub and southern redbelly dace had higher biomass with greater debris accumulation (as might be facilitated by wood).

3.5.4 Wood as Habitat for Aquatic Invertebrates and Terrestrial Species

Aquatic invertebrates are very important in processing wood debris in forested streams and are key components of aquatic food webs. Large wood in streams provides a physical habitat for all parts of the food web, from bacteria to invertebrates to fish species (Cummins et al. 1984). The more complex the woody surface, the greater the resource availability and associated invertebrate species richness (Treadwell et al. 2007). If logs have holes, hollows, or branches, there are several shapes and sizes of habitats that can be formed (Phillips 2003). Wood is especially influential in sand-bed rivers, where it provides a stable substrate for important benthic invertebrate species (Benke et al. 1985; Phillips 2003; Smock et al. 1989). In sand-bed streams, wood also creates geomorphic complexity and structure and enhances vertical mixing of water (Mutz et al. 2007). Researchers also find that removing logs and branches in rivers can decrease invertebrate density, richness, and biodiversity (Benke et al. 1985).

Invertebrates are key prey for fish in streams and, by consuming biofilms and periphyton, play an important role in transferring energy to higher trophic levels. Invertebrate consumption varies by species, but detritivore assimilation of leaf litter was often thought to be much higher than wood (Hutchens et al. 1997). However, recent research found that wood biofilms—bacteria and fungi that grow on submerged woody surfaces—are an important source of nutrition for invertebrates (Eggert and Wallace 2007). Specifically, invertebrates ingest and assimilate wood biofilm at higher assimilation efficiencies than they assimilate leaves for some detritivore species (Eggert and Wallace 2007).

Accumulations of organic material around wood also provides important habitat for terrestrial species. Wood accumulations that form during high flow in spring or winter in many regions are often left dry in summer as water levels recede. During the summer wood in and around streams can provide habitat for a range of terrestrial and amphibian species (Howey and Dinkelacker 2009; Pittman and Dorcas 2009; Wojan et al. 2014).

The velocity refuge that aquatic fish enjoy can be used by terrestrial animals also, as small animals can use the calmer pools for foraging and bathing. If the large wood spans the stream channel, it can be used for crossing as well.

3.5.5 Assessing the Effectiveness of Wood Restoration

Following implementation of wood restoration projects, assessment of the effectiveness of the projects to achieve environmental and species goals is an essential component of adaptive learning and fiscally responsible management. Assessment can provide new scientific understandings of how wood restoration alters the environment, and how it provides habitat elements and controls fish production. These insights should guide funding and prioritization for habitat restoration and provide accountability for restoration investments.

CROSS-REFERENCE

Chapter 9, *Assessing Ecological Performance*, details the processes for monitoring and assessing project success, including a thorough discussion of Adaptive Management.

Three levels of restoration effectiveness can be distinguished. First, the most basic level of assessment is the accounting of location, cost, design, and expected habitat changes as well as the biological rationale for the restoration; this level of assessment should be included with all restoration projects (Kondolf 2000; Bernhardt et al. 2007). The second level evaluates the physical changes in habitat produced at various intervals post-construction (e.g., 1, 2, 5, 10, or 20 years) to assess the persistence of physical restoration effects with respect to the expectations and purpose of the restoration. The third level addresses the biological effects of restoration (i.e., increases in fish and/or benthic invertebrate abundance) at various intervals post-construction (Gowan and Fausch 1996). It is not practical or necessary to perform all three of these levels of assessment for every large wood restoration project. The cost and effective time period to produce useful results increase across these three levels and dictate the need for a strategic approach to restoration assessment. All restoration projects should include an assessment of physical habitat immediately post-construction; decisions to invest in detailed or long-term biological monitoring should depend on the resources available to the responsible agency and their capacity for using monitoring for adaptive management of ongoing restoration programs. While intensive biological monitoring may not be essential at all restoration sites, it is necessary for a subset of actions to ensure the effectiveness of restoration techniques, and to learn from past experience (Bernhardt et al. 2007).

3.6 Scale and the River Continuum Concept

The scale at which we consider streams for wood addition is generally the segment or reach scale, which ranges from a as little as 10 linear meters (33 linear feet) of stream to as much as a kilometer or more. Delineation of reaches in a stream network is usually based on geomorphic characteristics such as tributary confluences or valley form. Practically, however, reaches may also be delineated based on management concerns or features such as bridges, roads, or dams. Scaling up from reaches, streams are broadly categorized into size classes based on where they are in the system and how many feeder streams they have. The headwaters are smaller systems higher in the basins with few or no feeder streams. And mainstems generally refer to the larger channels lower in the basin that carry the accumulated flow from the headwaters. The River Continuum Concept (RCC) proposes that these reaches form a continuous ecological system that processes organic material and produces a distinct pattern of biological communities (Vannote et al. 1980). Leaves and other organic material are degraded and processed along the stream continuum, and downstream reaches are supported to increasing degrees by “leakage” of material and nutrients from upstream. While acknowledged as a simplification of a complex and dynamic system that includes discontinuities and floodplain interactions (Junk et al. 1989), the RCC is a reasonable framework within which to consider processes that occur across a gradient of stream sizes in forested landscapes. The concept envisions an idealized riverine system as a continuum of reaches grading from small headwater streams to alluvial middle sections, and deep, stable lower mainstem reaches. The role of the riparian zone and large wood in structuring habitats and biological communities changes moving downstream between these areas.

Small headwaters generally have narrow channels (less than 5 meters [15 feet]). Due to their size and their placement in the landscape, these smaller tributary streams are strongly influenced by the adjacent terrestrial ecosystem and riparian vegetation (Vannote et al. 1980; Wallace et al. 1997). Headwater reaches are often heavily shaded by riparian vegetation and support only limited photosynthesis within the stream (Fisher and Likens 1973). As a result headwater reaches are generally detrital-based and dependent on the breakdown of leaves from riparian forests (Vannote et al. 1980; Wallace et al. 1997). Large wood has important direct influences on habitat in headwater streams associated with pool formation or step formation in steeper streams (Bilby and Ward 1989).

Because stream channels are narrow and have limited power, the export of individual large wood pieces is often low, but these large stable wood pieces often collect smaller wood pieces and organic material and form a debris dam. The role of large wood in forming debris dams and other retention features is particularly important in these small headwater ecosystems. Indeed, some of the earliest work on wood function in streams focused on the role of wood in carbon retention (Bilby and Likens 1980; Bilby 1981; Bilby and Ward 1989), and subsequent studies have gone on to demonstrate that this carbon retention has important implications for stream biota and nutrient cycling (Wallace et al. 1997; Hall et al. 2000; Warren et al. 2007).

Debris dams created by large wood in headwater streams not only increase detrital food retention, they also change the substrate composition of the streambed around the wood (Wallace et al. 1995a; Lemly and Hilderbrand 2000; Flores et al. 2011; Wellnitz et al. 2014). By reducing stream energy upstream of the dam and (often) dissipating energy in a cascade, a dam's alteration of stream energy allows deposition and retention of finer material and reduces bedload movement (Wallace et al. 1995a; Lemly and Hilderbrand 2000). This in turn alters invertebrate communities around the dam itself (Wallace et al. 1995a).

In the RCC framework, mid-level reaches are characterized as having a moderate gradient with an increasing width that allows sunlight to reach the stream. Mid-level reaches may be constrained within a narrow valley, are more typically alluvial, and move back and forth across the floodplain in response to high flow events. The influence of the riparian zone on food production and habitat formation in mid-level reaches is less than in head-water reaches. Alluvial reaches have an abundance of gravel and rock and unconfined valley form, resulting in complex channels, side channels, and gravel bars. Lateral movement of the stream undercuts riparian trees, which increases the availability of large wood (Lienkaemper and Swanson 1987; Latterell and Naiman 2007). Sunlight associated with a wider channel allows greater photosynthesis in the form of algae on rock and on wood substrates (Coe et al. 2009), and algae production is enhanced by nutrient additions, which can come from the weathering of bedrock in the system, from natural processes in the watershed forest (e.g., the capture and conversion of nitrogen by plants like alder), by processes within the stream (e.g., the release of nutrients by carcasses of anadromous salmon), or from human processes occurring in the watershed (e.g., urbanization or agriculture). With an increase in stream algal production, the aquatic insect community in these areas is dominated by species that scrape the biofilm from wood and rocks or collect pieces of leaves or organic matter transported from upstream areas (Vannote et al. 1980).

A key biological function of wood in mid-level reaches is to structure point bars, pools, and side-channel units (Abbe and Montgomery 1996). Because large wood does not typically span the stream channel in mid-level reaches, wood is more susceptible to movement by high flow events, creating a highly dynamic system of diverse habitats. The threshold size of functional wood tends to increase as stream size increases (Abbe and Montgomery 1996a; Merten et al. 2010). In mid-level streams, smaller wood pieces are highly mobile and often function within the matrix of a debris jam that is held in place by one or two large logs (Warren and Kraft 2008). Collins et al. (2012) describe the role of large wood in alluviating reaches to create point bars, and form secondary channels and islands resulting in a patchwork of habitats and features. Large wood jams comprising many pieces of large and small stream wood can also span the stream channel, even if there is no single channel-spanning piece within it.

In mid-sized streams much of the interest in large wood has focused on its role in pool formation and the associated ecological benefits (see discussion above regarding habitat and reviews by Smokorowski and Pratt 2007; Roni et al. 2008; and Nagayama and Nakamura 2010). In mid-sized streams individual pieces of wood and wood jams can form scour pools or dammed pools, or wood can enhance the size and complexity of existing pool habitat. Scour pools are the most common type of pool formed by large wood in streams this size. Dammed pools can occur in association with wood jams in mid-sized streams, but they are less common than in smaller headwater streams. Pools provide holding areas for adult and juvenile fish and feeding stations for drift feeding species such as coho salmon (Berg et al. 1998; Warren and Kraft 2003). Enhancing complexity and providing areas of visual isolation can be particularly important in increasing the carrying capacity of a given pool. When fish are visually isolated, aggressive intra-species interactions decrease, as does predation risk (Sundbaum and Naslund 1998).

Wood is particularly important in mid-level reaches in systems with anadromous salmon, where wood creates holding pools and shelter for juvenile salmon and migrating adults. In addition, the bedload material (i.e., gravel) retained by stable large wood and wood jams can be particularly important spawning habitat. The addition of wood and other structural elements can be vitally important in retaining and re-establishing stable spawning substrates for anadromous salmon and trout (Roni et al. 2006).

In lower areas of river systems, channel width increases, gradient declines, depth generally increases, and the biological community becomes more dependent on transfer of large wood, nutrients, and organic material from upstream areas (Vannote et al. 1980). In larger stream reaches, large "key pieces" of wood can become quite stable and serve to anchor bars and other features (Abbe and Montgomery 1996; Collins et al. 2012). These large pieces are often derived from lateral erosion and channel avulsion from upstream reaches. The presence of a rootwad is particularly important in anchoring these key pieces and maintaining their stability over time (Abbe and Montgomery 2003). In large alluvial systems, anchored large wood leads to a more complex channel form and stabilizes floodplains (Abbe and Montgomery 2003; Collins et al. 2012). Large wood provides important habitat for many large river fish, and ecologists continue to advocate for wood augmentation in large streams to enhance fish habitat (Koehn and Nicol 2014).

Less work has been done on the dynamics and functions of large wood in larger river ecosystems than has been done in first- through fifth-order streams, but wood is also a key habitat feature in larger rivers (see Section 3.2.1, *Habitat Formation*). In higher order streams, the role of wood in pool formation is dependent on the size of the wood, and the size and energy of the stream (Abbe and Montgomery 1996). In large alluvial systems, wood and wood jams are important in creating and enhancing scour pool habitat (Latterell et al. 2006; Pess et al. 2012). In larger streams, the presence of a rootwad is particularly important in reducing transport, and large trees with large rootwads tend to be stable and can be instrumental in developing mid-channel islands on large alluvial streams (Abbe and Montgomery 1996). In many lower gradient rivers or in very wide rivers, there is not enough energy associated with scour around the wood to create a pool. Channel-spanning dams are very rare, and when present they are often removed to allow navigation by boats (large and small).

While the RCC is a useful conceptual framework for stream ecology, it has been criticized as a simplification (Statzner and Higler 1985). Most steams do not fit the idealized RCC stream, and few streams conform to the totality of the concept. Dams, tributary confluences, and valley constrictions can reset the continuum (Stanford and Ward 1993). Systems in which beaver occur are often a series of ponds, meadows, and streams that create discontinuities in the RCC (Burchsted et al. 2010). Thus, streams are more often a series of continua while still retaining aspects of the generalizations in the RCC. Also, the RCC does not address the fundamental role of floods and floodplains (Sedell and Froggatt 1984; Junk et al. 1989; Sedell et al. 1989). Nonetheless, the RCC is a useful framework for thinking about stream ecosystems and how they may respond to changes in various habitat and community features, and it continues to be a fundamental component of stream ecosystem theory and a useful template for contextualizing restoration of large wood.

Ultimately, most streams in North America enter into ocean ecosystems (except in the great basin region in western North America) (Maser and Sedell 1994). Large wood also functions to create habitat in intertidal and estuarine areas. As in low-gradient streams where substrates are dominated by unconsolidated and fine material, wood provides key stable habitat for many invertebrate species in marsh ecosystems. Wood also provides a food and habitat resource for the wood-boring isopods that occur in estuarine and marine ecosystems, which are absent from freshwater systems (Maser and Sedell 1994). Wood-borers in these ecosystems physically degrade wood much faster than any freshwater species, and wood persistence in marine systems is therefore quite short compared to freshwater habitats.

There has also been key research on the role of large wood in lakes that is directly relevant to the role of wood in low-gradient rivers where it may contribute minimally to controlling channel structure but may still provide structure, cover, and habitat for fish and other biota. Large wood in lakes provides no geomorphic effect other than to create habitat structure and heterogeneity, as well as providing substrate for periphyton and benthic invertebrates. However, studies have shown that the presence and abundance of small forage fish are closely related to the abundance of littoral wood. Helmuss and Sass (2008) showed that removal of 70% of large wood from the littoral zone of a small temperate lake resulted in a four-fold decline of yellow perch, the most abundant fish in the lake, likely as a result of decreased refuge from predatory bass (Sass et al. 2006). Similarly, other studies have shown that reduction in littoral large wood and habitat complexity in lakes reduces abundance and diversity of fish. These effects can also reasonably be expected in low-gradient or warmwater rivers where the function of wood relates primarily to providing cover and structure, rather than influencing channel bedform, sediment storage, or transport as it does in steeper gradient streams. Thus, although the function of large wood may vary across steep and low-gradient landscapes and between cold- and warmwater fish communities, it generally plays an important ecological role across most systems.

3.7 Uncertainties and Research Needs

1. The amount of wood needed to achieve management objectives—how much is enough?
2. Because so much of the scientific literature reflects conditions for salmonids in high-rainfall areas of the Pacific Northwest, significant uncertainties exist regarding the role of wood in other environments and for other species.

3.8 Key Points

1. Large wood is an essential element of aquatic ecosystems and creates essential habitat features for many fish and invertebrate species.
2. The importance of wood as a habitat-forming element is highest in low-order streams (headwater streams) and decreases as stream order increases (larger rivers).
3. Wood is a dynamic habitat feature that changes over time, reflecting patterns of recruitment and decomposition.
4. Successful restoration of large wood in streams requires attention to systemic factors determining the supply and movement of large wood throughout the watershed including especially the integrity of riparian vegetation.
5. Large wood is one element of a hierarchy of factors controlling conditions in streams, hence, successful restoration requires consideration of the wood in the context of other factors limiting achievement of ecological and species goals.

3.9 References

Abbe, T. B. 2000. *Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System*. Ph.D. dissertation. University of Washington, Seattle, WA. 222 pp.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers: Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Ambrose, H. E., M. A. Wilzbach, and K. W. Cummins. 2004. Periphyton Response to Increased Light and Salmon Carcass Introduction in Northern California Streams. *Journal of the North American Benthological Society* 23(4):701–712.

Armstrong J. D., and K. H. Nislow. 2006. Critical Habitat During the Transition from Maternal Provisioning in Freshwater Fish, with Emphasis on Atlantic Salmon (*Salmo salar*) and Brown Trout (*Salmo trutta*). *Journal of Zoology* 269,403–413.

Bartz, K. K., K. M. Lagueux, M. D. Scheuerell, T. Beechie, A. D. Haas, and M. H. Ruckelshaus. 2006. Translating Restoration Scenarios into Habitat Conditions: An Initial Step in Evaluating Recovery Strategies for Chinook Salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Science*s 63(7):1578–1595.

Beecher, H. A., B. A. Caldwell, S. B. DeMond, D. Seiler, D., and S. N. Boessow. 2010. An Empirical Assessment of PHABSIM Using Long-Term Monitoring of Coho Salmon Smolt Production in Bingham Creek, Washington. *North American Journal of Fisheries Management* 30(6):1529–1543. doi:10.1577/M10.

Bencala, K. E. 2005. Hyporheic Exchange Flows. *Encyclopedia of Hydrological Sciences*, M. G. Anderson and J. J. Mcdonnell (eds.). Wiley-Blackwell. 3,456 pp.

Benda, L. E., D. Miller, K. Andras, P. E. Bigelow, G. H. Reeves, and D. Michael. 2007. NetMap: A New Tool in Support of Watershed Science and Resource Management. *Forest Science* 53(2):206–219.

Benke, A. C., R. L. Henry III, D. M. Gillespie, and R. J. Hunter. 1985. Importance of Snag Habitat for Animal Production in Southeastern Streams. *Fisheries* 10:8–12.

Berg, N. A., A. Carlson, and D. Azuma. 1998. Function and Dynamics of Woody Debris in Stream Reaches in the Central Sierra Nevada, California. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1807–1820.

Bernhardt, E. S., E. B. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, J. Follastad-Shah, B. A. Hassett, R. Jenkinson, R. Lave, J. Rumps, and L. Pagano. 2007. Restoring Rivers One Reach at a Time: Results from a Survey of U.S. River Restoration Practitioners. *Restoration Ecology* 15(3):482–493.

Beschta, R. L. 1997. Restoration of Riparian and Aquatic Systems for Improved Aquatic Habitats in the Upper Columbia River Basin. Pages 475-491 in D. J. Stouder and P. A. Bisson (eds.). *Pacific Salmon and Their Ecosystems: Status and Future Options.* New York: Chapman Hall.

Beverton, R. J. H., and S. J. Holt. 1957. On the Dynamics of Exploited Fish Populations. *U.K. Ministry of Agriculture, Fisheries Investigation Service* 2(19):553.

Bilby, R. E. 1981. Role of Organic Debris Dams in Regulating the Export of Dissolved and Particulate Matter from a Forested Watershed. *Ecology* 62(5):1234–1243.

Bilby, R. E., and P. A. Bisson. 1998. Function and Distribution of Large Woody Debris. Pages 324–346 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coast Ecoregion*. New York, NY: Springer-Verlag.

Bilby, R. E., and G. E. Likens. 1980. Importance of Debris Dams in the Structure and Function of Stream Ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E., and J. W. Ward. 1989. Changes in Characteristics and Function of Woody Debris With Increasing Size of Streams in Western Washington. *Transactions of the American Fisheries Society* 118:368–378.

Bilby, R. E., B. R. Fransen, P. A. Bisson, and J. K. Walter. 1998. Response of Juvenile Coho Salmon (*Oncorhynchus kisutch*) and Steelhead (*Oncorhynchus mykiss*) to the Addition of Salmon Carcasses to Two Streams in Southwestern Washington, U.S.A. *Canadian Journal of Fisheries and Aquatic Science* 55:1909–1918.

Blair, G. R., L. C. Lestelle, and L. E. Mobrand. 2009. The Ecosystem Diagnosis and treatment Model: A Tool for Assessing Salmonid Performance Potential Based on Habitat Conditions. Pages 289–309 in E. E. Knudsen and J. J. Michael, Jr., *Pacific Salmon Environment and Life History Models:*

Advancing Science for Sustainable Salmon in the Future. Bethesda, MD: American Fisheries Society.

Boisclair, D. 2001. Fish Habitat Modeling: From Conceptual Framework to Functional Tools. Canadian *Journal of Fisheries and Aquatic Sciences* 58:1–9.

Boulton, A. J., T. Datry, T. Kasahara, M. Mutz, and J.A. Stanford. 2010. Ecology and Management of the Hyporheic Zone – Groundwater Interactions of Running Waters and Their Floodplains. *Journal of the North American Benthological Society* 29:26–40.

Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor, and J. Henriksen. 1998. *Stream Habitat Analysis using the Instream Flow Incremental Methodology*. Washington, DC: U.S. Geological Survey.

Boyce, M. S., and L. L. McDonald. 1999. Relating Populations to Habitats Using Resource Selection Functions. *Trends in Ecology and Evolution* 14(7):268–272.

Bradford, M. J., J. Korman, and P. S. Higgins. 2005. Using Confidence Intervals to Estimate the Response of Salmon Populations (*Oncorhynchus spp*.) to Experimental Habitat Alterations. *Canadian Journal of Fisheries and Aquatic Sciences* 62(12):2716–2726.

Braun, A., K. Auerswald, and J. Geist. 2012. Drivers and Spatio-Temporal Extent of Hyporheic Patch Variation: Implications for Sampling*. PLOS One* 7:e42046.

Bretherton, W. D., J. S. Kominoski, D. G. Fischer, and C. J. LeRoy. 2011. Salmon Carcasses Alter Leaf Litter Species Diversity Effects on In-stream Decomposition. *Canadian Journal of Fisheries and Aquatic Sciences* 68(8):1495–1506.

Buffington, J. M., and D. R. Montgomery. 1999b. Effects of Hydraulic Roughness on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3507–3521.

Buffington, J. M. and D. Tonina. 2009. Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange. *Geography Compass* 3:1038–1062.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun. 2010. The River Discontinuum: Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. *BioScience* 60(11):908–922.

Cederholm, C. J., M. D. Kunze, T. Murota, and A. Sibatani. 1999. Pacific salmon Carcasses: Essential Contributions of Nutrients and Energy for Aquatic and Terrestrial Ecosystems. *Fisheries* 24(10):6–15.

Chapman, D. W. 1966. Food and Space as Regulators of Salmonid Populations in Streams. *American Naturalist* 100:345–357.

Claussens, L., C. L. Tague, P. M. Groffman, and J. M. Melack. 2010. Longitudinal and Seasonal Variation of N Uptake in an Urbanizing Watershed: Effect of organic Matter, Stream Size, Transient Storage and Debris Dams. *Biogeochemistry* 98:45–62.

Coe, H. J., P. M. Kiffney, G. R. Press, K. K. Kloehn, and M. L. McHenry. 2009. Periphyton and Invertebrate Response to Wood Placement in Large Pacific Coastal Rivers. *River Research and Applications* 25(8):1025–1035.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Conquest, L. L., and S. C. Ralph. 1998. Statistical Design and Analysis Considerations for Monitoring and Assessment. Pages 455-475 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. New York: Springer.

Cramer, S. P., and N. K. Ackerman. 2009. Prediction of Stream Carrying Capacity for Steelhead; The Unit Characterization Method. Pages 255–288 in *Pacific Salmon Environment and Life History Models*. Bethesda, MD: American Fisheries Society.

Cummins, K. W. 1974. Structure and Function of Stream Ecosystems. *BioScience* 24(11):631–641.

Cummins, K. W., G. W. Minshall, J. R. Sedell, C. E. Cushing, and R. C. Petersen. 1984. Stream Ecosystem Theory. *Internationale Vereinigung fur theoretische und angewandte Limnologie, Verhandlungen* 22:1818–1827.

Daniels, M. D., and Rhoads, B. L. 2004. Effect of Large Woody Debris Configuration on Three-Dimensional Flow Structure in Two Low-Energy Meander Bends at Varying Stages. *Water Resources Research* (40):W11302.

Eggert, S. L., and J. B. Wallace. 2007. Wood Biofilm as a Food Resource for Stream Detritivores. *Limnology and Oceanography* 52(3):1239–1245.

Ehrman, T. P., and G. A. Lamberti. 1992. Hydraulic and Particulate Matter Retention in a 3rd-Order Indiana Stream. *Journal of the North American Benthological Society*. 11:341–349.

Ensign, S. H., and M. W. Doyle. 2005. In-channel Transient Storage and Associated Nutrient Retention: Evidence from Experimental Manipulations. *Limnology and Oceanography* 50(6):1740–1751.

Environmental Agency. 2009. *The Hyporheic Handbook. a Handbook of the Groundwater-Surface Water Interface and Hyporheic Zone for Environmental Managers.* Science Report SC050070. 264 pp. Available: http://www.hyporheic.net/SCHO1009BRDX-e-e.pdf. Accessed: June 13, 2014.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to Riverscapes: Bridging the Gap Between Research and Conservation of Stream Fishes. *BioScience* 52(6):483–498.

Findlay, S., J. Tank, S. Dye, H. M. Valett, P. J. Mulholland, W. H. McDowell, S. L. Johnson, S. K. Hamilton, J. Edmonds, W. K. Dodds, and W. B. Bowden. 2002. A Cross System Comparison of Bacterial and Fungal Biomass in Detritus Pools of Headwater Streams. *Microbial Ecology* 43(1):55–66.

Fisher, S. G., and G. E. Likens. 1972. Stream Ecosystem—Organic Energy Budget. *Bioscience* 22(1):33-35.

Flebbe, P. A. 1999. Trout Use of Wood Debris and Habitat in Wine Spring Creek, North Carolina. *Forest Ecology and Management* 114:367–376.

Flores, L., A. Larranaga, J. Diez, and A. Elosegi. 2011. Experimental Wood Addition in Streams: Effects on Organic Matter Storage and Breakdown. *Freshwater Biology* 56(10):2156–2167.

Frissell, W. J., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A Hierarchical Framework for Stream Habitat Classification: Viewing Streams in a Watershed Context. *Environmental Management* 10(2):199–214.

Gandy, C. J., and A. P. Jarvis. 2006. *Attenuation of Nine Pollutants in the Hyporheic Zone.* Environment Agency, Bristol, England, June. 33 pp.

Garshelis, D. L. 2000. Delusions in Habitat Evaluation: Measuring Use, Selection, and Importance. Pages 11–165 in L. Boitani and T. K. Fuller (eds.), *Research Techniques in Animal* Ecology. New York: Columbia University Press.

Gowan, C., and K. D. Fausch. 1996. Long-Term Demographic Responses of Trout Populations to Habitat Manipulation in Six Colorado Streams. *Ecological Applications* 6(3):931–946.

Grizzel, J., M. McGowan, D. Smith, and T. Beechie. 2000. Streamside Buffers and Large Woody Debris Recruitment: Evaluating the Effectiveness of Watershed Analysis Prescriptions in the North Cascades Region. TFW-MAGI-00-003. Washington State Timber, Fish & Wildlife.

Hall, L. S., P. R. Krausman, and M. L. Morrison. 1997. The Habitat Concept and a Plea for Standard Terminology. *Wildlife Society Bulletin* 25(1):173–182.

Hall, R. O., J. B. Wallace, and S. L. Eggert. 2000. Organic Matter Flow in Stream Food Webs with Reduced Detrital Resource Base. *Ecology* 81(12):3445–3463.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

Hayes, D. B., C. P. Ferreri, and W. W. Taylor. 1996. Linking Fish Habitat to Their Population Dynamics. *Canadian Journal of Fisheries and Aquatic Sciences* 53(S1):383–390.

Hedman, C. W., D. H. Van Lear, and W. T. Swank. 1996. In-Stream Large Woody Debris Loading and Riparian Forest Seral Stage Associations in the Southern Appalachian Mountains. *Canadian Journal of Forest Research* 26:1218–1227.

Helmus, M. R. and G. G. Sass. 2008. The Rapid Effects of a Whole-Lake Reduction of Coarse Woody Debris on Fish and Benthic Macroinvertebrates. *Freshwater Biology* 53:1423–1433.

Hester, E. T., and M. W. Doyle. 2008. In-Stream Geomorphic Structures as Drivers of Hyporheic Change. *Water Resources Research* 44:W03427.

Hester, E. T., and M. N. Gooseff. 2010. Moving Beyond the Banks: Hyporheic Restoration is Fundamental to Restoring Ecological Services and Functions of Streams. *Environmental Science and Technology* 44:1521–1525.

Hilborn, R., and M. Mangel. 1997. *The Ecological Detective*. Princeton, NJ: Princeton University Press.

Hilborn, R., and C. J. Walters. 1992. *Quantitative Fish Stock Assessment*. London: Chapman and Hall.

Hoellein, T. J., J. L. Tank, E. J. Rosi-Marshall, S. A. Entrekin, and G. A. Lamberti. 2007. Controls on Spatial and Temporal Variation of Nutrient Uptake in Three Michigan Headwater Streams. *Limnol. Oceanogr*.52:1964–1977.

Howey, C. A. F., and S. A. Dinkelacker. 2009. Habitat Selection of the Alligator Snapping Turtle (*Macrochelys temminckii*) in Arkansas. *Journal of Herpetology* 43(4):589–596.

Hutchens, J. J., E. F. Benfield, and J. R. Webster. 1997. Diet and Growth of a Leaf-Shredding Caddisfly in Southern Appalachian Streams of Contrasting Disturbance History. *Hydrobiologia* 346:193–201.

Johnson, L. B., D. H. Breneman, and C. Richards. 2003. Macroinvertebrate Community Structure and Function Associated with Large Wood in Low Gradient Streams. *River Research and Applications* 19:199–218.

Jonsson, B., and N. Jonsson. 2003. Migratory Atlantic Salmon as Vectors for the Transfer of Energy and Nutrients Between Freshwater and Marine Environments. *Freshwater Biology* 48:21–27.

Johnston, N. T., S. A. Bird, D. L. Hogan, and E. A. MacIsaac. 2011. Mechanisms and Source Distances for the Input of Large Woody Debris to Forested Streams in British Columbia, *Canada Canadian Journal of Forest Research*. 41(11):2231–2246.

Jowett, I. G., J. W. Hayes, and M. J. Duncan. 2008. *A Guide to Instream Habitat Survey Methods and Analysis.* NIWA Science and Technology Series No. 54. Available: http://www.niwa.co.nz/sites/niwa.co.nz/files/a_guide_to_instream_habitat_survey_methods_and_analysis.pdf**.**

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The Flood Pulse Concept in River Floodplain Systems. Pages 110-127 in D. P. Dodge (ed.), *Proceedings of the International Large River Symposium.*

Keeton, W. S., C. E. Kraft, and D. R. Warren. 2007. Mature and Old-Growth Riparian Forests: Structure, Dynamics and Effects on Adirondack Stream Habitats. *Ecological Applications* 17:852–868.

Kennedy, B. P., K. H. Nislow, and C. L. Folt. 2008. Habitat-Mediated Foraging Limitations Drive Survival Bottlenecks for Juvenile Salmon. *Ecology* 89(9):2529–2541.

Koehn, J. D., and S. J. Nicol. 2014. Comparative Habitat Use by Large Riverine Fishes. *Marine and Freshwater Research* 65(2):164–174.

Kondolf, G. M. 2000. Some Suggested Guidelines for Geomorphic Aspects of Anadromous Salmonid Habitat Restoration Proposals. *Restoration Ecology* 8:48–55.

Kratzer, J. F., and D. R. Warren. 2013. Factors Limiting Brook Trout Biomass in Northeastern Vermont Streams. *North American Journal of Fisheries Management* 33(1):130–139.

Krause, S., M. J. Klaar, D. M. Hannah, J. Mant, J. Bridgeman, M. Trimmer, and S. Manning-Jones. 2014. The Potential of Large Woody Debris to Alter Biogeochemical Processes and Ecosystem Services in Lowland Rivers. *Wiley Interdisciplinary Reviews (WIREs): Water* 1:263–275.

Lancaster, S. T., S. K. Hayes, and G. E. Grant. 2001. Modeling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds. *Geomorphic Processes and Riverine Habitat, Water Science and Application Volume 4*:85–102. American Geophysical Union.

Latterell, J. J., and R. J. Naiman. 2007. Sources and Dynamics of Large Logs In a Temperate Floodplain River. *Ecological Applications* 17:1127–1141.

Latterell, J. J., J. S. Bechtold, T. C. O'Keefe, R. Van Pelt, and R. J. Naiman. 2006. Dynamic Patch Mosaics and Channel Movement in an Unconfined River Valley of the Olympic Mountains *Freshwater Biology* 51(3):523–544.

Lautz, L. K., and R. M. Fanelli. 2008. Biogeochemical Hotspots in the Streambed around Restoration Structures. *Biogeochemistry* 91:85–104.

Lautz, L. K., D. I. Siegel, and R. L. Bauer. 2006. Impact of Debris Dams on Hyporheic Interaction along a Semi-Arid Stream. *Hydrological Processes* 20:183–196.

Lautz, L. K., R. M. Fanelli, N. Kranes, and D. I. Siegel. 2007. Abstract. Sediment distribution around Debris Dams: Impacts on Streambed Hydrology, Biogeochemistry and Temperature Dynamics in Small Streams. *Geological Society of America Annual Meeting* (28–31 October 2007), Paper No. 180-4.

Lemly, A. D., and R. H. Hilderbrand. 2000. Influence of Large Woody Debris on Stream Insect Communities and Benthic Detritus. *Hydrobiologia* 421:179–185.

Lichatowich, J. A., L. E. Mobrand, L. Lestelle, and T. Vogel. 1995. An Approach to the Diagnosis and Treatment of Depleted Pacific Salmon Populations in Freshwater Ecosystems. *Fisheries* 20(1):10–18.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of Large Woody Debris in Streams in Old-Growth Douglas-Fir Forests. *Canadian Journal of Forest Research* 17:150–156.

Manga, M., and J. W. Kirchner. 2000. Stress Partitioning in Streams by Large Woody Debris. *Water Resources Research* 36:2373–2379.

Manly, B. F. 2002. *Resource Selection by Animals*. Springer, New York.

Manners, R. W., M. W. Doyle, and M. J. Small. 2007. Structure and Hydraulics of Natural Woody Debris Jams. *Water Resources Research* 43, doi:10.1029/2006WR004910.

Maser, C., and J. R. Sedell. 1988. From the Forest to the Sea: the Ecology of Wood in Streams, Rivers, Estuaries and Oceans. Delray Beach, FL: St. Lucie Press.

Maser, C. and J. R. Sedell, J.R. 1994. From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans. St. Lucie Press. 200 pp.

Mathur, D., W. H. Bason, E. J. Purdy, and C. A. Silver. 1985. A Critique of Instream Flow Incremental Methodology. *Canadian Journal of Fisheries and Aquatic Science* 42(4):825–831.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source Distances for Coarse Woody Debris Entering Small Streams in Western Oregon and Washington. *Canadian Journal of Forest Research* 20:326–330.

McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. *Viable Salmonid Populations and the Recovery of Evolutionary Significant Units*. U.S. Department of Commerce, Seattle, WA. NOAA Tech. Memo NMFS-NWFSC-42.

McMahon, T. E. 1983. *Habitat Suitability Index Models: Coho Salmon*. U.S. Fish and Wildlife Service.

McNeely, C., and M. E. Power. 2007. Spatial Variation in Caddisfly Grazing Regimes Within a Northern California Watershed. *Ecology* 88(10):2609–2619.

Merten, E., J. Finlay, L. Johnson, R. Newman, R., H. Stefan, and B. Vondracek. 2010. Factors Influencing Wood Mobilization in Stream. *Water Resources Research* 46:W10514.

Merz, J., and P. B. Moyle. 2006. Salmon, Wildlife and Wine: Marine-Derived Nutrients in Human--Dominated Ecosystems of Central California. *Ecological Applications* 13(3):999–1009.

Miller, D., C. Luce, and L. Benda. 2003. Time, Space, and Episodicity of Physical Disturbance in Streams. *Forest Ecology and Management* 178(1):121–140.

Montgomery, D. R., and J. M. Buffington. 1998. Channel Processes, Classification and Response. Pages 13–42 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion.* New York: Springer.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Moore, M. K. 1977. Factors Contributing to Blowdown in Streamside Leave Strips on Vancouver Island. *Land Management Report No. 3.* Victoria, BC: Province of British Columbia Ministry of Forests, Information Division.

Morrison, M. L., B. G. Marcot, and R. W. Mannon. 1998. *Wildlife-Habitat Relationships. Concepts and Applications*. Madison, WI: University of Wisconsin Press.

Moussalli, E., and R. Hilborn. 1986. Optimal Stock Size and Harvest Rate in Multistage Life History Models. *Canadian Journal of Fisheries and Aquatic Sciences* 43(1):135–141.

Mulholland, P. J., and J. R. Webster. 2010. Nutrient Dynamics in Streams and the Role of J-NABS. *Journal of the North American Benthological Society* 29:100–117.

Mulholland, P. J., and 33 others. 2009. Nitrate Removal in Stream Ecosystems Measured by 15N Addition Experiments: Denitrification. *Limnology and Oceanography* 54:666–680.

Murphy, M. L., and K. V. Koski. 1989. Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. *North American Journal of Fisheries Management* 9(4):427-436.

Murphy, M. L., J. Heifetz, S. W. Johnson, K. V. Koski, and J. F. Thendinga. 1986. Effects of Clear-Cut Logging with and without Buffer Strips on Juvenile Salmonids in Alaskan Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 43:1521–1533.

Mutz, M., E. Kalbus, and S. Meinecke. 2007. Effect of Instream Wood on Vertical Water Flux in Low-Energy Sand Bed Flume Experiments. *Water Resources Research* 43:W10424.

Nagayama, S., and F. Nakamura. 2010. Fish Habitat Rehabilitation Using Wood in the World. *Landscape and Ecological Engineering* 6(2):289–305.

Naiman, R. J., K. L. Fetherston, S. McKay, and J. Chen. 1998. Riparian Forests. Pages 289-323 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag: New York.

Naiman, R. J., R. E. Bilby, D. E. Schindler, and J. M. Helfield. 2002c. Pacific Salmon, Nutrients, and the Dynamics of Freshwater and Riparian Ecosystems. *Ecosystems* 5:399–417.

Nickelson, T. E., and P. W. Lawson. 1998. Population Viability of Coho Salmon, *Oncorhynchus kisutch*, in Oregon Coastal Basins: Application of a Habitat-Based Life Cycle Model. *Canadian Journal of Fisheries and Aquatic Sciences* 55:2383–2392.

Nickelson, T. E., M. F. Solazzi, S. L. Johnson, and J. D. Rodgers. 1993. An Approach to Determining Stream Carrying Capacity and Limiting Habitat For Coho Salmon (*Oncorhynchus kisutch*). Paper read at *Proceedings of the Coho Workshop*, May 1992, Nanaimo, B.C.

O'Connor J. E., M. A. Jones, and T. L. Haluska. 2003. Flood Plain and Channel Dynamics of the Quinault and Queets Rivers, Washington, U.S.A. *Geomorphology* 52:31–59.

O'Connor, M., and G. Watson, 1998. *Geomorphology of Channel Migration Zones and Implications for Riparian Forest Management.* Available: http://www.oei.com/Reports/Geomorph_of_CMZ.htm.

O'Connor, R. R., and F. J. Rahel. 2009. A Patch Perspective on Summer Habitat Use by Brown Trout *Salmo trutta* in a High Plains Stream in Wyoming, USA. *Ecology of Freshwater Fish* 18(3):473–480.

Oliver, C. D. 1980. Forest Development in North America Following Major Disturbances. *Forest Ecology and Management* 3:153–168.

Pess, G. R., D. R. Montgomery, E. A. Steel, R. E. Bilby, B. E. Feist, and H. M. Greenberg. 2002. Landscape Characteristics, Land Use, and Coho Salmon (*Oncorhynchus kisutch*) Abundance, Snohomish River, Washington, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 59:613–623.

Pess, G. R., M. C. Liermann, M. L. Mchenry, R. J. Peters, and T. R. Bennett. 2012. Juvenile Salmon Response to the Placement of Engineered Log Jams (Eljs) in the Elwha River, Washington State, USA. *River Research and Applications* 28(7):872–881.

Phillips, E. C. 2003. Habitat Preference of Aquatic Macroinvertebrates in an East Texas Sandy Stream. *Journal of Freshwater Ecology* 18(1):1–11.

Pianka, E. R. 1994. *Evolutionary Ecology*. Harper-Collins.

Pickett, S. T. A., and K. H. Rogers. 1997. Patch Dynamics: The Transformation of Landscape Structure and Function. Pages 101–127 in J. A. Bissonette (ed.), *Wildlife and Landscape Ecology*. New York: Springer-Verlag.

Pittman, S. E., and M. E. Dorcas. 2009. Movements, Habitat Use, and Thermal Ecology of an Isolated Population of Bog Turtles (*Glyptemys muhlenbergii*). *Copeia*(4):781–790.

Ptolemy, R. A. 1993. Maximum Salmonid Densities in Fluvial Habitats in British Columbia. Paper read at Proceedings of the Coho Workshop, May 26–28, 1992, at Nanaimo, B.C.

Quinn, T. P., S. M. Carlson, S. M. Gende, and H. B. Rich. 2009. Transportation of Pacific Salmon Carcasses from Streams to Riparian Forests by Bears. *Canadian Journal of Fisheries and Aquatic Science* 87:195–203.

Railsback, S. F., and J. Kadvany. 2008. Demonstration Flow Assessment: Judgment and Visual Observation in Instream Flow Studies. *Fisheries* 33:217–227.

Railsback, S. F., H. Stauffer, and B. Harvey. 2003. What can Habitat Preference Models Tell Us? Tests using a Virtual Trout Population. *Ecological Applications* 13(6):1580–1594.

Reeves, G. H., F. H. Everest, and T. E. Nickelson. 1989. Identification of Physical Habitats Limiting the Production of Coho Salmon in Western Oregon and Washington. Portland, OR: USDA Forest Service.

Reisenbichler, R. R. 1989. Utility of Spawner-Recruit Relations for Evaluating the Effect of Degraded Environment on the Abundance of Chinook Salmon, *Oncorhynchus tshawytscha*. Pages 21–32 in C. D. Levings, L. B. Holtby, and M. A. Henderson (eds.), *Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks: Canadian Special Publication on Fisheries and Aquatic Sciences* 105.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and Function of Large Woody Debris in Subalpine Rocky Mountain Streams in Northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Robison, E. G. and R. L. Beschta. 1990. Identifying Trees in Riparian Areas that can Provide Coarse Woody Debris to Streams. *Forest Science* 36:790–801.

Roni, P., T. Bennett, S. Morley, G. R. Pess, K. Hanson, D. Van Slyke, and P. Olmstead. 2006. Rehabilitation of Bedrock Stream Channels: The Effects of Boulder Weir Placement on Aquatic Habitat and Biota. *River Research and Applications* 22(9):967–980.

Roni, P., K. Hanson, and T. Beechie. 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management* 28(3):856–890.

Roni, P., G. Pess, T. Beechie, and S. Morley. 2010. Estimating Changes in Coho Salmon and Steelhead Abundance from Watershed Restoration: How Much Restoration is Needed to Measurably Increase Smolt Production? *North American Journal of Fisheries Management* 30(6):1469–1484.

Roni, P., T. J. Beechie, G. R. Pess, and K. M. Hanson. 2014a. Wood Placement in River Restoration: Fact, Fiction and Future Direction. *Canadian Journal of Fisheries and Aquatic Sciences.*

Roni, P., G. R. Pess, and T. J. Beechie. 2014b. *Fish-Habitat Relationships and Effectiveness of Habitat Restoration.* National Marine Fisheries Service. Seattle, WA. NOAA Technical Memorandum NMFS-NWFSC-127.

Rose, K. A. 2000. Why are Quantitative Relationships Between Environmental Quality and Fish Populations so Elusive? *Ecological Applications* 10(2):367–385.

Rosenfeld, J. 2003. Assessing the Habitat Requirements of Stream Fishes: an Overview and Evaluation of Different Approaches. *Transactions of the American Fisheries Society* 132:953–968.

Rosenfeld, J. S. 2014. Modelling the Effects of Habitat on Self-thinning, Energy Equivalence, and Optimal Habitat Structure for Juvenile Trout. *Canadian Journal of Fisheries and Aquatic Sciences.* 71(9):1395–1406.

Rosenfeld, J. S., and S. Boss. 2001. Fitness Consequences of Habitat Use for Juvenile Cutthroat Trout: Energetic Costs and Benefits in Pools and Riffles. *Canadian Journal of Fisheries and Aquatic Sciences* 58(3):585–593.

Rosenfeld, J., and T. Hatfield. 2006. Information Needs for Assessing Critical Habitat of Freshwater Fish. *Canadian Journal of Fisheries and Aquatic Sciences 63:*683–698.

Rosenfeld, J. S., and R. Ptolemy. 2012. Modelling Available Habitat Versus Available Energy Flux: Do PHABSIM Applications that Neglect Prey Abundance Underestimate Optimal Flows for Juvenile Salmonids? *Canadian Journal of Fisheries and Aquatic Sciences* 69(12):1920–1934.

Rot, B. 1993. Windthrow in Stream Buffers on Coastal Washington Streams. ITT-Rayonier Inc. 49 pp.

Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream Channel Configuration, Landform, and Riparian Forest Structure in the Cascade Mountains, Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 57:699–707.

Rutherford, I., B. Anderson, and A. Ladson. 2007. Managing the Effects of Riparian Vegetation on Flooding. In S. Lovett and P. Price (eds.), *Principles for Riparian Lands Management*. Land & Water Australia, Canberra.

Sabater, S., V. Acuña, A. Giorgi, E. Guerra, I. Muñoz, and A. M. Romaní, 2005. Effects of Nutrient Inputs in a Forested Mediterranean Stream Under Moderate Light Availability. *Archiv für Hydrobiologie* 163:479–496.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish Community and Food Web Responses to a Whole-Lake Removal of Coarse Woody Habitat. *Fisheries* 31:321–330.

Sawyer, A. H., and M. B. Cardenas. 2012. Effect of Experimental Wood Addition on Hyporheic Exchange and Thermal Dynamics in a Losing Meadow Stream. *Water Resources Research* 48:W10537.

Sawyer, A. H., M. B. Cardenas, and J. Buttles. 2011. Hyporheic Exchange due to Channel-Spanning Logs. *Water Resources Research* 47(8):W08502.

Sawyer, A. H., M. B. Cardenas, and J. Buttles. 2012. Hyporheic Temperature Dynamics and Heat Exchange Near Channel-Spanning Logs. *Water Resources Research* 48:W01529.

Schenk, E. R., J. W. McCargo, B. Moulin, C. R. Hupp, and J. M. Richter. 2014. The Influence of Logjams on Largemouth Bass (*Micropterus salmoides*) Concentrations on the lower Roanoke River, a Large Sand-Bed River. *River Research and Applications* 2014(DOI: 10.1002/rra.2779).

Scheuerell, M. D., R. Hilborn, M. H. Ruckelshaus, K. K. Bartz, K. M. Lagueux, A. D. Haas, and K. Rawson. 2006. The Shiraz Model: A Tool for Incorporating Anthropogenic Effects and Fish–Habitat Relationships in Conservation Planning. *Canadian Journal of Fisheries and Aquatic Sciences* 63(7):1596–1607.

Schlosser, I. J., and P. L. Angermeier. 1995. Spatial Variation in Demographic Processes of Lotic Fishes: Conceptual Models, Empirical Evidence, and Implications for Conservation. Pages 392–401 in J. L. Nielsen and D. A. Powers (eds.), *Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation.* Bethesda, MD: American Fisheries Society.

Schmetterling, D. A., and R. W. Pierce. 1999. Success of Instream Habitat Structures After a 50-Year Flood in Gold Creek, Montana. *Restoration Ecology* 7(4):369–375.

Sedell, J. R., and J. L. Frogatt. 1984. Importance of Streamside Forests to Large Rivers: The Isolation of the Willamette River, Oregon, U.S.A., from its Floodplain by Snagging and Streamside Forest Removal. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1828–1834.

Sedell, J. R., J. E. Richey, and F. J. Swanson. 1989. The River Continuum Concept: A Basis for the Expected Ecosystem Behavior of Very Large Rivers? *Canadian Special Publication of Fisheries and Aquatic Sciences* 106:49–55.

Sharma, R., A. B. Cooper, and R. Hilborn. 2005. A Quantitative Framework for the Analysis of Habitat and Hatchery Practices on Pacific Salmon. *Ecological Modeling* 18:231–250.

Smock, L. A., G. M. Metzler and J. E. Gladden. 1989. Role of Debris Dams in the Structure and Functioning of Low Gradient Headwater Streams. *Ecology* 70:764–775.

Smokorowski, K. E., and T. C. Pratt. 2007. Effect of a Change in Physical Structure and Cover on Fish and Fish Habitat in Freshwater Ecosystems - A Review and Meta-Analysis. *Environmental Reviews* 15:15–41.

Sobota, D. J., S. V. Gregory, S. V., and S. L. Johnson. 2007. Influence of Wood Decomposition on Nitrogen Dynamics in Stream Ecosystems: Interactive Effects of Substrate Quality and Nitrogen Loading. *North American Benthological Society 55th Annual Meeting.* Available: https://nabs.confex.com/nabs/2007/techprogram/P1365.HTM.

Southwood, T. R. E. 1977. Habitat, the Template for Ecological Strategies? *Journal of Animal Ecology* 46:337–365.

Spanhoff, B., and E. Cleven. 2010. Wood in Different Stream Types: Epixylic Biofilm and Wood-Inhabiting Invertebrates in a Lowland Versus an Upland Stream. *Annales De Limnologie-International Journal of Limnology* 46(3):169–179.

Spanhoff, B., and E. I. Meyer. 2004. Breakdown Rates of Wood in Streams. *Journal of the North American Benthological Society* 23(2):189–197.

Stanford, J. A. and J. V. Ward. 1988. The Hyporheic Habitat of River Ecosystems. *Nature* 335:64–66.

Stanford, J. A., and J. V. Ward. 1993. An Ecosystem Perspective of Alluvial Rivers: Connectivity and the Hyporheic Corridor. *Journal of the North American Benthological Society* 12(1):48–60.

Stanford, J. A., and J. V. Ward. 1995. The Serial Discontinuity Concept: Extending the Model to Floodplain Rivers. *Regulated Rivers: Research and Management:*159–168.

Statzner, B., and B. Higler. 1985. Questions and Comments on the River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Science* 42:1038–1044.

Steinhart, G. S., G. E. Likens, and P. M. Groffman. 2000. Denitrification in Stream Sediments in Five Northeastern (USA) Streams. *Verhandlungen Internationale Vereinigung für Theorertische und Angewandte Limnologie* 27:1331–1336.

Stewart, G. B., H. R. Bayliss, D. A. Showler, W. J. Sutherland, and A. S. Pullin. 2009. Effectiveness of Engineered In-Stream Structure Mitigation Measures to increase Salmonid Abundance: A Systematic Review. *Ecological Applications* 19(4):931–941.

Stewart, P. M., S. Bhattarai, M. W. Mullen, C. K. Metcalf, and E. G. Reategui-Zirena. 2012. Characterization of Large Wood and its Relationship to Pool Formation and Macroinvertebrate Metrics in Southeastern Coastal Plain Streams, USA. *Journal of Freshwater Ecology* 27(3):351–365.

Stiehl, R. B. 1998. *Habitat Evaluation Procedures Workbook.* Fort Collins, CO: U.S. Geological Survey.

Stockner, J. G. (ed.). 2003. Nutrients in Salmonid Ecosystems: Sustaining Production and Biodiversity. Bethesda, MD: American Fisheries Society.

Stofleth, J. M., F. D. Shields, Jr., and G. A. Fox. 2007. Hyporheic and Total Transient Storage in Small, Sand-Bed Streams. *Hydrological Processes* 22:1885–1894.

Sundbaum, K. and I. Naslund. 1998. Effects of Woody Debris on the Growth and Behavior of Brown Trout in Experimental Stream Channels. *Canadian Journal of Zoology* 76:56–61.

Thompson, D. M. 2006. Did the Pre-1980 Use of In-Stream Structures Improve Streams? A Reanalysis of Historical Data. *Ecological Applications* 16(2):784–796.

Tonina, D., and J. M. Buffington. 2009. Hyporheic Exchange In Mountain Rivers I: Mechanics and Environmental Effects. *Geography Compass* 3:1063–1086.

Townsend, C. R. 1989. The Patch Dynamics Concept of Stream Community Ecology. *Journal of the North American Benthological Society* 8(1):36–50.

Treadwell, S., J. Koehn, S. Bunn, and A. Brooks. 2007. Wood and Other Aquatic Habitat. Chapter 7 in S. Lovett and P. Price (eds.), *Principles for Riparian Lands Management*. Land and Water Australia, Canberra.

Trotter, E. H. 1990. Woody Debris, Forest-Stream Succession, and Catchment Geomorphology. *Journal of the North American Benthological Society* 9(2):141–156.

Valett, H. M., C. L. Crenshaw, and P. F. Wagner. 2002. Stream Nutrient Uptake, Forest Succession, and Biogeochemical Theory. *Ecology* 83:2888–2901.

Van Horne, B. 1983. Density as a Misleading Indicator of Habitat Quality. *Journal of Wildlife Management* 47:893–901.

Van Sickle, J., and S. V. Gregory. 1990. Modeling Inputs of Large Woody Debris to Streams from Falling Trees. *Canadian Journal of Forest Research* 20(10):1593–1601.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Science* 37(1):130–137.

Wallace, J. B., J. R. Webster, and J. L. Meyer. 1995a. Influence of Log Additions on Physical and Biotic Characteristics of a Mountain Stream. *Canadian Journal of Fisheries and Aquatic Sciences* 52:2120–2137.

Wallace, J. B., M. R. Whiles, S. Eggert, T. F. Cuffney, G. H. Lugthart, and K. Chung. 1995b. Long-Term Dynamics of Coarse Particulate Organic-Matter in 3 Appalachian Mountain Streams. *Journal of the North American Benthological Society* 14(2):217–232.

Wallace, J. B., S. L. Eggert, J. L. Meyer, and J. R. Webster. 1997. Multiple Trophic Levels of a Forest Stream Linked to Terrestrial Litter Inputs. *Science* 277:102–104.

Walter, R. C., and D. J. Merritts. 2008. Natural Streams and the Legacy of Water-Powered Mills. *Science* 319:299–304.

Warren, D. R., and C. E. Kraft. 2003. Brook Trout (*Salvelinus fontinalis*) Response to Wood Removal from High-Gradient Streams of the Adirondack Mountains (NY, USA). *Canadian Journal of Fisheries and Aquatic Sciences* 60(4):379-389.

Warren, D. R., and C. E. Kraft. 2008. Dynamics of Large Wood in an Eastern US Mountain Stream. *Forest Ecology and Management* 256(4):808–814.

Warren, D. R., E. S. Bernhardt, R. O. Hall Jr., and G. E. Likens. 2007. Forest Age, Wood and Nutrient Dynamics in Headwater Streams of the Hubbard Brook Experimental Forest. *N.H. Earth Surface Processes & Landforms* 32(8):1154–1163.

Warren, D. R., C. E. Kraft, W. S. Keeton, J. S. Nunery, and G. E. Likens. 2009. Dynamics of wood recruitment in streams of the northeastern *U.S. Forest Ecology and Management* 258:804-813.

Warren, D. R., J. D. Dunham, and D. Hockman-Wert. 2014. Geographic Variability in Elevation and Topographic Constraints on the Distribution of Native and Nonnative Trout in the Great Basin. *Transactions of the American Fisheries Society* 143:205–218.

Webster, J. R., and E. F. Benfield. 1986. Vascular Plant Breakdown in Freshwater Ecosystems. *Annual Review of Ecology and Systematics* 17(1):567–594.

Webster, J. R., J. L. Tank, J. B. Wallace, J. L. Meyer, S. L. Eggert, T. P. Ehrman, B. R. Ward, B. L. Bennet, P. F. Wagner, and M. E. McTammy. 2000. Effects of Litter Exclusion and Wood Removal on Phosphorus and Nitrogen Retention in A Forest Stream. *Verhandlungen der Internationale Vereinigung für Limnologie* 27:1337–1340.

Wellnitz, T., S. Y. Kim, and E. Merten. 2014. Do Installed Stream Logjams Change Benthic Community Structure? *Limnologica* 49:68–72.

White, S. L., C. Gowan, K. D. Fausch, J. G. Harris, and W. C. Saunders. 2011. Response of Trout Populations in Five Colorado Streams Two Decades After Habitat Manipulation. *Canadian Journal of Fisheries and Aquatic Sciences* 68(12):2057–2063.

Whiteway, S. L., P. M. Biron, A. Zimmermann, O. Venter, and J. W. A. Grant. 2010. Do In-Stream Restoration Structures Enhance Salmonid Abundance? A Meta-Analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 67:831–841.

Whittaker, R. H., S. A. Levin, and R. B. Root. 1973. Niche, Habitat and Ecotope. *American Naturalist* 107(955):321–338.

Williams, K. L., S. W. Griffiths, K. H. Nislow, S. McKelvey, and J. D. Armstrong. 2009. Response of Juvenile Atlantic Salmon, *Salmo salar*, to the Introduction of Salmon Carcasses in Upland Streams. *Fisheries Management and Ecology* 16(4):290–297.

Williams, R. N. (ed.). 2006. Return to the River: Restoring Salmon Back to the Columbia River. New York: Elsevier.

Winemiller, K. O., A. S. Flecker, and D. J. Hoeinghaus. 2010. Patch Dynamics and Environmental Heterogeneity in Lotic Ecosystems. *Journal of the North American Benthological Society* 29:84–99.

Wipfli, M. S., and C. V. Baxter. 2010. Linking Ecosystems, Food Webs, and Fish Production: Subsidies in Salmonid Watersheds. *Fisheries* 35(8):373–387.

Wipfli, M. S., J. Hudson, and J. P. Caouette. 1998. Influence of Salmon Carcasses on Stream Productivity: Response of Biofilm and Benthic Macroinvertebrates in Southeastern Alaska, U.S.A. *Canadian Journal of Fisheries and Aquatic Science* 55:1503–1511.

Wipfli, M. S., J. Hudson, and J. P. Caouette. 2003. Marine Subsidies in Freshwater Ecosystems: Salmon Carcasses Increase the Growth Rates of Stream-Resident Salmonids. *Transactions of the American Fisheries Society* 132:371–381.

Wohl, E., and D. J. Merritts. 2007. What is a Natural River? *Geography Compass* 1(4):871–900.

Wojan, C., A. Devoe, E. Merten, and T. Wellnitz. 2014. Web-building Spider Response to a Logjam in a Northern Minnesota Stream. *American Midland Naturalist* 172(1):185–190.

Wondzell, S. M. 2011. The Role of the Hyporheic Zone across Stream Networks. *Hydrological Processes* 25:3525–3532.

Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards. 2009. Changes in Hyporheic Flow Following Experimental Removal of a Small, Low-Gradient Stream. *Water Resources Research* 45:W05406, 13 pp.

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Chapter 4
GEOMORPHOLOGY AND HYDROLOGY CONSIDERATIONS

Point Bar Structure, Salmon River, Near Welches, Oregon. Photo credit: Brian Bair.

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4.1 Introduction

Geomorphology is the study of landscape morphology and the processes that create it. Hydrology is the study of the water cycle from precipitation to how water moves through the landscape (both as surface and subsurface water), and back to the atmosphere. With respect to wood, both of these topics are critically important, influencing the type of trees growing within a watershed and the fate of wood within the channel network. Most important is understanding that trees and wood influence geomorphology and hydrology. Vegetation can play an important landscape morphology by influencing surface water runoff and erosion. Forests moderate runoff, diminish downstream flooding, and stabilize stream banks and hillslopes. Because precipitation provides the water responsible for surficial erosion, sediment yield should increase with increasing precipitation. But in reality, erosion and sediment yield tends to decrease with increasing precipitation due to vegetation (Langbien and Schumm 1958, Figure 4-1)

Within channel networks, wood can trap significant quantities of sediment and organic matter, define the morphology of channels and floodplains, reduce rates of bank erosion, limit long-term rates of incision that influence valley formation, and provide habitat resilience to extreme events. There are also instances where wood can result in localized erosion by deflecting flow toward a bank.

Human development since the industrial revolution has had a dramatic impact on forests and wood in streams. Establishing and protecting mature riparian forests along streams provides a passive, long-term means of restoring wood and the functions it once provided, but that can take over a century to establish and start to reverse the geomorphic changes impacting the stream. Re-introducing wood to a stream can be an essential part of rehabilitating a stream's morphology and ecosystem. Wood can also be a cost-effective means for treating channel incision and lateral bank erosion that results in hundreds of millions of dollars in damage to infrastructure throughout the country. It is important to understand the processes by which instream wood can be a benefit or hazard. Properly designed and placed, engineered wood placements can be important in managing unstable wood debris that could otherwise be a problem.

Geomorphic and hydrologic assessments are essential for understanding the past and present conditions within a stream, including how wood naturally influenced the system and how it can be used to restore it. Wood can be used to have either minor or significant hydraulic and geomorphic effects depending on the severity of disturbance and site constraints.

4.2 Geomorphology

A well-founded understanding of the physical and biological processes influencing landscape development is critical to stream restoration and management. Geomorphology is the study of the Earth's surface, the processes that formed it, and how it will change in the future. Fluvial geomorphology focuses on streams: the flow of water through a channel network; the movement of sediment and woody debris; the factors controlling channel form, the stability of stream beds and banks, and the rate and magnitude to which channels move; and how large wood and logjams influence flow conditions to alter the channels and floodplains (Keller and Swanson 1979; Abbe and Montgomery 1996; O'Connor et al. 2003; Montgomery and Abbe 2006; Collins et al. 2012; Wohl 2013). To sustain the functions wood provides to a fluvial system it is imperative to restore mature riparian forests (Abbe and Montgomery 1996; Abbe 2000; Keeton et al. 2007; Collins et al. 2012; Wohl 2013).

One of the most important contributions geomorphology brings to any project is an understanding of how and why a stream looks and functions the way it does over time. Geomorphologists explain the processes and factors influencing landscape evolution: erosion and sedimentation. The climate, intensity and magnitude of precipitation, geologic and soil characteristics, topographic relief, vegetation, and development all influence the flow of surface and subsurface water and the movement of sediment through a watershed. The magnitude and rate of changes to the landscape depend on how these factors change over time. The characteristics of any landscape, including stream channels, is the cumulative result of geomorphic processes over time. Morphological changes to stream channels can occur on timescales ranging from hours to thousands of years. Stream channel morphology will adjust to processes acting on it. If the processes remain relatively constant over time (such as periods of climatic stability), channel morphology adjusts to reflect the process regime and can remain relatively constant. This state is referred to as *equilibrium*. A sediment budget provides a simple illustration of morphologic equilibrium. If the input of sediment into a stream reach is equal to the output, the sediment supply and sediment transport capacity are in a state of equilibrium, and no morphologic adjustments are likely. In cases where the sediment transport capacity extends the sediment supply, the output of sediment exceeds the input. The difference is the erosion within the reach that is enlarging the channel. Conversely, if the sediment output is less than the input (the supply exceeds the transport capacity), sediment storage within the reach is reducing the channel area and altering its morphology. In stream restoration the application of a "reference reach" is based on assumption that the reference reach reflects an equilibrium state under the same set of processes and conditions that affect the project site. The presence of an equilibrium state is limited to relatively low relief watersheds not subject to major physical or biologic disturbances. Even in these areas the term "dynamic equilibrium" is far more applicable because it refers to a range of morphologic conditions a stream will experience over time, Any changes to a stream in dynamic equilibrium represent the variance about a mean and do not reflect long-term adjustments. Factors that will knock a stream out of equilibrium or alter the magnitude and rate of morphologic adjustment include changes to the flow regime (either increased peak flows due to development or reductions due to dams), changes in riparian vegetation or wood loading, or changes to the stream's base level (e.g., influence of sea level fluctuations, tectonics, and landslides on stream outlet elevation). Streams, by definition, are dynamic and subject to spatial and temporal changes (Figure 4-2). Understanding fluvial geomorphology of the system you are working in is essential to defining how the system has been impacted, what the current processes are that restoration design must take into account, defining restoration targets, understanding how watershed and external factors will influence the site and developing designs that accommodate these factors, and predicting how the site will evolve under different restoration scenarios. Channel dynamics influence wood recruitment and the structure of riparian forests. Bedrock channels tend to have relatively low wood quantities due to low rates of wood recruitment and high transport capacities. Wood stability increases when it becomes embedded, so wood is most prevalent in alluvial channels. Alluvial channel dynamics tend to increase proportional to discharge and inversely to the grain size of their beds and banks. Wood input (recruitment rate) increases with the rate at which adjacent riparian forests are eroded. Therefore, wood loading tends to increase in higher order (larger, lower gradient) channels, a trend explained in more detail in Section 1.3.2, *Wood Loading in Natural Settings*, above.

In many situations human-induced changes may have so altered fluvial processes that finding a reference condition that reflects the natural or pre-disturbance condition of the project site will not be possible. Understanding what geomorphic changes a site has undergone and why is the first step in restoring or rehabilitating streams. The next step is defining the desired state of the stream and understanding whether and how wood can be used. Wood can be an essential element in rehabilitating channel form and process, but not in all settings. The role of wood will vary by geology, hydrology, location within the channel network, the local climate, size and type of riparian trees, and historic development.

Wood is naturally found in alluvial streams throughout the United States, in essentially any location where trees grow along the channel or upstream. Wood provides geomorphic and ecologic functions throughout a watershed, from the headwaters to estuaries (e.g., Keller and Swanson 1979; Maser et al. 1988; Maser and Sedell 1994; Abbe 2000; Abbe and Montgomery 2003). There are types of channels where wood isn't typically found or has relatively little effect, such as bedrock canyons or stable confined channels subject to deep flows. Within these locations there is little local recruitment, and wood entering from upstream tends to pass through due to deep fast flows.

The connection between large wood and channel processes, substrate, and morphology has been well documented. Numerous studies—such as, but not limited to Baker (1979), Keller and Swanson (1979), Abbe and Montgomery (1996, 2003), Buffington and Montgomery (1999b), Manga and Kirchner (2000), Baillie and Davies (2002), Stewart and Martin (2005), Magilligan et al. (2008), Montgomery and Abbe (2006), Brummer et al. (2006), and Cordova et al. (2007)—have shown that large wood promotes in-channel sediment storage as the logs deflect flow and increase channel roughness. Large wood promotes heterogeneity in channel form by creating flow divergence and changing local base level. These processes lead to sediment deposition in both upstream and downstream eddies (e.g., Abbe and Montgomery 1996).

When streams are straightened and confined the resulting increase in energy can trigger incision, which then leads to a sequence of morphological stages that have been described in channel evolution models (e.g., Schumm et al. 1984; Schumm 1999; Simon 1989, 1994; Doyle and Shields 2000; Simon and Rinaldi 2006). Because wood can be the dominant grade control in many streams (e.g., Keller and Tally 1979; Abbe 2000; Wallerstein and Thorne 2004) and effectively reduces the shear stress available for sediment transport (e.g., Manga and Kirchner 2000), it follows that wood removal can lead to export of this sediment, channel incision, and subsequent widening (e.g., Guardia 1933; Baker 1979; Hartopo 1991; Abbe 2000; Brooks et al. 2003; Wallerstein and Thorne 2004; Stock et al. 2005; Abbe and Brooks 2011; Daley 2012; Phillips 2012).

GUIDANCE

Basic Geomorphic Questions that Apply to Any Project

- Is the channel profile stable, incising, or aggrading?
- What are local and temporal variances in channel profile versus long-term trends?
- Is the channel moving laterally?
- Is the channel hydraulic geometry stable or does it change over time or within reaches of similar discharge?
- What is the natural variability of stream morphology over time?
- What are the time scales and rates over which the morphologic change occurs?
- Are the current hydrologic, hydraulic, and sediment conditions representative of future conditions?
- How have historic disturbances altered development of the alluvial landscape? Can the system truly be "restored" or simply rehabilitated?
- What physical controls did wood impose on the system under undisturbed natural conditions (e.g., pool formation, channel grade, anabranching and side channels, sediment retention, water surface profile)?

The degree to which wood can influence stream channels is demonstrated in southeastern Australia where floodplain forests have been intact for hundreds of thousands of years. Erskine and Webb (2003) indicated that streams in southeastern Australia that had a history of de-snagging were significantly more incised, had higher flow velocities, and were wider than adjacent streams that were left undisturbed. Brooks and Brierly (2002) describe the complex and stable morphology of the sand-bedded Thurra River in southeastern Australia that is characterized by high wood loading. Brooks et al. (2003) show a dramatic difference in morphology between the Thurra and Cann rivers, sites with similarly sized adjacent catchments, but different riparian conditions. The Thurra valley was preserved and the Cann River was historically cleared of riparian vegetation and instream wood. Brooks and Brierly (2004) go on to describe how the Cann River experienced a 150-fold increase in the rate of channel migration and a 700% increase in channel capacity. Examples exist all across the United States of channel incision where riparian areas were cleared, wood was removed, channels were straightened, dams have impounded bed replenishing sediment, and development has increased peak flows. In most cases of channel incision, wood can play a fundamental role in the restoration of fluvial processes. Applications of engineered log jams have been shown to effectively treat channel incision (e.g., Daley 2012).

Instream wood, as with the addition of any channel roughness, will tend to increase water elevations. Ice jams can have a dramatic influence on river stage and flooding (e.g., Pariset et al. 1966; Beltaos 1983; Smith and Reynolds 1983; Prowse 2001). Logjams form similar but more permanent blockages, and historic accounts recognized how logjams obstructed flow to impound rivers to create lakes (Lyell 1830; Guardia 1933; Harvey et al. 1988; Barrett 1996). The widespread presence of wood in rivers of the United States led to aggressive wood removal by the federal government with the intent of improving navigation and drainage (e.g., Ruffner 1886; Collins et al. 2002).

Channel clearing has had dire consequences to the geomorphology and ecology of streams that largely remain unrecognized, particularly by the public works and flood control districts responsible for managing most of our waterways. This chapter and the manual as a whole demonstrate that the perception that wood is bad is fundamentally flawed. Many of the problems attributed to wood have more to do with inadequately designed infrastructure, such as an undersized culvert or bridge, and encroachment of human development within the floodplain and channel migration zone. The problems also have to do with the fact that humans have changed the character of wood entering our streams. Where we still have riparian forests, the old-growth trees that are inherently stable have been replaced by dense forests of small trees, and the wood entering the river is much smaller and simply flows downstream to cause problems. Restoring and using wood can range from moderate enhancements of edge habitat in highly constrained reaches to valley-altering placements.

In the right placements large wood can contribute to flood and erosion protection, but when inappropriately placed or managed it can also adversely impact flooding. Riparian forests and instream wood can have a significant effect on increasing local flood storage and decreasing the celerity or velocity of flood waves (Anderson 2006; Thomas and Nisbet 2006). Instream wood adds roughness that slows flow velocities and raises water levels, which increases overbank connectivity (e.g., Brummer et al. 2006). Therefore, the defining attributes of forested rivers are trees and wood spreads out a flood hydrograph, increasing the duration of flood inundation while reducing maximum flood stage in downstream reaches (e.g., Anderson 2006; Thomas and Nisbet 2006). This provides a very important ecological enhancement by increasing the duration of floodplain inundation and water retention in reaches with high wood loading, which in turn sustains important aquatic refugia, traps organics and fine sediments, and recharges shallow groundwater. Logjams form preferred habitat for largemouth bass (*Micropterus salmoides*) in the low-gradient sand-bedded rivers of the mid-Atlantic coastal plain (Schenk et al. 2014a), flathead catfish (*Pylodictis olivaris*) in rivers of the Great Plains region (Paukert and Makinster 2008), and smallmouth bass (*Micropterus dolomieu*) and rock bass (*Ambloplites rupestris*) in the Great Lakes (e.g., Bovee et al. 1994). Wood can also store significant quantities of sediment and organic matter that would otherwise move downstream where it could aggravate flooding. Wood restoration projects can therefore be the principal means of restoring both channel and floodplain habitat and can indirectly contribute to reducing downstream flooding. Complex wood structures have been successfully applied to protect banks in a manner that enhances instream and riparian habitat (e.g., Abbe et al. 1997, 2003b, 2003c; Brooks et al. 2004, 2006; Abbe and Brooks 2011).

4.2.1 Wood Structures

Trees enter streams through a variety of mechanisms, such as landslides, avalanches, windstorms, fires, and bank erosion.

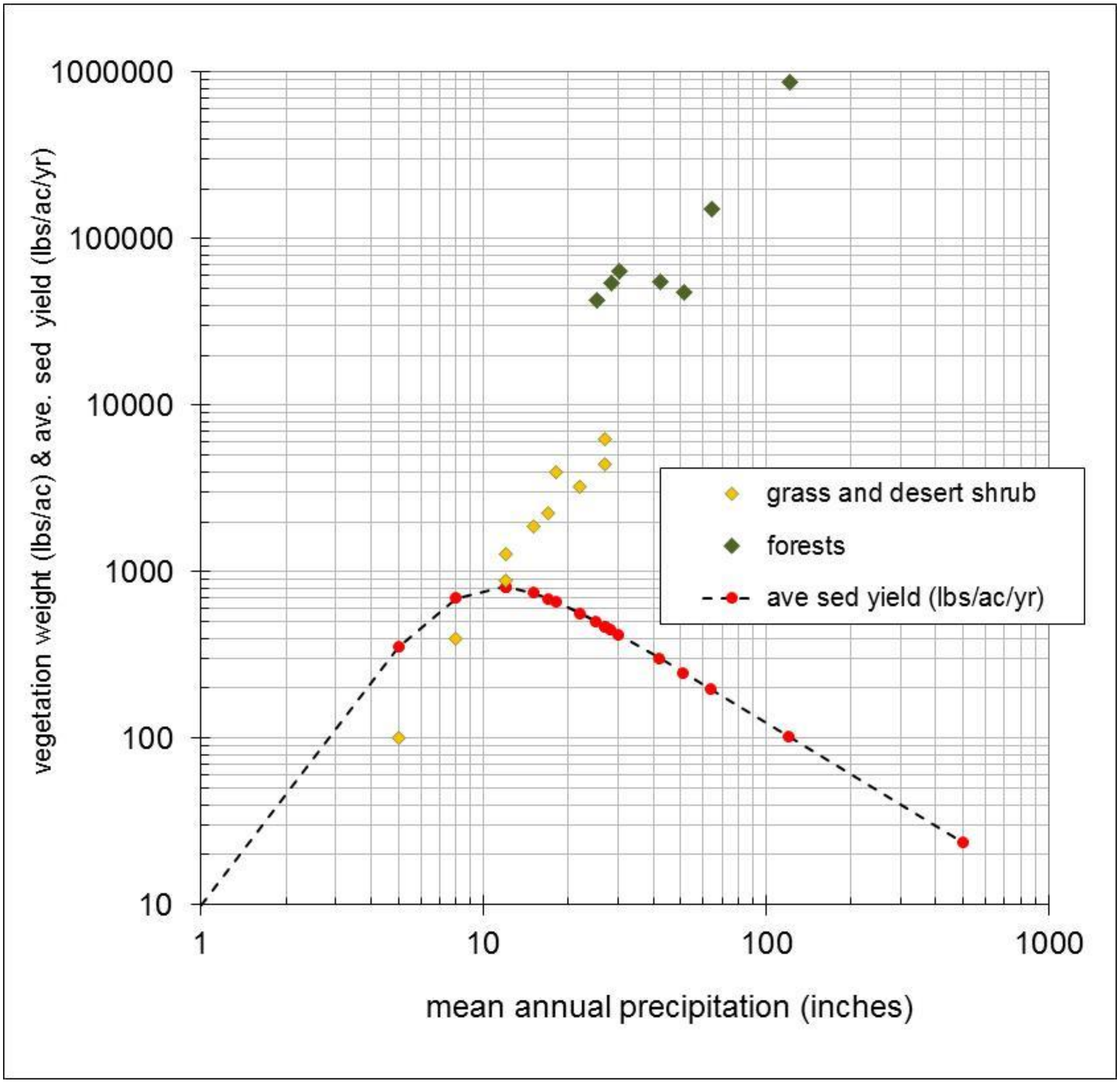
CROSS-REFERENCE

How wood enters and behaves in streams is described in Chapter 1, *Large Wood Introduction*.

Once in a channel, wood can remain exactly where it entered and stay for centuries, or it can move downstream depending on its size and the transport capacity of the channel. Wood that does not move far from where it entered will accumulate mobile wood and form logjams. Wood that moves downstream but ends up embedded in the channel creates snags that can also initiate logjams. The geologic record shows that wood entering a channel network can end up preserved in alluvial sediments. Much of the wood deposited on bars and floodplains will decompose or be consumed within decades by fungi or termites (Hyatt and Naiman 2001; Scherer 2004; Latteral and Naiman 2007). Wood buried in the channel or floodplain that remains within the water table or anaerobic conditions can persist for very long periods (Guyette and Stambaugh 2003; Montgomery and Abbe 2006; Gestaldo and Demko 2011). Some fraction of the wood will end up in lakes or the ocean, and will continue to play a fundamental ecological role (Harmon et al. 1986; Maser et al. 1988; Maser and Sedell 1994).

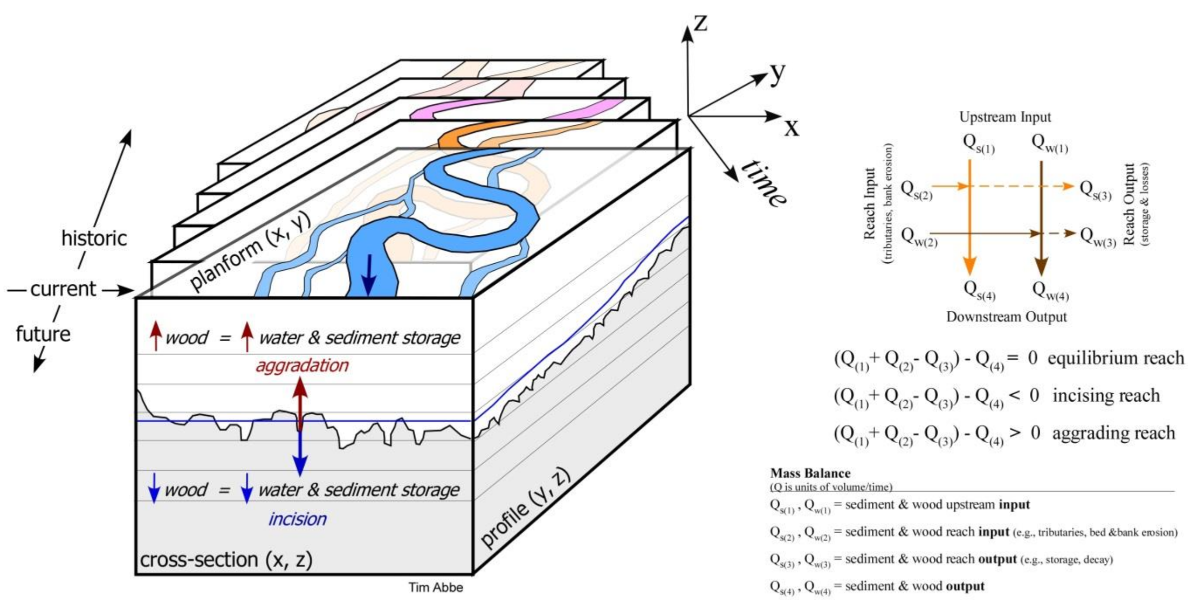
Just as sediment can accumulate into distinct bedforms depending on flow conditions and the characteristics of the grain size distribution, wood can accumulate into distinctive deposits. Studies have documented unique types of wood accumulations or jams in the Pacific Northwest (Abbe 2000; Abbe and Montgomery 2003), northern New York (Kraft and Warren 2003; Keeton et al. 2007), northern Michigan (Morris et al. 2010), South Carolina (Wohl et al. 2011), and the Italian Alps and Chilean and Argentinean Andes (Comiti et al. 2006, 2008). Unique natural wood accumulations occur in different parts of a channel network and have different geomorphic effects (Figure 4-3A). Each of these natural accumulations have inherent physical complexity due to the size and shape of the trees forming the snags. Natural accumulations also include the accumulation of mobile wood debris, referred to as “racking” material. The recognition that natural wood accumulations or logjams can influence channel morphology, limit channel incision, and protect floodplain areas led to the concept of ELJs (Figure 4-3B) (Abbe et al. 1997, 2003b, 2003c; Brooks et al. 2004, 2006; Abbe and Brooks 2011). Wood placement in streams for improving habitat is not new (e.g., Van Cleef 1885; Hewitt 1934; Thompson 2002, 2005), but emulating natural complexity is unique to recent efforts to re-introduce wood to streams. Structure and channel complexity are defining characteristics of engineered logjams that makes some of the current work on wood placement unique from all historical efforts. Complexity is used to refer to the architecture of individual structures designed to include complex shapes and assortments of wood, as well as collect and shed wood debris through time. Complexity also refers to the spatial arrays of ELJs that are used to rehabilitate fluvial processes and morphology, such as restoring anabranching, channel systems, floodplain connectivity, and diverse riparian forest communities.

Figure 4-1. Although Precipitation Increases Surficial Runoff, Erosion Rates Diminish (as measured by sediment yield) due to the Influence of Vegetation



Adapted from Langbein and Schumm (1958).

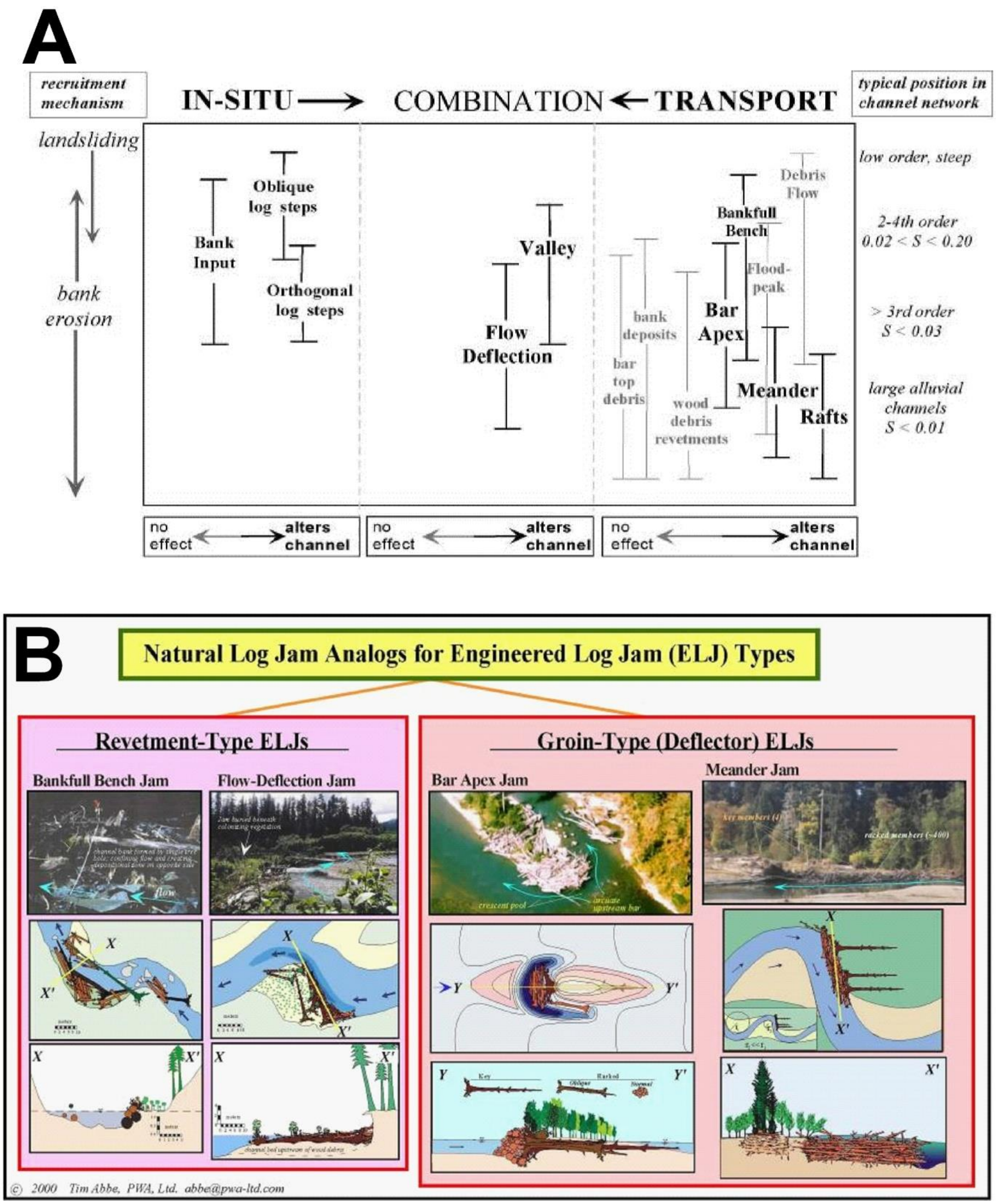
Figure 4-2. Illustration of Several Basic Fundamentals of Fluvial Geomorphology, including Spatial and Temporal Change over Time, the Importance of Sediment Budgets, and the Role of Wood



change over time

channel x-s area (x, z)	floodplain inundation (x, z)	channel location (x, y)	channel profile (y, z)	Channel State	Relationship to Stable Wood
stable	stable	stable	stable	**equilibrium**	more wood increases variance of channel morphology
stable	stable	unstable	stable	**dynamic equilibrium**	more wood diminishes channel migration rates
increasing	decreasing	stable	decreasing	**Incising**	less wood increases sediment transport capacity
decreasing	increasing	unstable	increasing	**Aggrading**	more wood decreases sediment transport capacity

Figure 4-3. (A) General Distribution of Natural Wood Accumulation Types Within a Watershed; (B) Application of Four of Those Types to Engineered Logjam Structures



Sources: (A) Abbe and Montgomery (2003); (B) Abbe et al. (2003).

4.2.2 Big Trees

Wood is a common component of the particulate matter in streams throughout the world.

CROSS-REFERENCE

A detailed description of wood in streams is provided in Chapter 3, *Ecological and Biological Considerations*.

In many areas wood constitutes the largest individual particles found in the stream (Figure 4-4). The size and shape of a tree is critical with regard to its stability in a channel and how it can influence channel morphology (Abbe and Montgomery 1996, 2003; Abbe et al. 2003a; Montgomery et al. 2003; Abbe and Brooks 2011). Keeton et al. (2007) found the number of stable debris jams increased as a function of large logs in Adirondack streams of northern New York, with much greater frequency in old-growth forests. Therefore, the size of riparian trees directly affects the magnitude of the geomorphic effects and extent of the channel network affected. Almost all of the old-growth riparian forests in the United States have been cleared, but historical accounts not only describe the large trees that once existed, but the effect they had on altering rivers. The eastern sycamore (*Platanus occidentalis*), native to stream banks throughout much of the East and Midwest (Figure 4-5), historically formed giant snags even in the largest rivers such as the Mississippi (Dacy 1921). When George Washington visited the Ohio Valley in 1771 he noted sycamores with basal diameters over 4 meters (13 feet) (Federal Writers' Project 1952). American chestnuts (*Castanea dentata*) in the Appalachian Mountains reached diameters of 5 meters (16 feet) (Grimm 1967). The old-growth bald cypress (*Taxodium distichum*) forests that included trees 4.5 meters (15 feet) in diameter, currently cover only 0.01% of the 131 million acres in the southeastern United States that they did just 200 years ago (Stahle et al. 2006).

John Muir (1878) wrote of "sequoia stream-making," the process by which the falling of a single giant sequoia (*Sequoiadendron giganteum*) in the Sierra Nevada of California would impound streams and capture sediment, a process that created a series of bogs that merged together to provide the ideal growing conditions for these trees in an otherwise dry and steep landscape. Veatch (1906) noted how large trees would form "planters" in the bed of the Red River, Louisiana, which would then create logjams capable of impounding and redirecting the river. Eighteen feet of bed aggradation behind logjams initiated by large fallen trees was observed in the Middle Fork Teanaway River of Central Washington State (Russell 1898). Recent research has demonstrated that following logging and channel clearing, alluvial channels in West Fork Teanaway River disappeared and the river cut 1–2 meters (3.3–6.6 feet) into the underlying bedrock at a mean rate of 30 millimeters (1.2 inches) per year, 600 times faster than the geologic incision rate (Stock et al. 2005). Hazard (1948) wrote of fallen cedar trees blocking the lower Quinault River, and Wolff (1916) noted that "a close study of conditions shows that in every instance the current was first deflected by an accumulation of drift, the huge timber of this section serving readily in its formation." From the few records of what rivers were once like, we can get a glimpse of historic wood loading (Figure 4-6).

Today, to restore wood within the full range of environments it once influenced, we need to engineer solutions using smaller trees to provide the function large trees once provided. Engineered wood placements have been successfully used to reverse incision of rivers impacted by historic clearing and splash damming (Abbe and Brooks 2011). In low-order streams a single piece of wood can have dimensions easily exceeding those of the channel itself and create steps that can account for the majority of the vertical drop of a channel (e.g., Keller and Tally 1979; Montgomery et al. 1995b, 1996b; Montgomery and Buffington 1997; Abbe 2000; Abbe and Montgomery 2003). In larger order channels a piece of relatively large wood can form the nucleus of much larger accumulations (i.e., logjams) that can redirect currents, alter channel planform, or even completely block the channel (e.g., Abbe and Montgomery 1996, 2003). It is now well recognized that wood can be the principal control in channel avulsions and anabranching (Figure 4-7) (Hickin 2004; Sedell and Frogatt 1984; Abbe and Montgomery 1996; Makaske et al. 2002; Abbe et al. 2003a; Montgomery and Abbe 2006; Sear et al. 2010; Phillips 2012) and defining the structure of floodplain forests (Figure 4-8) (Collins et al. 2012).

4.2.3 Hydraulic Influence of Wood

Observations described above are largely due to the hydraulic influence of wood, particularly in reducing the stream's erosive capacity by partitioning shear stress. Wood induces geomorphic change by controlling the hydraulic processes that erode, transport, and deposit sediments. A detailed discussion regarding the forces acting on wood is provided in Chapter 6, *Engineering Considerations*, but because wood can influence sediment transport and bank erosion, a brief discussion is included here.

Stable wood adds roughness to a channel that can range from bed texture to obstructions that occlude the entire channel. The simplest hydraulic expression that accounts for frictional energy loss due to channel roughness is the commonly used Manning's equation that incorporates a roughness coefficient, the Manning's n:

Equation 4-1:

$$U = \frac{R^{2/3} S^{1/2}}{n}$$

where

U = mean flow velocity—meters/second

R = hydraulic radius = A/P, m

A = cross-sectional area of flow—square meters

P = wetted perimeter of cross-section—meters

S = energy gradient ~ channel gradient

n = Manning's roughness coefficient

Because discharge, Q, is the product of mean velocity, U, and cross-sectional area of the flow, A, substituting the Manning's expression for U yields:

Equation 4-2:

$$Q = \frac{A\, R^{2/3} S^{1/2}}{n}$$

For a wide rectangular channel cross-section, R can be approximated by average channel depth, h. Because the cross-section area, A, is simply width. w, multiplied by depth, h:

Equation 4-3:

$$Q = \frac{h\, w\, h^{2/3} S^{1/2}}{n}$$

$$= \frac{w\, h^{5/3} S^{1/2}}{n}$$

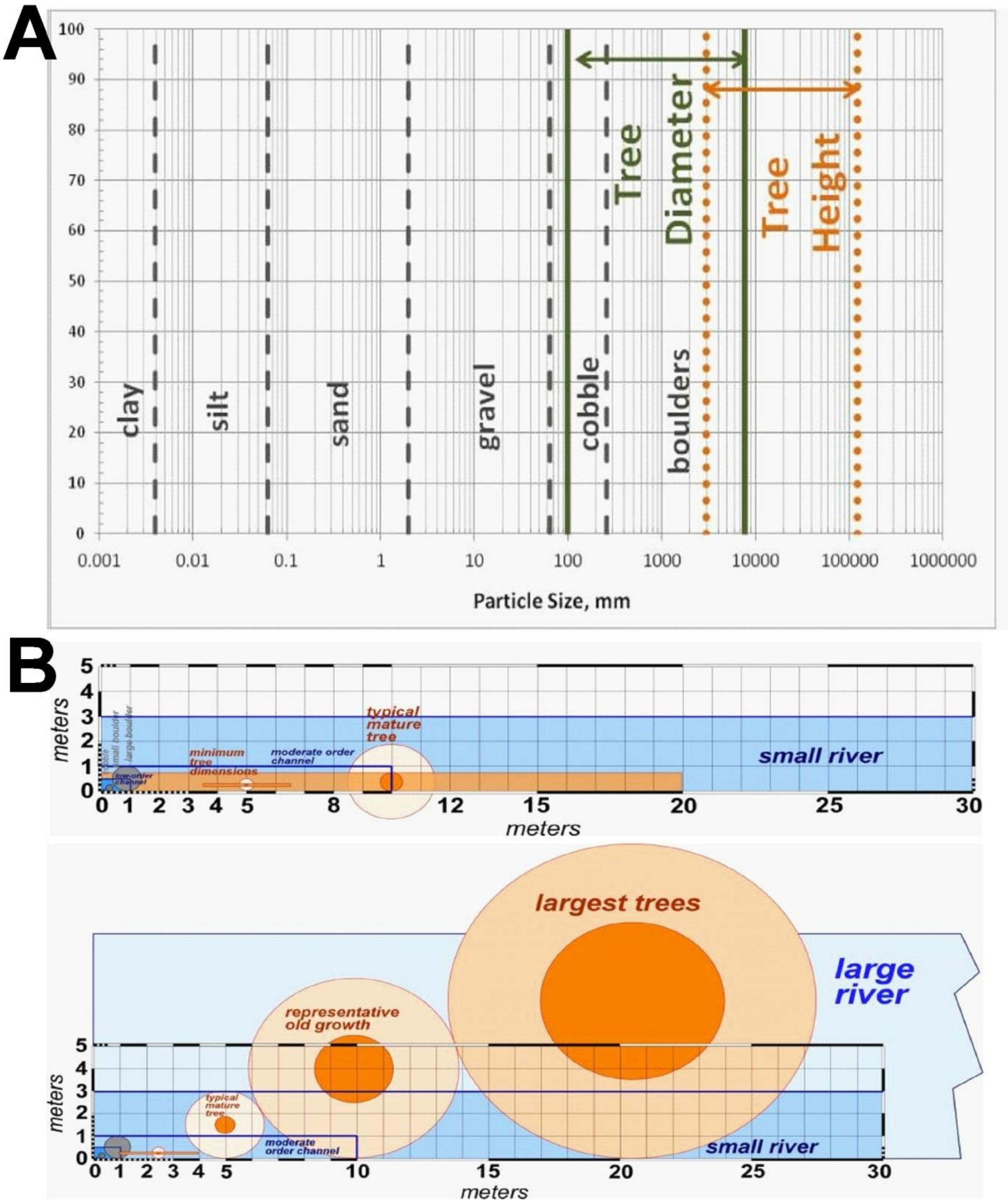
Solving for depth gives:

Equation 4-4:

$$h = \left(\frac{Qn}{(wS^{0.5})}\right)^{3/5}$$

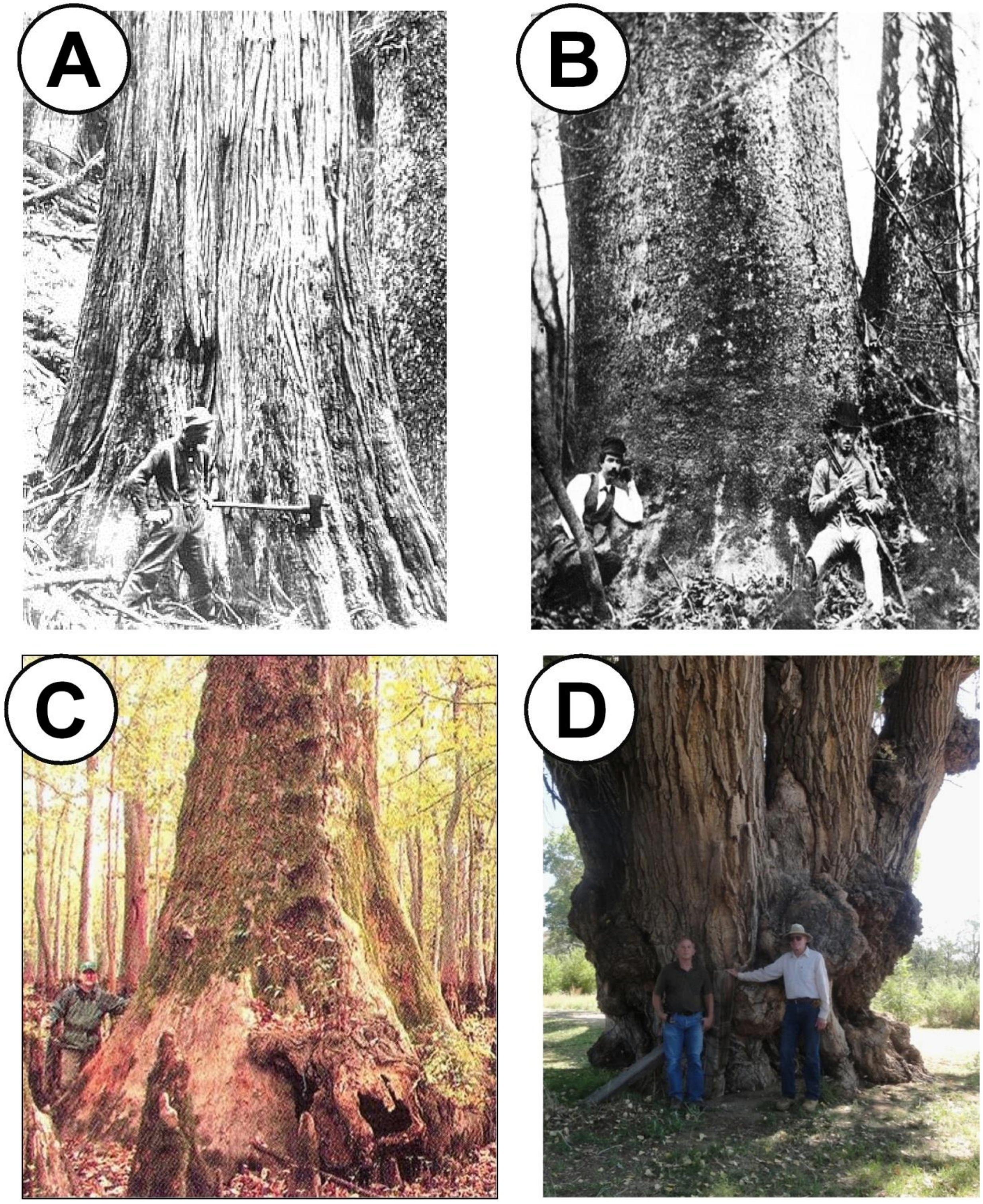
Based on this simple expression we see that water depth increases with roughness when other variables are held constant.

Figure 4-4. Wood is Typically the Largest Bed Material Entering Streams and Tends to Get Larger in Lower Elevations of a Watershed (Larger Channels), the Inverse of Rock Particles



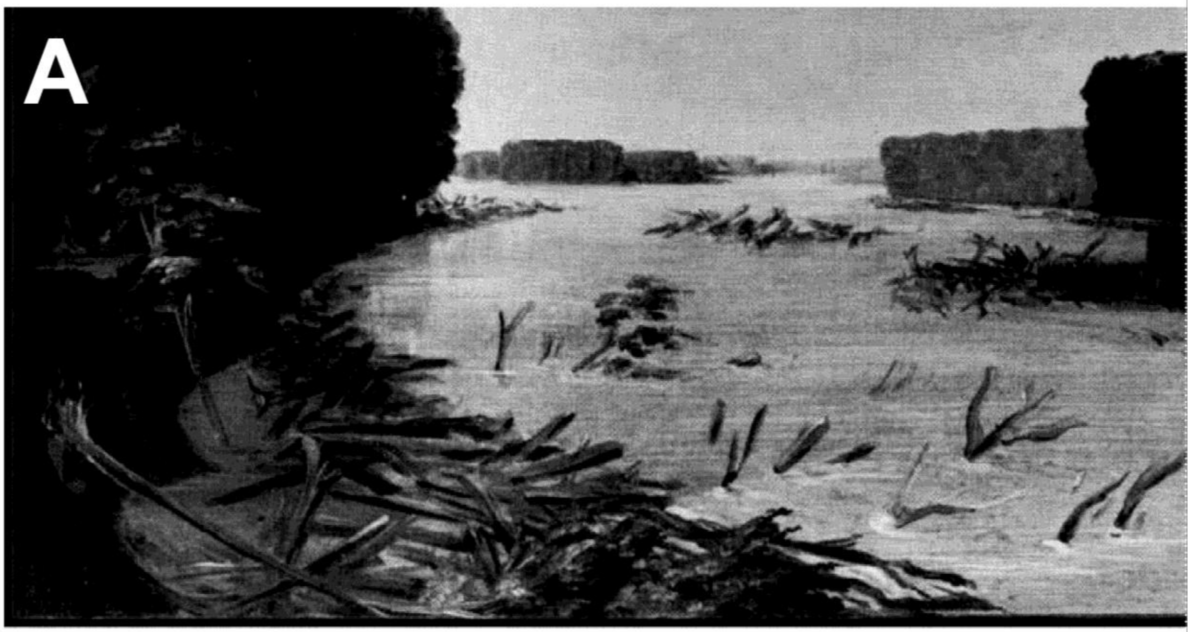
(A) A plot of particle size illustrating the range of tree size. (B) Looking at the size of snags relative to different channel dimensions.

Figure 4-5. Big Trees Were Historically Common Along Streams Throughout the United States



(A) Western Red Cedar, Washington. (B) American Sycamore, Indiana. (C) Bald Cypress, Arkansas (Stahle et al. 2006). (D) Fremont Cottonwood, Arizona.

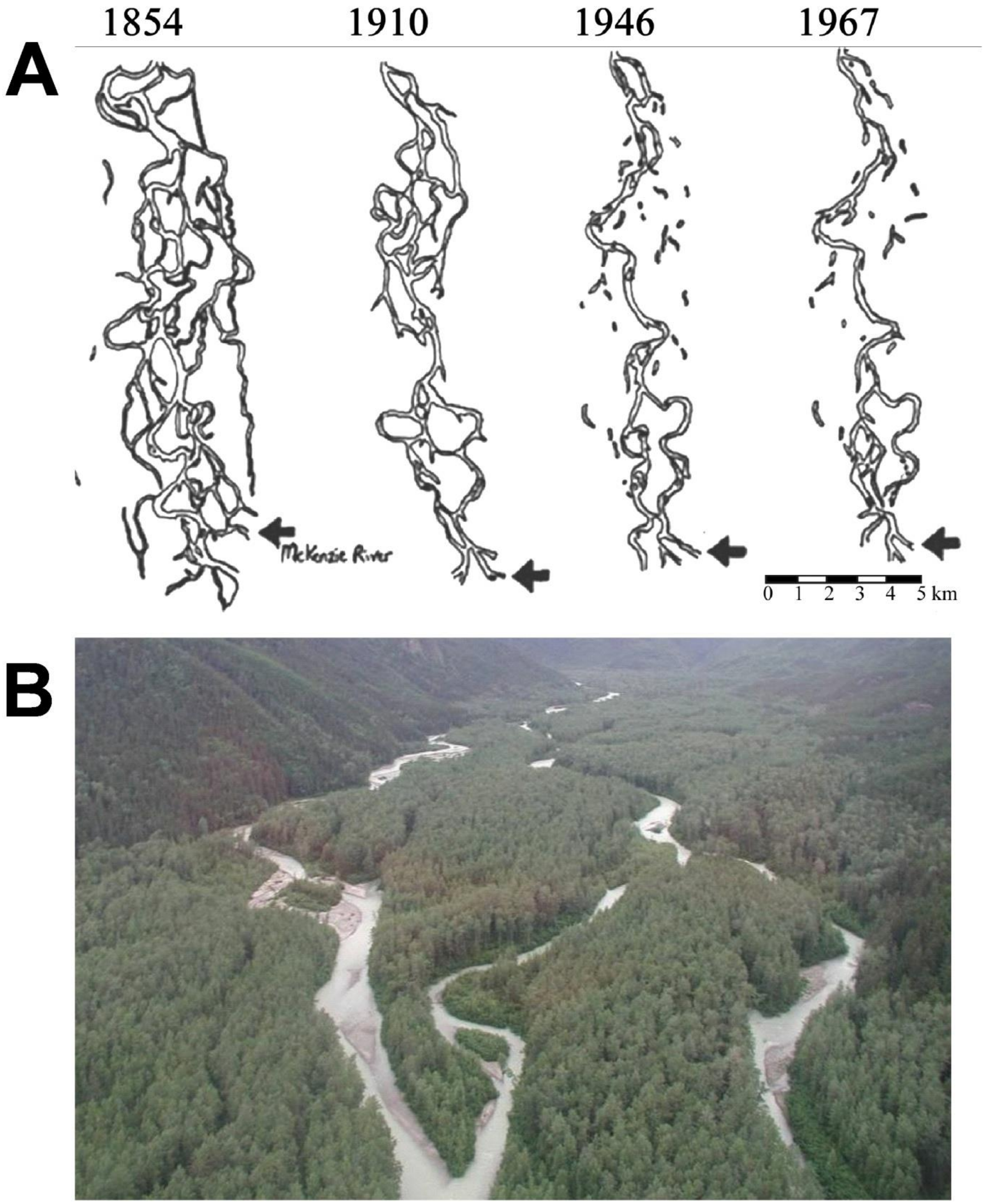
Figure 4-6. (A) Snags and Logjams, Were Common Throughout Much of the Missouri and other Midwestern Rivers, as Depicted in this Illustration by George Catlin in 1832; (B) Undated Photo, Circa Early 1900s, of a River on the Olympic Peninsula of Washington Loaded with Sitka Spruce (*Picea sitchensis*) Snags



"View on the Missouri, Alluvial Banks Falling in, 600 Miles above St. Louis"
George Catlin, 1832. National Museum of American Art, Smithsonian Institution.

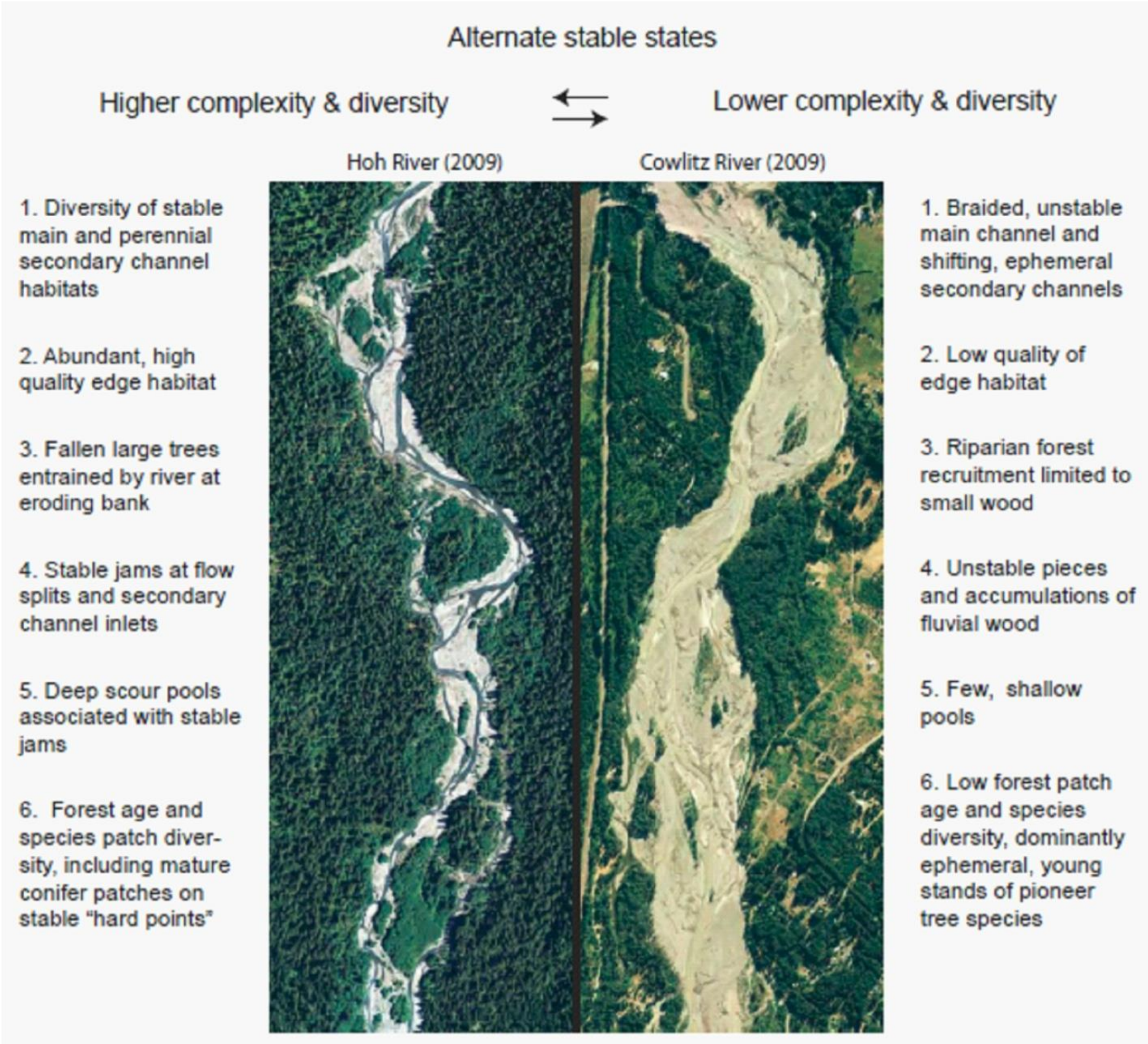
Property of University of Washington Libraries, Special Collections Division. PH Coll 341

Figure 4-7. (A) Historic Changes to the Upper Willamette Transforming the Natural Anabranching Morphology into a Single-Thread Channel; (B) Lower Taiya River, a Wood-Rich Anabranching River in Southeastern Alaska



Sources: (A) from Sedell and Frogatt 1984; (B) from Abbe et al. 2003b.

Figure 4-8. Comparison of an Alluvial River with Wood (Hoh River, Washington) to One Where Wood Has Been Removed (Cowlitz River, Washington)



Source: Collins et al. (2012).

Manning's n tends to diminish with increasing water depth, except in cases where wood extends through the range of water depths and is even suspended over the current channel, in which cases there may be no change or even an increase in n. When the roughness begins to reduce the channel's cross-sectional area, w, the increase in water depth is even greater. Wood has to obstruct 10% or more of a channel before it has an appreciable effect on conveyance and stage (Gippel et al. 1992, 1994; Gippel 1995). When blockage coefficients rise above 0.1 (wood is obstructing 10% of channel cross-sectional area), there is a substantial (non-linear) decrease in conveyance and an associated increase in water elevations (depths).

Manning's n is the sum of all the factors contributing roughness or frictional energy loss:

Equation 4-5:

$$n = n_{GS} + n_{BF} + n_{WD} + n_{PF} + n_{others}$$

where:

n = Manning's roughness coefficient

n_{GS} = roughness contribution from grain size of bed material

n_{BF} = roughness contribution from bedforms

n_{WD} = roughness contribution from wood

n_{PL} = roughness contribution from channel planform = f (sinuosity, width variance)

n_{others} = roughness contribution from other factors

Shields and Gippel (1995) and Buffington and Montgomery (1999a, 1999b, 1999c) demonstrate how the roughness contribution of wood partitions roughness, alters flow conditions, and creates more complex bed textures. Examining flow around a snag illustrates some of the basic hydraulic effects wood can impose and how it can change channel bed topography and substrate characteristics (Figure 4-9). Unobstructed flow vectors are dominated by a downstream horizontal component. As flow approaches a bluff body such as a snag or logjam, the downstream horizontal component diminishes while the downward and lateral components increase. This generates vortex flow and bed scour immediately upstream of the obstruction. Flow around a bluff body creates three distinct domains of flow: (1) accelerated downstream flow in the constricted unobstructed portion of the channel, (2) an eddy of lower velocity recirculating flow immediately downstream (leeward) of the obstruction, and (3) a "vortex street" separating the two domains (Figure 4-9). Wood imposes fluid resistance that is referred to as drag and is proportional to the fluid velocity squared in turbulent flow that occurs in streams. There are several different types of drag associated with instream wood, The most important is *form* (or *pressure*) *drag*, which results from the shape and relative size (to the wetted cross-section) of the wood structure. Secondary types of drag that are usually not considered are *skin friction* (or *surface*) *drag* and *wake drag*. Skin drag is due to friction water encounters along the surface area or skin of the wood. An object in flowing water also creates a wake that dissipates energy and thus contributes to drag. When flow moves through an array of objects (pieces of wood comprising a logjam), the wakes begin to interfere with one another. The closer the spacing of the array, the greater the wake interference and the greater the reduction in the water's local approach velocity, until the array (logjam) behaves like a bluff body defined by its form drag.

Because drag is a measure of the energy losses, it can be used to illustrate how wood reduces a stream's energy available to do work such as sediment transport and bank erosion. Shear stress is commonly defined by the depth slope product:

$$\tau_o = \rho\ g\ h\ S$$

where:

τ_o = shear stress (Pa),

ρ = fluid density (kg/m^3),

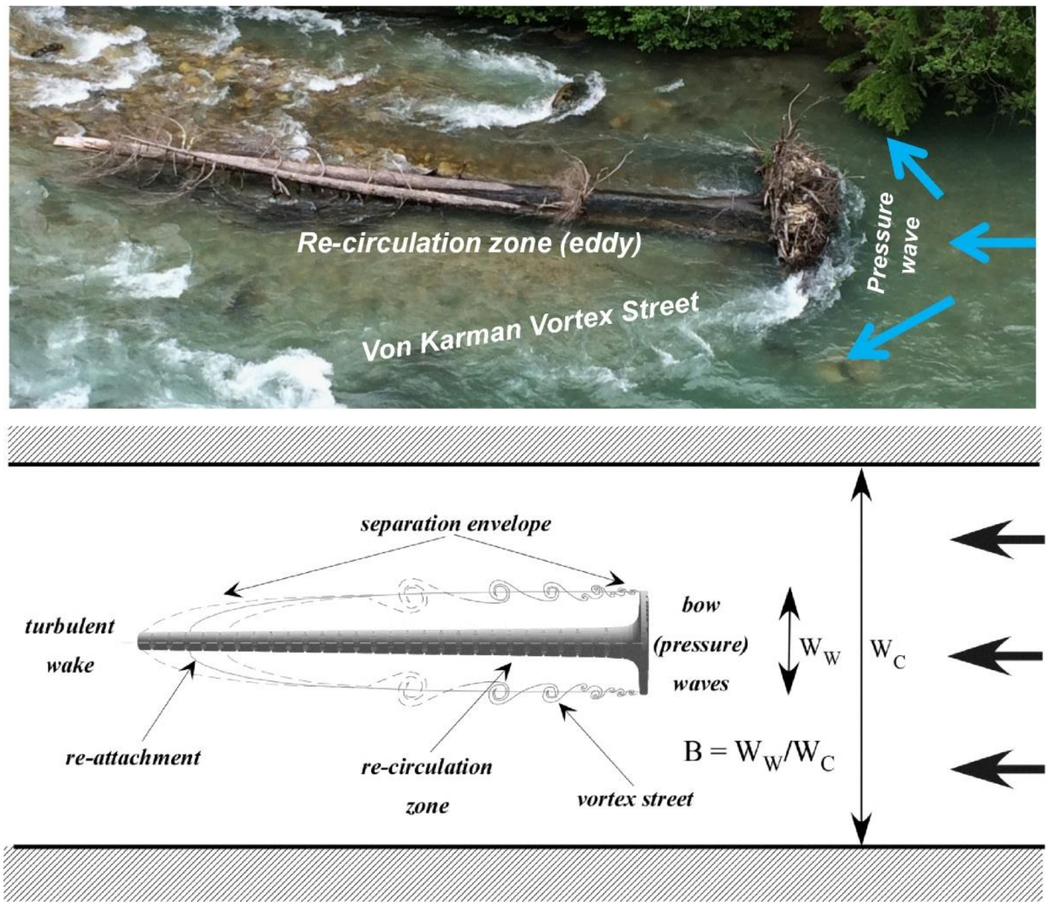
g = gravitational acceleration (m/s^2),

h = fluid depth (m), and

S = energy gradient (~water surface slope).

This expression represents the total shear stress acting on the bed and is thus the sum of the shear stresses acting on different objects within the stream channel, principally sediment and wood. So the more wood engages flow, the greater the shear stress acting on wood and the less shear stress there is to transport sediment or erode the channel. This concept is referred to as *stress partitioning* and is key to understanding some of the hydraulic and geomorphic effects of wood.

Figure 4-9. Flow Around a Stable Snag

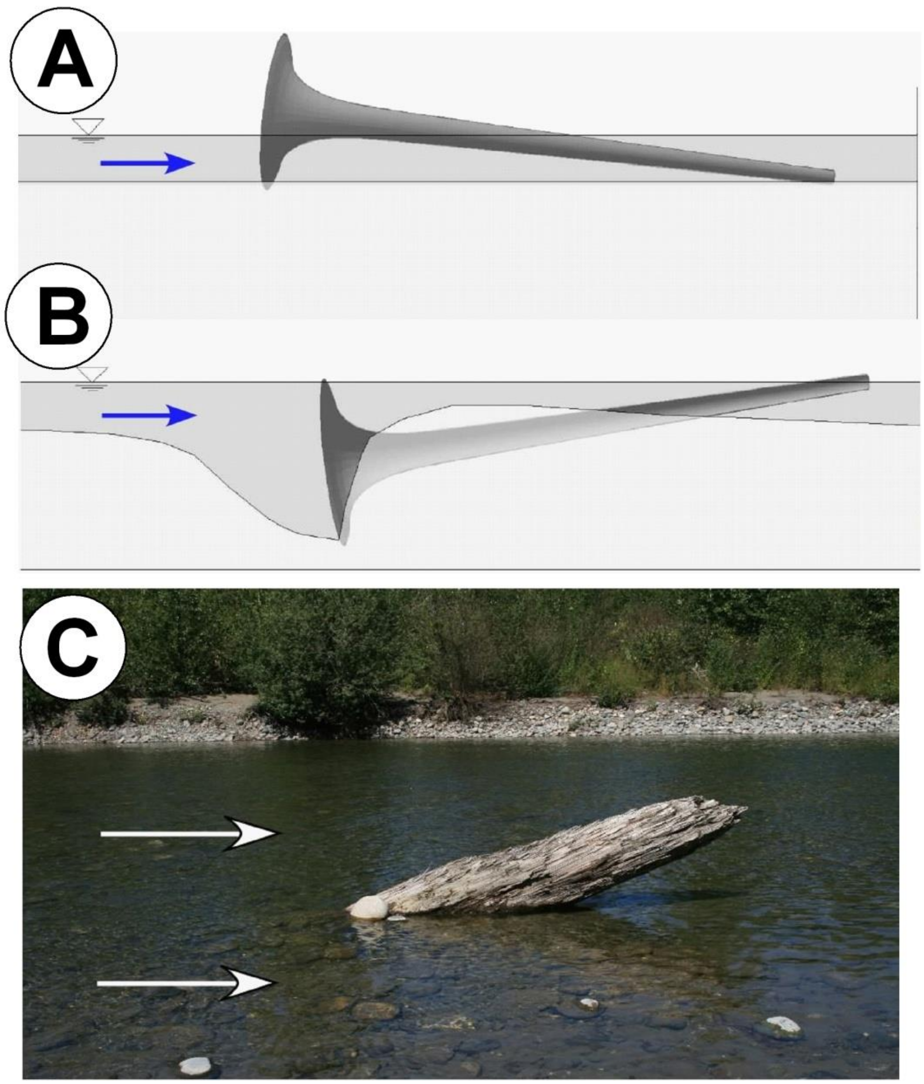


Scour around the rootwad and sedimentation within the eddy increases passive earth resistance stabilizing the snag. The ratio of the snag (or logjam) width, W_W, to the channel width, W_C, is defined as the blockage coefficient, B. The upstream width of the snag or logjam defines the downstream flow separation envelope and recirculation zone (eddy). The length of the obstruction has no effect on the re-circulation zone. The approach velocity and shape and permeability of the structure affect vortex development at flow separation. In cases where vortex diameter, DA, approaches $0.5W_W$, turbulent exchange in the re-circulation zone limits sediment accumulation. Therefore, conditions where $W_W >> 2D_A$ best promote the development of bars and islands. The deposition of bed material increases resisting forces by adding surcharge (vertical load) and passive earth pressure (lateral load) that counteract buoyant and drag forces to help stabilize the wood (e.g., Abbe 2000; Abbe et al. 2003b; Abbe and Brooks 2011). The re-circulation zone creates hydraulic refugia for fish, and sediment deposition can create areas more suitable for spawning.

The hydraulic effects of wood are also reflected in the flow patterns within the stream. Individual snags or logjams create obstructions that alter streamlines and increase turbulence. Downstream velocities are reduced immediately upstream of an obstruction, then accelerate as they move around. The vortices that form can contribute to bed scour that can affect the wood's stability (both positively and negatively). Scour allows wood to become more embedded within the stream (increasing stability) or remove sediment that provided resistance (decreasing stability). If the wood forms a large enough obstruction it creates an eddy of recirculating lower velocity flow (where sediment can settle out) and increasing stability by adding surcharge (burial) and passive earth pressures (buttressing) (Abbe and Montgomery 1996; Abbe 2000; Abbe et al. 2003b; Brooks et al. 2004, 2006; Abbe and Brooks 2011). Natural snags are often observed embedded in a river channel with their tips pointed downstream (Figure 4-10).

Scour at the upstream end of a snag allows the rootwad or basal end of the snag to settle into the stream bed (Figures 4-9 and 4-10). Embedment dramatically increases the resisting forces acting on the snag and its stability (Abbe and Montgomery 1996; Abbe et al. 2003b; Abbe and Brooks 2011). For snags that aren't large enough, the increase in buoyancy associated with settlement can destabilize them, and they can move down the river by spinning 360° before stopping again and the process repeating itself. Engineered solutions can be to simply install posts or piles on either side of a snag immediately downstream of its rootwad, thereby providing the passive earth pressure resistance of a large buried rootwad.

Figure 4-10. Process by Which a Snag Becomes Imbedded in a Channel Bed



Downward and lateral acceleration of water velocity upstream of snag (see Figure 4-9) produces vortices that scour the bed around the rootwad (A, B). If the snag has net downward gravitational force, the rootwad settles into the stream bed (B, C). Adapted from Abbe (2000).

Manga and Kirchner (2000) provide an examination of partitioning shear stress to demonstrate how wood reduces the available energy for sediment transport, thereby diminishing the median grain size of a channel bed:

Equation 4-6:

$$\tau_0 = \tau_{GS} + \tau_{BF} + \tau_{LW} + \tau_{others}$$

where:

τ_0	=	total bed shear stress, ρgRS
ρ	=	water density
g	=	gravity
R	=	hydraulic radius
S	=	slope of energy grade line
τ_{GS}	=	grain stress that is effective shear stress available to sediment transport
τ_{BF}	=	stress component due to wood
τ_{LW}	=	stress component due to wood
τ_{others}	=	stress component due to wood

Manga and Kirchner (2000) present three different arguments for how wood reduces the shear stress available to do work on the bed and banks of a channel based on drag force it imposes:

1. Drag associated with water velocity
2. Drag inferred from water slopes
3. Drag from water steps

All three of these effects are visually apparent in steep channel wood accumulations, such as those illustrated in Figure 4-10 where the wood is clearly slowing down flow velocities, reducing water slopes, and forming distinct steps in the channel profile. The force of water acting on an obstruction such as wood is expressed as

Equation 4-7:

$$\frac{F}{A_{LW}} = \frac{1}{2}\rho\, C_D U^2$$

where:

F	=	drag force per unit area
C_D	=	drag coefficient
A_{LW}	=	area of projection normal to flow (e.g., ELJ width * depth)
ρ	=	density of water (1,000 kilograms per cubic meter)
U	=	design flow in channel; suggested V_{100}

C_D is dependent on Reynolds number ($Re = \rho u_* D_{50}/\mu$), Froude number ($Fr = U/(gh)^{0.5}$), the object's shape, and the object's orientation. Drag coefficients for wood have been estimated in several laboratory and field studies (e.g., Shields and Gippel 1995; Hygelund and Manga 2003; Manners et al. 2007; Shields and Alonso 2012). Measurements of C_D found that the extent to which wood obstructs or blocks flow can influence drag. Shields and Gippel (1995) used experimental data (Gippel el al. 1992, 1994) to derive an expression for the apparent drag coefficient based on blockage:

Equation 4-8:

$$C_{Da} = \frac{C_D}{(1-B)^2}$$

where:

u_*	=	shear velocity = U κ $(\ln(h/0.258\ D_{90}))^1$ (Wilcock et al. 1996)
μ	=	dynamic viscosity (0.00089 N s/m^2)
k	=	von Karman's constant = 0.4
D_{90}	=	grain size for which 90% of bed is finer
D_{50}	=	median grain size of the bed
C_{Da}	=	apparent drag coefficient due to blockage effect
B	=	blockage coefficient = A_{LW}/A_c
A_{LW}	=	area of wood projected normal to flow
A_c	=	cross-section area of flow

The blockage coefficient, B, can be reduced to the ratio of the submerged height of wood, H, to average water depth, h. For a submerged log, H is equivalent to log diameter (Manga and Kirchner 2000):

Equation 4-9:

$$B = \frac{H}{h}$$

Dividing the drag force imposed on wood by the channel bed area provides an estimate of the reach-averaged resistance or drag due to wood:

Equation 4-10:

$$\tau_{LW} = \rho\, C_{Da} \frac{H}{2L} U^2$$

where L = distance between wood.

The role of submerged wood in stress partitioning can then be examined using a force balance equation using only bed texture and large wood roughness (Manga and Kirchner 2000). The first term in the equation below is equivalent to τ_{GS}, the second term to τ_{LW}, and the third to τ_0.

Equation 4-11:

$$\underbrace{\rho C_B\, U^2}_{\tau_{GS}} + \underbrace{\rho C_{Da} \frac{H}{2L} U^2}_{\tau_{LW}} = \underbrace{\rho\, g\, h\, S}_{\tau_0}$$

where C_B = drag coefficient for the channel bed.

Another approach examined by Manga and Kirchner (2000) uses water surface slope measurements to infer drag. They measured a reach averaged bed slope, S_b, of 0.00346, but the average water surface slope, S_w, between large wood was considerably less, between 0.0009 and 0.0021. Therefore, in the sub-reach scale between large wood the flow is not uniform (bed and water slopes are not equal). The energy gradient, S, can be estimated using energy arguments (Robert 1997):

Equation 4-12:

$$S = S_w - Fr^2\,(S_w - S_b)$$

where:

- Fr = Froude number = $U/(gh)^{0.5}$
- S_b = average bed slope
- S_w = average slope between wood

In the example from Manga and Kirchner (2000), Fr = 0.19. The average bed stress, $\tau_{GS} = \rho g h S_w$. The additional resistance provided by wood causes a reduction in slope of the water surface and is expressed by

Equation 4-13:

$$\tau_{LW} = \rho\, g\, \bar{h}\, (S_b - S_w)$$

where $\bar{h}$ = average water depth.

The slope reduction between a series of log steps provides a simple illustration. By dissipating energy in vertical drops, the steps reduce the energy throughout the channel length. Sediment storage between the steps reflects the reduction in transport capacity resulting from the steps. In their example, Manga and Kirchner (2000) found the water surface slope between wood is about half the reach-averaged slope, so the large wood must be responsible for about half the resistance to flow. Using a form of the Bernoulli equation, assuming h=0.36m, S_b=0.0035, and S_w=0.0018, then τ_{LW} = 6.0 Pa.

Manga and Kirchner (2000) go on to show the effect of wood by looking at water surface steps. The magnitude of energy dissipation over a step can be estimated by defining energy per unit volume in cross-section of flow.

Equation 4-14:

$$E_m = \rho g(z + h) + \frac{1}{2}\rho\, \alpha\, U^2$$

$$= \rho g(z + h) + \frac{\rho \alpha q^2}{2h^2}$$

where:

- z = bed elevation above arbitrary datum
- q = discharge per unit width
- h = local water depth
- $\bar{h}$ = average water depth
- α = coefficient between 1 and 1.4 that accounts for the fact that the square of velocity is somewhat less than the mean of the squared velocities of the individual water parcels comprising the flow (Richards 1982)

Manga and Kirchner (2000) show that if the water surface elevation drops by Δh (from $h+\Delta h/2$ to $h-\Delta h/2$), the energy, E_m, will be reduced by ΔE_m,

Equation 4-15:

$$\Delta E_m \approx -\rho g \Delta h + \frac{\rho \alpha q^2 \Delta h}{\bar{h} h^2}$$

Loss of potential energy — Gain of kinetic energy

If gh >> U^2 (equivalent to the condition that Fr^2 is small), then change in kinetic energy will be small compared to change in potential energy (Manga and Kirchner 2000). The effect of large wood in terms of an average shear stress is the sum of energy loss over the cross-section, and averaging over the area of the bed yields

Equation 4-16:

$$\tau_{LW} \approx \rho g \bar{h} \frac{\Delta h}{L}$$

where L is the spacing between large wood and the respective water surface steps.

The difference between the average bed slope, S_b, and average water slope between wood, S_w, is equal to ratio Δh/L, so Equation 4-16 is equivalent to

Equation 4-17:

$$\tau_{LW} = \rho g (S_b - S_w).$$

The effect of wood on reducing sediment transport capacity is directly proportional to the relative head loss (Δh/Δz), where Δz is total vertical drop channel and Δh is vertical drop due to wood. Wood can account for more 90% of the vertical drop in natural channels (Keller and Tally 1979; Abbe 2000; Abbe and Montgomery 2003). Energy dissipation by wood affects flow conditions, channel form, and sediment storage (Figure 4-11). These effects can occur throughout much of a channel network, from steep headwater channels to large low-gradient channels.

Figure 4-11. Natural Log Steps Influencing Water Elevations and Distribution of Shear Stress in Fisher Creek in the North Cascades, Washington

The wood impounds the channel into a series of steps that lower the water surface slope, which partitions shear stress and lowers the shear stress available for sediment transport. This increases sediment storage and reduces the median grain size of the bed.

4.2.4 Channel Morphology

The physical effect of wood is clearly evident when looking at the variations in bed topography and texture variability of channels with and without wood (Figure 4-12). Montgomery and Buffington (1997) found that channel morphology at the reach scale is not just controlled by discharge and sediment supply, but also wood. In their channel classification they demonstrate how wood can "force" changes in bed morphology such as transforming a plane bed into a pool-riffle channel type. Montgomery and Buffington (1993) stratify specific channel morphologies into three basic reach categories as a function of reach average slope (Table 4-1).

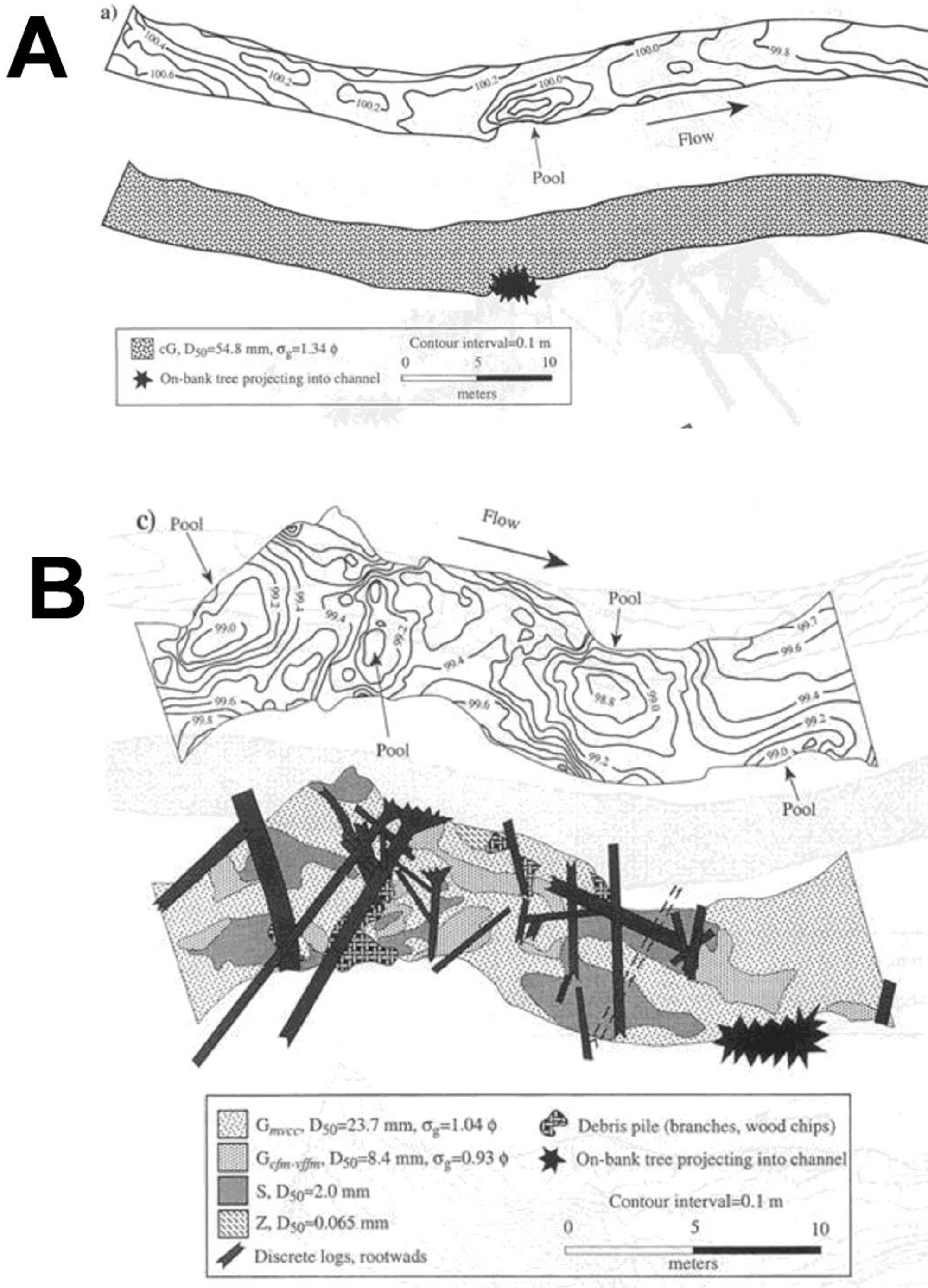
Low-gradient channels ("response" reaches) are particularly susceptible to morphologic alteration due to changes in discharge and sediment load, which can result from land development (e.g., Hammer 1972; Leopold 1973; Graf 1975; Dunne and Leopold 1978; Booth 1990, 1991; Booth and Reinelt 1993; Moscrip and Montgomery 1997). The presence and age of riparian forests have a significant effect on stream channel morphology. Lunetta et al. (1997) found the percentage of forced pool-riffle reaches went from 100% for channels with late seral stage riparian buffers (30 meters [98 feet] on each bank) to 35% in non-forest lands (urban, agriculture, rangeland). Ditching, diking, and dredging in floodplains primarily found in urban and agricultural regions was associated with 73% of the coho salmon rearing habitat losses in the Skagit River system (Beechie and Wyman 1992). Rot et al. (2000) show that the number of stream pools with residual depths > 0.5 meter (1.6 feet) increases rapidly with riparian forest stand age, diminishing only after stands reach ages of more than 200 years (Figure 4-13A). Hilderbrand et al. (1997) found that pool area increased after wood placement in low-gradient streams of southwest Virginia.

Table 4-1. Channel Reach Classification

Reach Category	Channel Reach Slope (S)	Typical Channel Morphology (Pacific Northwest)
Source	≥ 0.20	Headwater colluvial channels prone to debris flows
Transport	0.04 ≤ S < 0.20	Cascade and step-pool
Response	S < 0.04	Plane-bed,[1] forced pool-riffle[2] (0.01 < S < 0.04) Riffle dominated pool-riffle[1] (0.01 ≤ S < 0.02) Pool-riffle[3] (S < 0.01)

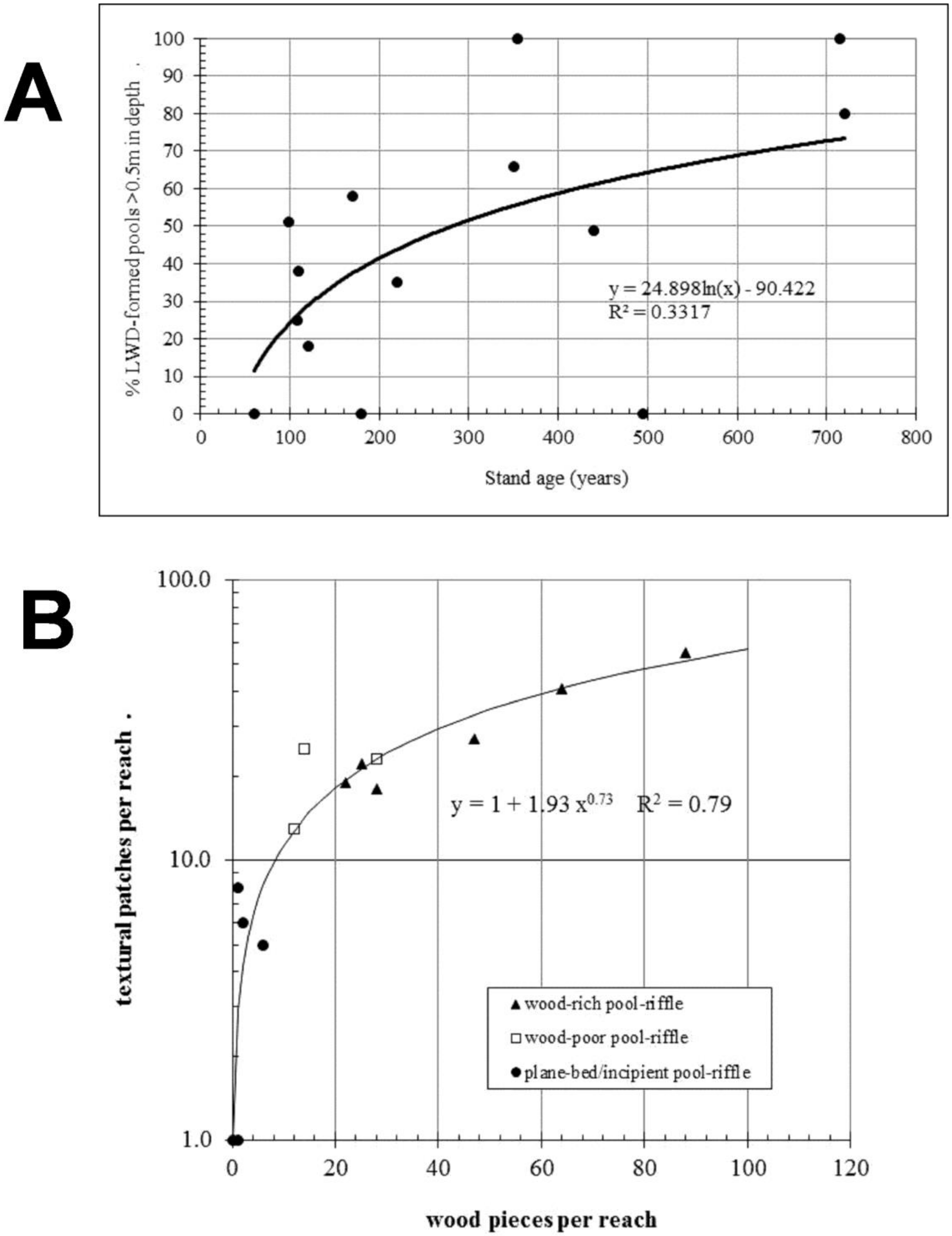
Source: Montgomery and Buffington (1997).
[1] Low large wood loading
[2] High large wood loading
[3] Independent of large wood loading, but large wood loading will control pool frequency and the morphologic complexity of the channel (e.g., Buffington and Montgomery 1999b, c; Abbe 2000).

Figure 4-12. Examples of Alluvial (Gravel-Bed) Stream Channels With Low Wood Loading (A) and High Wood Loading (B)



Source: from Buffington and Montgomery (1999b, Figure 8a, page 3515 and 8b, page 3516).

Figure 4-13. (A) Correlation Between Percent of Large Wood Pools (with residual depth > 0.5 meter [1.6 feet]) Formed by Wood as a Function of Riparian Forest Stand Age; (B) Frequency of Textural Patches as a Function of Wood Pieces per Reach for Streams Draining the West Slope of the Olympic Mountains in Northwestern Washington



Source: (A) Rot et al. (2000, Figure 6, page 704); (B) Buffington and Montgomery (1999b, Figure 9, page 3518).

Urbanization tends to increase peak flows in a basin (James 1965; Hollis 1975) by removing vegetation (decreasing evapotranspiration and interception) and primarily by decreasing soil permeability through compaction and impervious surfaces. The hydrologic effects of urbanization are usually assessed by estimating the percentage of impervious surface of a drainage area (e.g., Dunne and Leopold 1978). An increase in the frequency of peak flows (decrease in recurrence interval of a particular discharge) goes on to directly alter channel morphology, primarily through increases in depth (i.e., incision) and width (Hammer 1972; Leopold 1973; Booth 1990, 1991) and stream ecology (Booth and Reinelt 1993; Luchetti and Fuerstenberg 1993). The frequency of peak flows increases significantly when a catchment is urbanized. Moscrip and Montgomery (1997) report that flows with a 10-year recurrence interval prior to urbanization occurred with a 1- to 4-year recurrence interval after urbanization of 14% or more of catchments in the Puget Sound lowlands. These results were consistent with predictions by Booth (1990) that urbanization would transform 10-year flows into 2- to 5-year flows within the Puget Sound region. Wood can be an important element in moderating these increases in peak flows.

As discussed above, stable wood in stream channels can have significant hydraulic effects by increasing boundary roughness and forming flow obstructions. The presence of flow obstructions is probably the single most effective means of increasing the diversity and range of physical habitat. As flow approaches an obstruction, its downstream horizontal velocity diminishes and its vertical velocity accelerates part-way down the water column before decelerating to zero close to the bed where the flow can be directed upstream (Abbe and Montgomery 1996; Abbe 2000). The horizontal component of flow normal to the original streamlines then accelerates as flow is constricted around the obstruction. Vortices are generated directly upstream of the obstruction that can scour the bed. Flow "separates" as it moves past the obstruction, forming three distinct flow regions (Abbe 2000): (i) a recirculation zone (eddy) downstream of the obstruction, where flow is constricted around the obstruction; (ii) the streamline zone of principal flow past the obstruction; and (iii) a shear layer separating (i) and (ii) sometimes referred to as the von Karman vortex street. All of these flow patterns result in a complex assemblage of dramatically different velocities and depths within a very small area, each usually associated with different substrate textures. Mapping of textural patches within a channel (Buffington and Montgomery 1999c) can provide valuable insight into the hydraulic characteristics of a channel.

These physical responses translate into extremely beneficial habitat for different salmonid species and life stages. When the flow obstructions are formed by snags (fallen trees) and logjams, they also provide intricate cover and shade. Buffington and Montgomery (1999a, 1999b) demonstrate how the presence of wood can dramatically alter the texture and topographic complexity of a channel (Figure 4-12) and offer quantitative means of assessing stream condition.

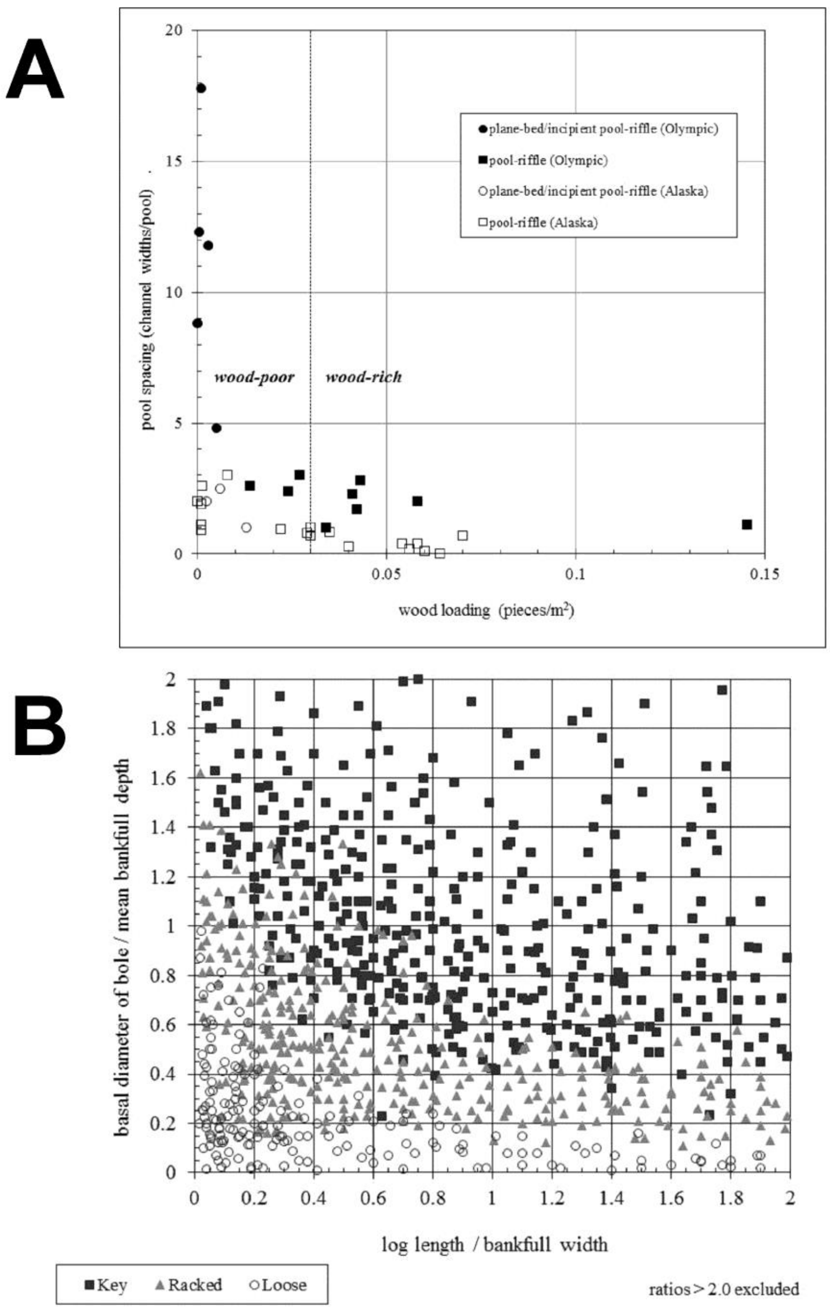
As the frequency of functional wood (stable wood impinging on flow) increases in a reach, the rate by which the number of textural patches in the reach increase is initially exponential, then gradually diminishes (~20 pieces/reach in Figure 4-13B). As wood loading increases there is a decrease in pool spacing (inverse of pool frequency) that approaches a constant value at wood loading of about 0.03 piece per square meter (Figure 4-14A). Wood increases the complexity of channel topography, bed textures, and substrate material (organic and inorganic). Channel complexity increases ecological productivity and resilience (e.g., Power et al. 1995; Power and Dietrich 2002). Stability of a piece of wood is dependent on its size relative to the channel's hydraulic geometry, its density, and its shape (Abbe 2000; Abbe et al. 2003b; Abbe and Brooks 2011). Size (length and diameter) and density will affect a log's weight and buoyancy under particular flow conditions and the resistance it may encounter with the channel bed, banks, or pre-existing obstructions. Shape can have a pronounced effect on how the weight of a log is distributed and the frictional resistance the log encounters within the channel (Abbe 2000; Abbe et al. 2003b, 2003c; Abbe and Brooks 2011). Measurements of key, racked, and loose pieces of wood in five different channel reaches of the Queets River system in northwestern Washington (west slope of the Olympic Peninsula) provide an empirical means for estimating the size log (i.e., tree) necessary to form key members, based on the average bankfull width and depth of the channel (Figure 4-14B). In many relatively small channels where the key piece size can be obtained for creating functional wood (e.g., Abbe and Montgomery 1996, 2003), simply adding wood to the channel can result in a significant improvement in habitat (Figure 4-15).

One of the principal means by which wood increases physical complexity is in splitting flow to create islands and multi-thread channel systems referred to as anabranching or anastomosing channel patterns. Anabranching is the most effective means of adding channel length and edge habitat to a river. In addition to island formation, logjams also create secondary channels by raising water elevations high enough for overbank flows to carve new floodplain channels. This process has been observed in a range of different physiographic regions throughout North America (e.g., Hickin 1984; Abbe and Montgomery 1996, 2003; Webster et al. 2002; Phillips 2012; Wohl 2013). Measurements from the Queets River show how channel meanders with logjams have significantly smaller radii of curvature than those without (Figure 4-16A). Decreasing the radius of curvature of a meander can raise water elevations through super-elevation around the bend. Using the data on channel curvature we can see how water elevations at the logjam meanders can be 0.3–1 meter (1–3 feet) higher than the unobstructed meanders (Figure 4-16B). As discussed earlier, wood can be a primary driver in bifurcating or splitting flow and creating anabranching rivers that may otherwise be braided or single-thread meandering channels. Historic channel clearing transformed many complex anabranching rivers with numerous forested islands into single, wide meandering channels lacking smaller channels or highly braided and dynamic wide channel networks (Figure 4-17; Abbe et al. 1997). Adding logjams can not only increase the number of pools within a channel segment, but can also increase the range of pool depths within the system, as seen after ELJs were constructed in the lower Elwha River (Figure 4-18A). The same channel segment where the ELJs were installed also experienced a significant reduction in median grain size, consistent with the stress partitioning done by the wood (Figure 4-18B). This reduction in grain size can then be used to demonstrate how the ELJs could alter channel morphology.

Eaton et al. (2010) examined thresholds between single thread, anabranching (or anastomosing), and braided channels. Using Elwha River data shows how the reduction in grain size increases the dimensionless formative discharge and pushes the Elwha channel from a single thread to anabranching form (Figure 4-19). This is exactly what happened where the ELJs were installed. By splitting flow and raising water elevations, wood can have a dramatic effect on the quantity and quality of aquatic habitat. Using channel bank length as a metric for edge habitat, we can see that in an unconfined anabranching channel reach there is significantly more habitat than in incised and leveed reaches of the exact same river (Figure 4-20). Hydraulic modeling of the Lower White River in Washington shows that over a wide range of flow discharge, the wood-rich anabranching reach of the river has far more bank length than reaches with a single-thread channel constrained by levees or incision downstream of a dam.

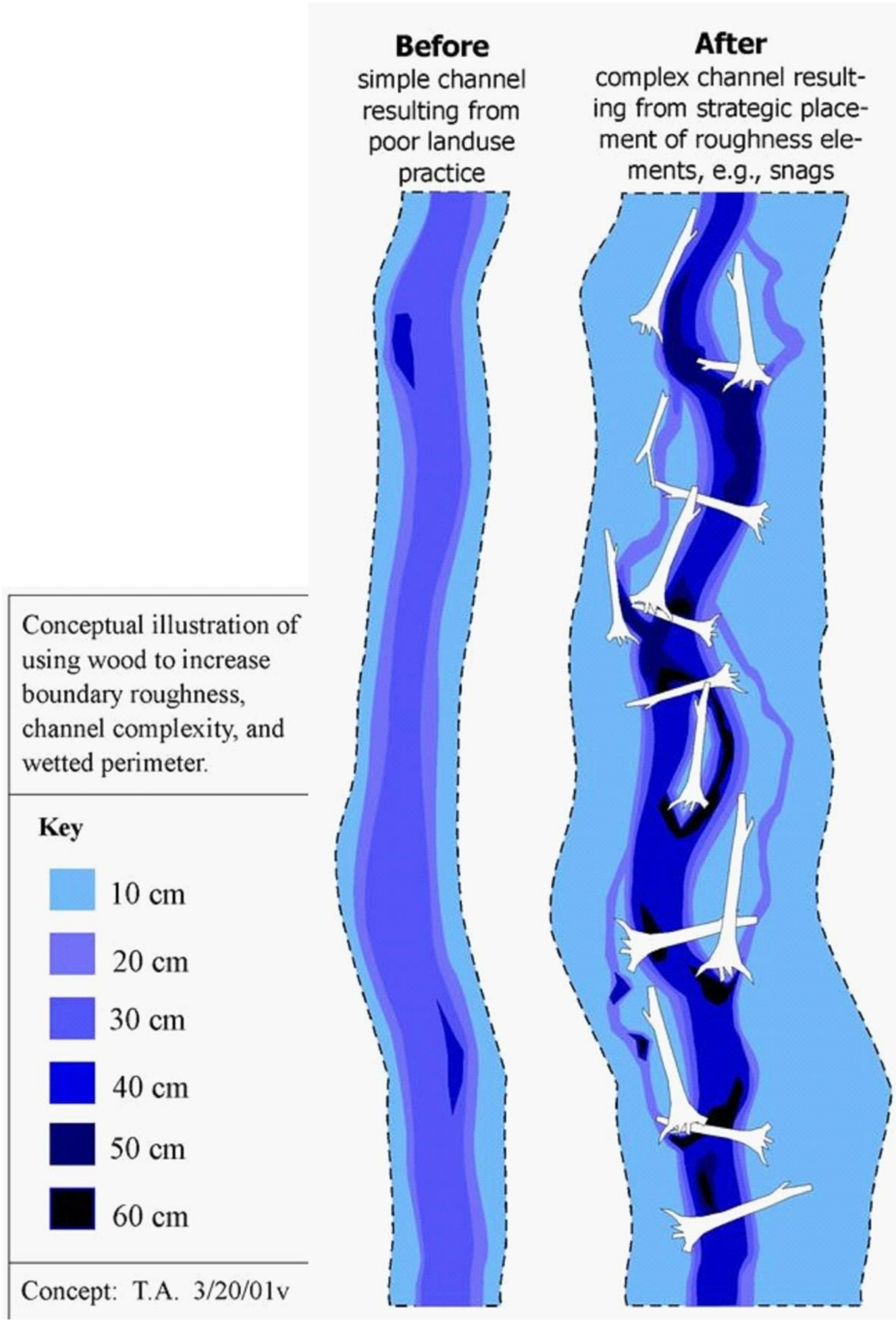
Logjams can create major blockages that are very effective at increasing the frequency of overbank inundation. A large logjam in the Deschutes River near Olympia, Washington, raised low-flow water elevations over 1.2 meters (3.9 feet) (Figure 4-21A). During high flows the relative effect of the logjam diminished because flow was already out on the floodplain (Figure 4-21A). The logjam also showed a temporal hysteresis with respect to water levels. During low flows the wood settles into the channel and creates a denser or lower porosity obstruction, so that during the rising limb of a hydrograph the logjam has a greater effect on water elevations (Figure 4-21B). By the time the hydrograph begins to wane, much of the wood has become buoyant, and the permeability of the obstruction has increased; thus, it has a diminished effect on water elevations during the receding limb of the hydrograph (Figure 4-21B).

Figure 4-14. (A) Threshold of Effective Wood Loading Based on Pool Frequency as a Function of Wood Loading per Square Meter of Channel Bed; (B) Size of Functional Wood in Queets River Basin



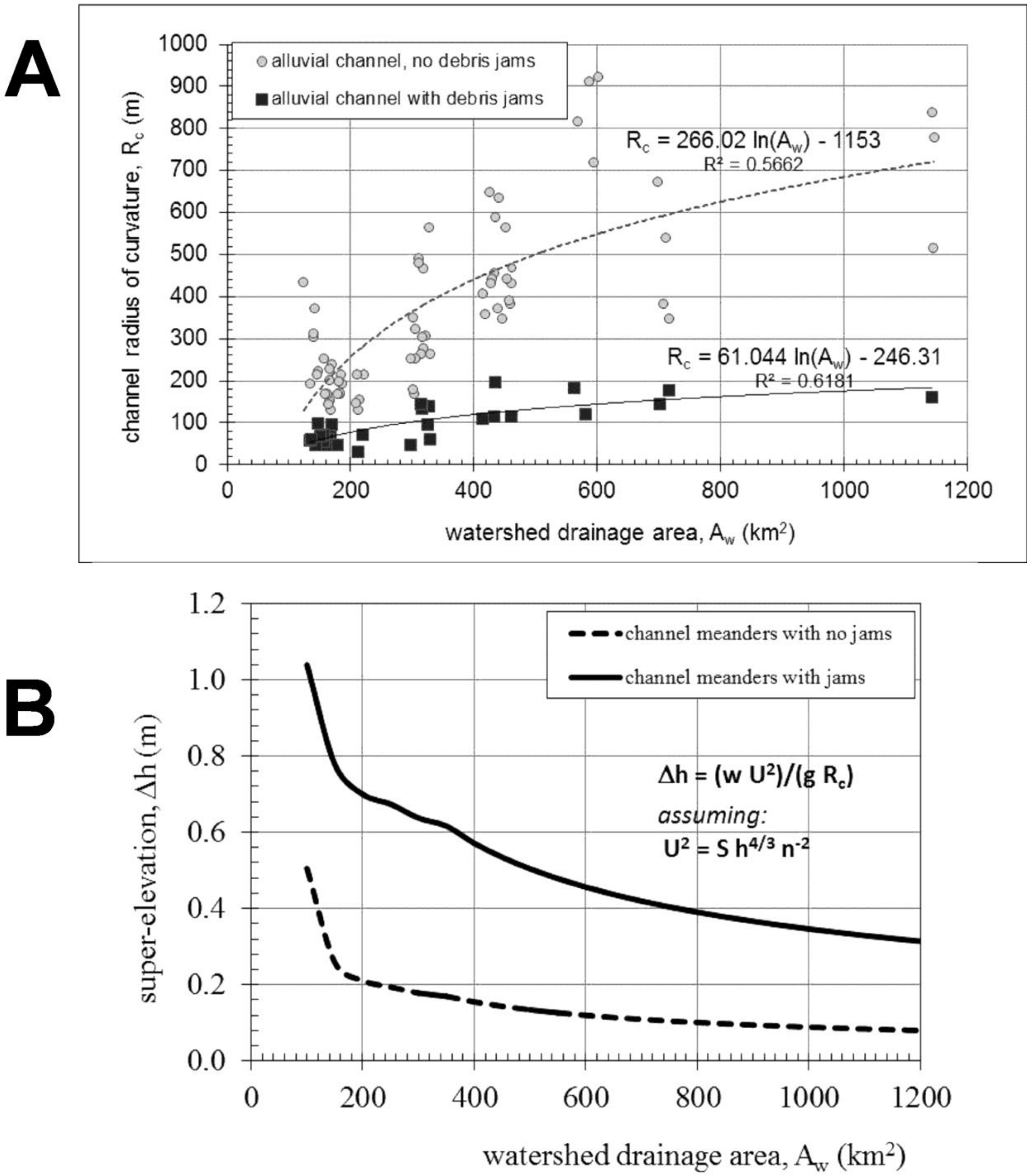
(A) defined by Buffington and Montgomery (1999b, Figure 2, page 3511); (B) source = Abbe (2000) and Abbe and Montgomery (2003).

Figure 4-15. Conceptual Illustration of How Wood Introduces Physical Complexity to a Simplified Channel



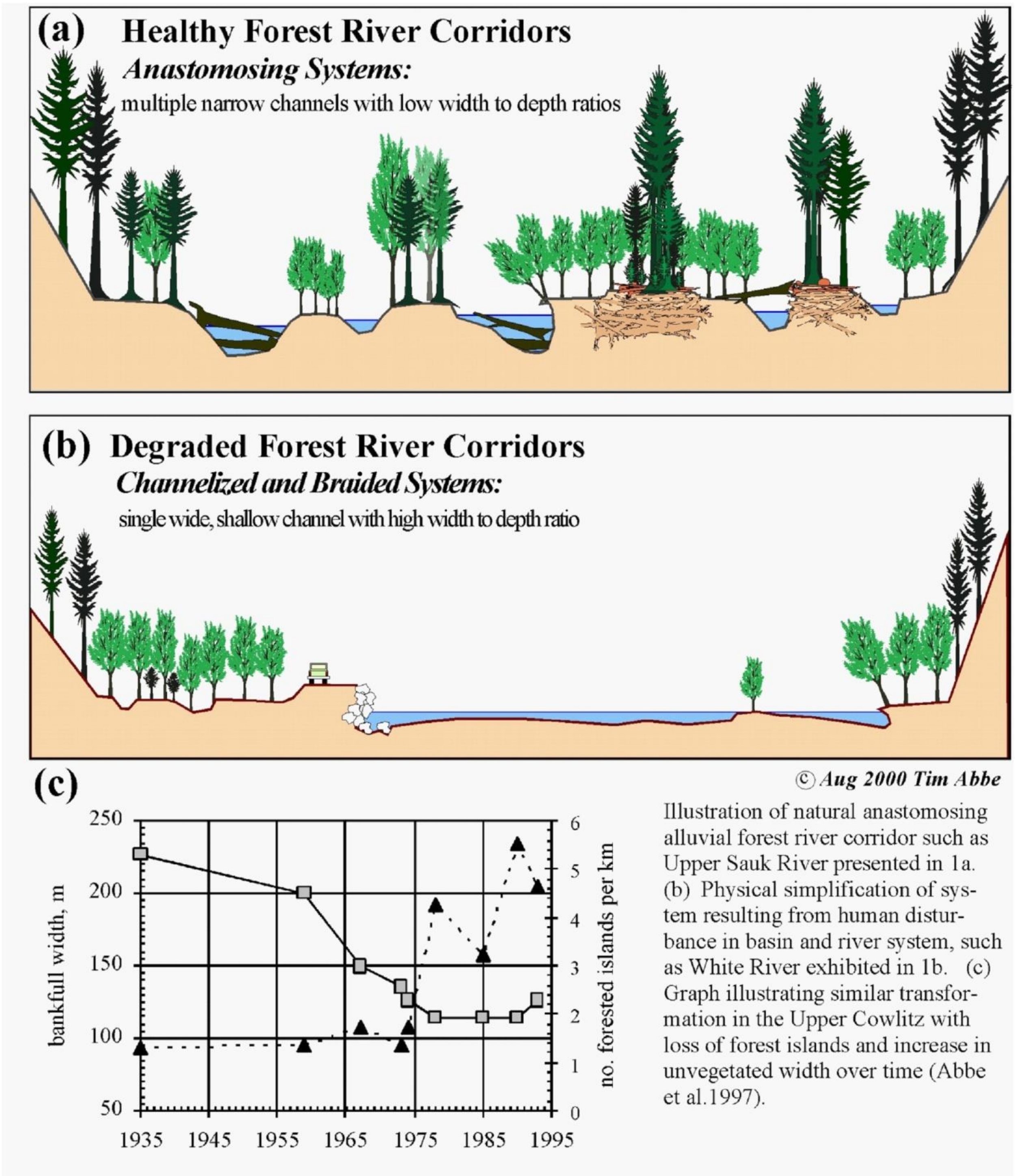
This complexity creates the greatest ecological diversity and resilience, and supports a much more productive food web (e.g., Power et al. 1995; Power and Dietrich 2002).

Figure 4-16. (A) Role of Natural Logjams in Reducing the Radius of Curvature of Channel Meanders in the Queets River, Washington; (B) Based on Assumptions for Channel Sizing Relative to Drainage Area, the Super Elevation Associated with Smaller Radii of Curvature Results in an Increase in Water Elevations of 0.35–1.0 meters (1.1–3.3 feet), Demonstrating Another Way Logjams Increase Floodplain Connectivity and Drive Side Channel Formation



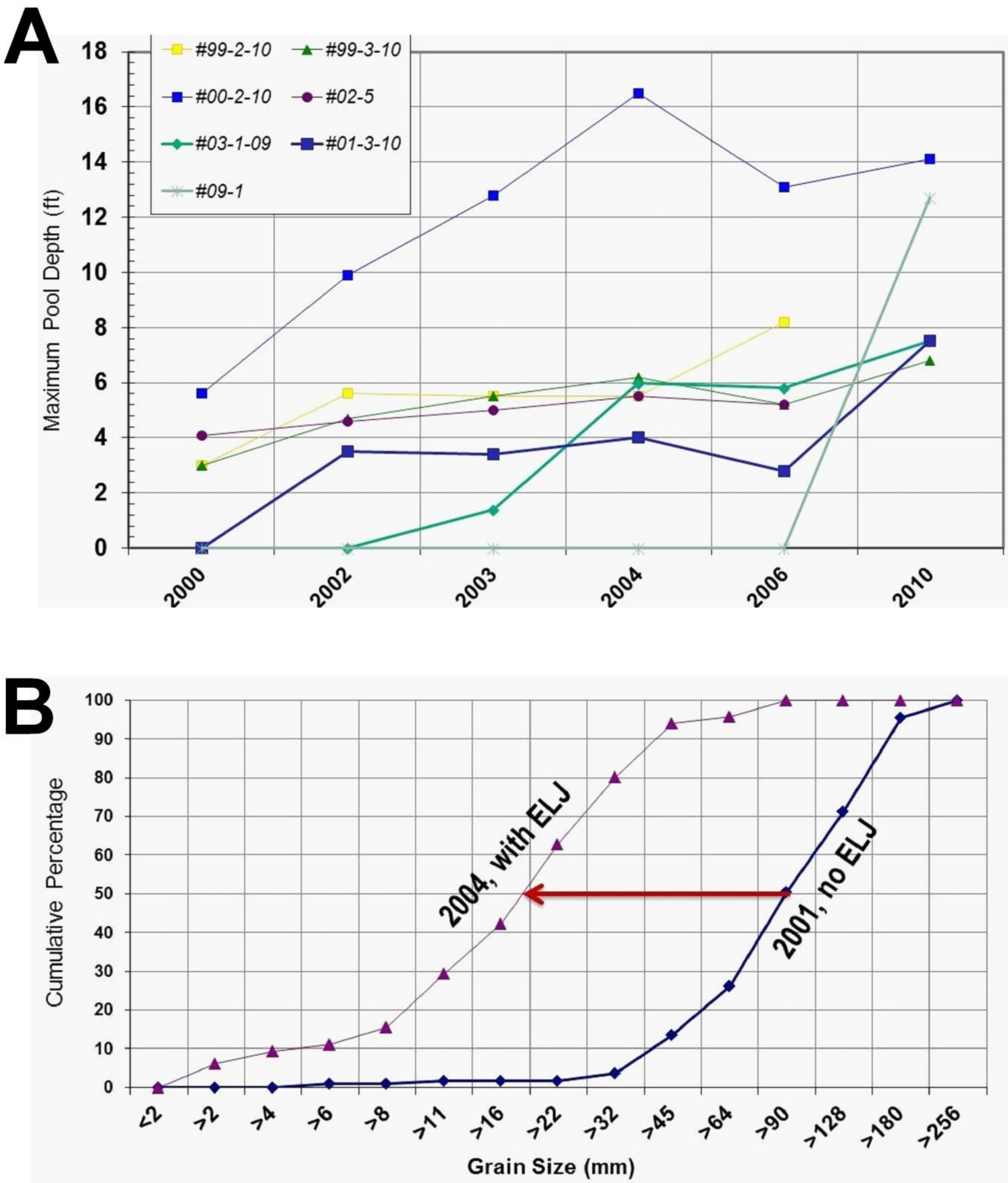
Source: (A) Abbe (2000) and Abbe and Montgomery (2003; (B) Abbe (2000).

Figure 4-17. Wood Forces Channel Complexity Such as Anabranching (a); the Removal of Wood Can Transform These Multi-Thread Systems Into a Wide Single-Thread Channel (b); Observations of the Upper Cowlitz River in Washington Show the Loss of Vegetated Island Coincident With Increasing Channel Width (c)



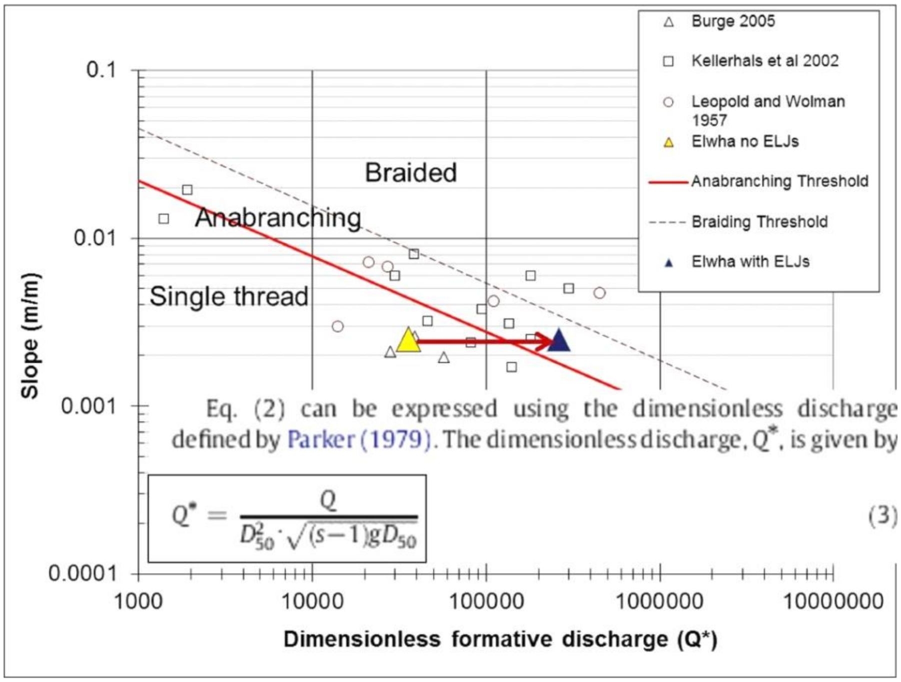
Source: Abbe et al. (1997)

Figure 4-18. Geomorphic Changes in Lower Elwha River, Washington, Associated with ELJ Placement



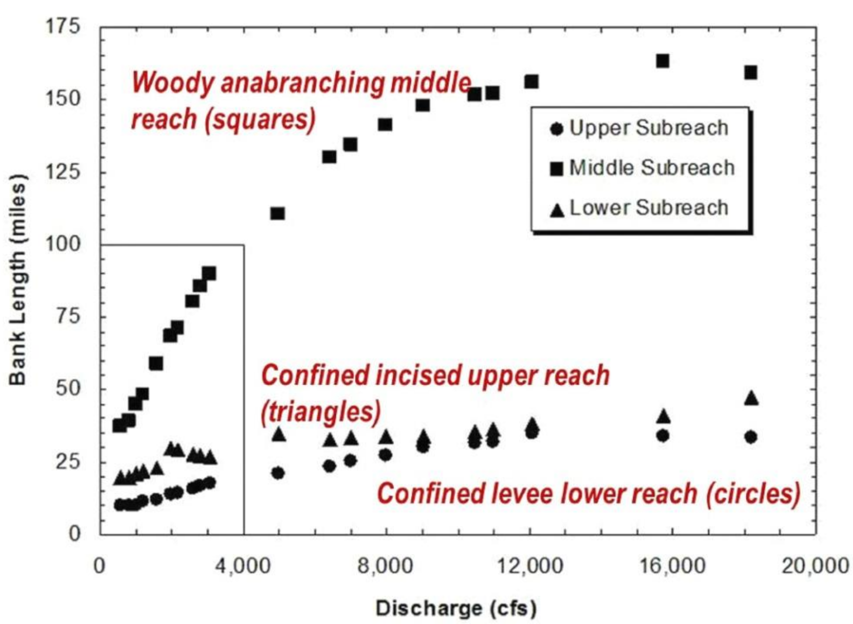
For years prior to dam removal. (A) Pool depths at seven ELJs increased. (B) Median grain size (D50) diminished from 90 to 19 millimeters (3.5 to 0.8 inches), a 79% decrease due to stress partitioning of the wood (data from Mike McHenry, Elwha Tribe).

Figure 4-19. Predicting Channel Planform Morphology Based on Formative Discharge (Q*), Median Grain Size (D50), and Channel Slope



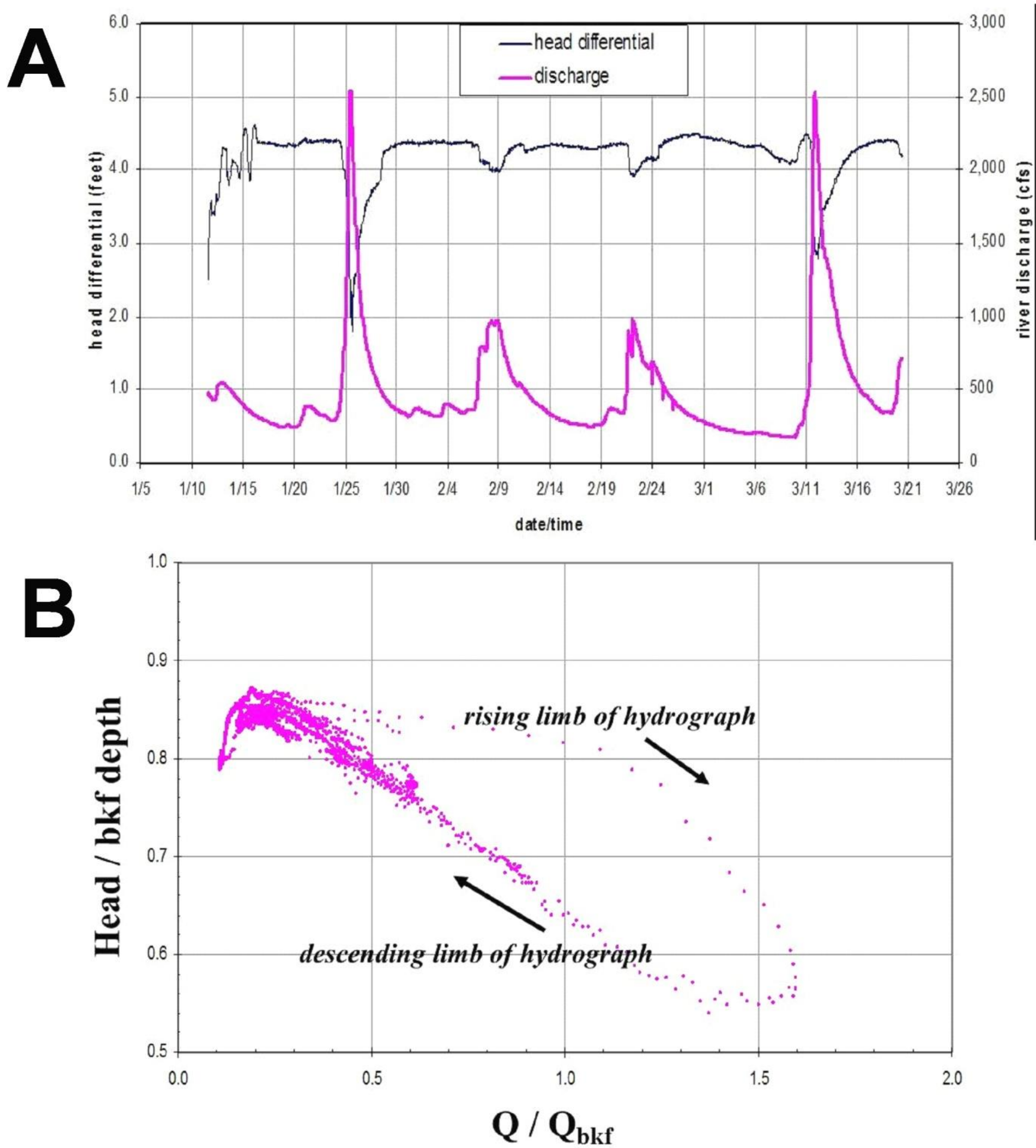
The stress partitioning imposed by Elwha River ELJs effectively pushes river from single thread to anabranching (Eaton et al. 2010).

Figure 4-20. Illustration From White River in Western Washington Showing the Difference in Cumulative Bank Length (2x channel length) for Unconfined Anabranching Reach With Numerous Logjams Versus Confined Reaches



For identical flows in the same river, the wood-dominated anabranching reach has 2 to 5 times the amount of habitat as measured by channel length.

Figure 4-21. (A) Hydrograph Showing the Influence of a Large Channel Spanning Logjam in the Deschutes River, South of Olympia, Washington[1]; (B) Hysteresis Curve Showing How the Logjam Has the Most Significant Effect on Head (Dz) During Rising Limb of Hydrograph[2]



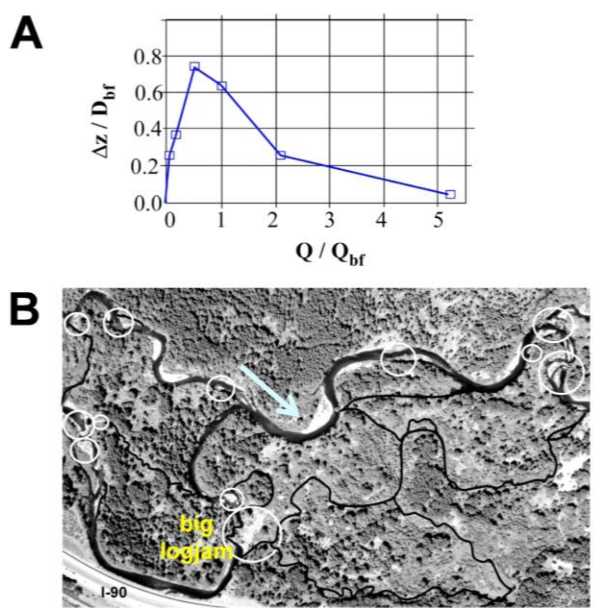
[1] As discharge increases (lower curve) the relative effect (head differential) of the logjam dimensions. This is because the logjam obstructs most of the bankfull cross-section and as flow increases it spreads out across the floodplain.

[2] This is because logjam permeability increases with rising flood and therefore there is higher conveyance on the descending limb of the hydrograph.

Source: Data provided by Thurston County Public Works pressure transducer stage gages installed downstream and upstream of logjam.

The hydraulic effect of obstructions was modeled to simulate these effects (Figure 4-22A) (Brummer et al. 2006). These large logjams can occur in surprising places without adverse impacts, such as a channel-spanning logjam in the Upper Yakima River right off Interstate 90 in Washington State (Figure 4-22B).

Figure 4-22. (A) Dimensionless Plot of How Wood Obstructing 80% of the Ozette River, Washington, Increases Water Elevations Using a 1D Hydraulic Model[1]; (B) Channel Spanning Logjam on Upper Yakima River, West of Easton, Kittitas County, Washington[2]



1 As discharge, Q, increases relative to the bankfull discharge, Qbf, there is a substantial increase in water elevation, Dz, relative to bankfull depth, Dbf. As flows overtop the banks, the relative effect dimensions. (Adapted from Brummer et al. 2006)

2 Logjam raises water elevations to feed extensive side channel network. Logjam is located just off Interstate-90 and never caused flood problems due to intact floodplain it retains. Circles highlight logjams; flow is left to right. (1998 photo)

4.2.5 Wood and Channel Incision

Starting in headwater channels, wood can play a fundamental role in dissipating energy, capturing sediment, and limiting down-cutting or incision. In smaller channels only a small portion of a log may be inside the wetted channel, but it can still be effective (Figure 4-23).

Figure 4-23. Wood in Steep (S=0.18) Headwater Channel of Olympic Peninsula, Washington

Logs create sediment traps and surface roughness that dissipates energy of floods and debris flows. Logs are buried in alluvium and above the channel. As sediment accumulates, logs previously located above the channel can be incorporated into the stream bed. Without wood this would be an actively incising bedrock channel.

As wood traps bed material and aggrades the channel, wood that was previously suspended above the channel can become engaged with flow and continue the process of channel aggradation. With sediments and wood creating a mantle above the underlying bedrock or glacial deposits, wood effectively retards incision and stabilizes the landscape. Removal of wood can dramatically increase the rate of incision, and in a few decades the channel can cut down what would have otherwise taken thousands of years (e.g., Veatch 1906; Guardia 1933; Wadsworth 1966; Brooks and Brierly 2002; Stock et al. 2005). Steep headwater channels can be subject to extreme events such as debris flows or rock falls. In these systems, logs tend to easily span the channel width, and the diameter of the tree is an important factor; for the log to function it must withstand the forces the stream imposes. Because forest management and harvest can directly influence the size of riparian trees growing along headwater channels, policy can have significant geomorphic consequences. Modeling a channel spanning log as a cylindrical beam shows that diameter plays a critical role in the forces it can withstand without breaking (Figure 4-24) (Abbe 2000). This type of analysis demonstrates that trees can grow to sizes that are capable of withstanding extreme forces. By doing so, they can effectively diffuse debris flows near their initiation points, minimizing their inertia and distance traveled. This can reduce or limit downstream consequences to habitat and human communities.

Baker (1979) showed how logjam removal resulted in short-term increases in sediment supply and the transformation of channel substrate from alluvium to bedrock (Figure 25). By storing alluvial sediments, wood creates a protective barrier that slows the process of channel downcutting. Stock et al. (2005) document how wood removal in the Teanaway River in central Washington not only led to loss of alluvial channels, but approximately 2 meters (7 feet) of bedrock incision in 100 years. Cordova et al. (2007) found that 50% of the wood found in low-gradient streams of the upper Midwest were responsible for sediment storage. In a similar assessment of low-gradient coastal rivers in Maine, Magilligan et al. (2008) found that 5–20% of the wood was associated with sediment storage. Through cosmogenic dating of sediment in one of the same Maine rivers (the Ducktrap), Fisher et al. (2010) found that wood accumulations increased the residence time of sediment stored in the channel.

GUIDANCE

Potential Impacts of Channel Incision

- Transforms alluvial beds to bedrock.
- Disconnects the stream from its floodplain.
- Destabilizes its banks and adjacent hillslopes.
- Negatively impacts water quality.
- Increases downstream flood peaks.
- Delivers large quantities of sediment to downstream reaches (which are often in developed areas).
- Compromises the integrity of bridge abutments, pipelines, and road embankments.
- Increases the shear stresses acting on the bed due to flow confinement and lack of wood.

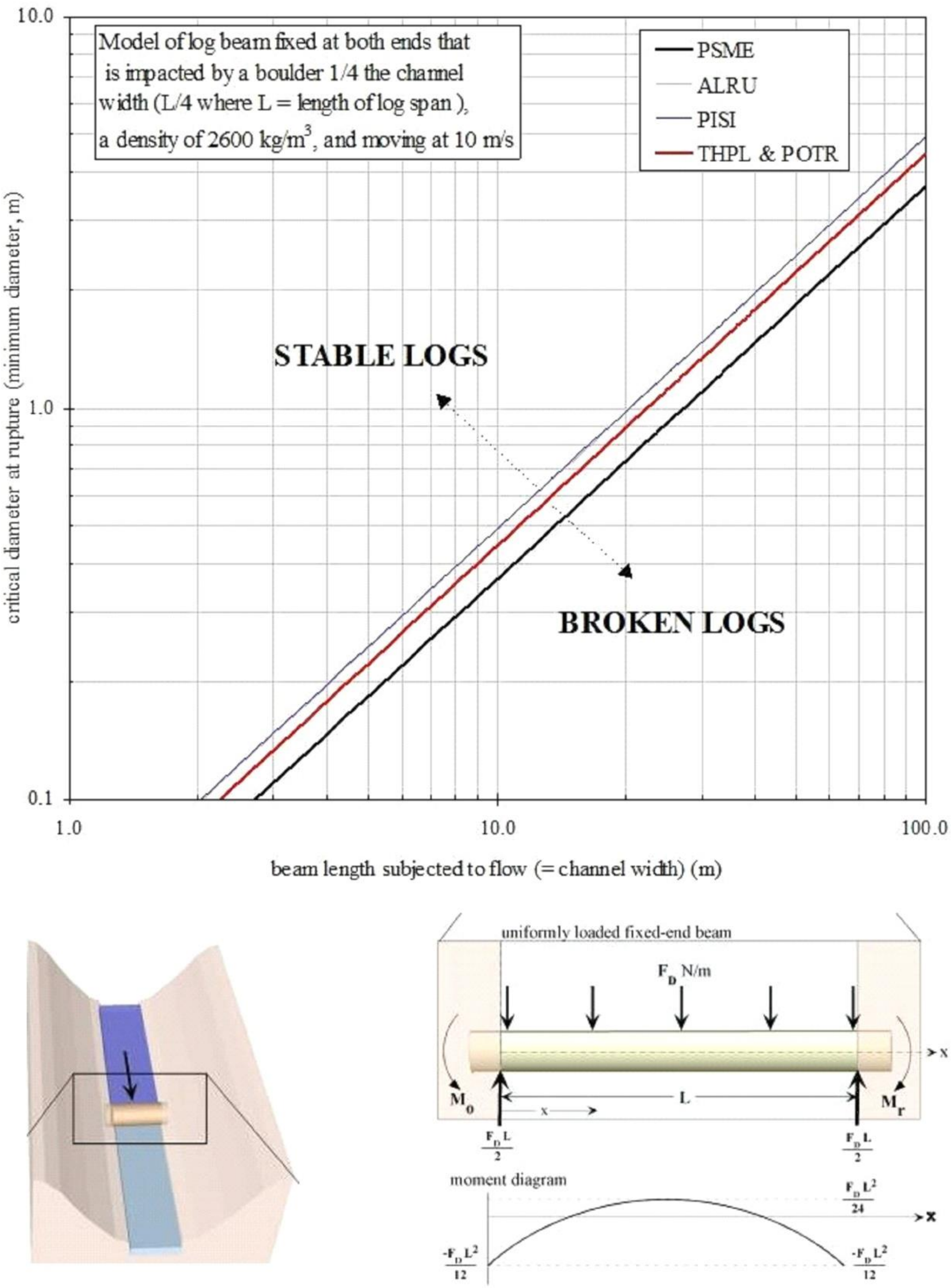
The consequences of wood removal in relatively small headwater streams can be seen in many urban stream corridors. Where mature riparian forests and wood was left intact it can provide resilience to major increases in peak flows that occur as a result of urbanization (Figure 4-26A). Similar streams in the same region where wood was removed have experienced incision of 6–18 meters (20–60 feet) (Figure 4-26B).

There are several well-established mechanisms initiating channel incision, such as a reduction in sediment supply (e.g., downstream effect of dams), an increase in peak flows (e.g., urbanization or climate change), or channelization (e.g., straightening and confinement of flood flows by levees). The role of wood removal as a trigger of incision has been recognized but under-appreciated, even in restoration. Recent geomorphic analysis of several Pacific Northwest rivers has demonstrated that larger rivers that have not been dammed, that experienced a significant increase in peak flows, or that have been channelized, are incising—despite experiencing an increase in sediment supply as a result of industrial logging. The most significant disturbance in these systems has been the loss of wood. The result of wood removal in the South Fork Nooksack River has been incision that has left areas occupied by the river just decades ago well above the 100-year flood elevations today (Figure 4-27) (Abbe et al. 2013). Bank stratigraphy can provide direct evidence of incision by revealing old alluvial channels once occupied by the river sitting on top of underlying geologic material (Figure 4-28). Given the size trees once attained, it should not be surprising that they were capable of trapping bed material and aggrading the channels of relatively large rivers. A single native old-growth tree can create a 3-meter-high, 30-meter-wide (10-foot-high, 98-foot-wide) impoundment across a river (Figure 4-29).

A geomorphic assessment should clearly describe and quantify the processes and rates of landscape evolution and predict what a project will be subjected to and how it will influence the evolution of the site (e.g., Schumm et al. 1984; Schumm 1999; Simon 1989, 1994; Doyle and Shields 2000; Wallerstein and Thorne 2004; Brummer et al. 2006; Simon and Rinaldi 2006). Channel incision begins a long-term channel evolution process (Figure 4-30) that can result in many decades before the restoration of some form of equilibrium. Therefore, designers should be well aware of what stage (I–VI) of channel evolution their system is in. For restoration sites in the early stages of downcutting (stages II–III), it may be possible to quickly reverse the process to re-establish the undisturbed condition (stage I). Channel widening (stages IV–V) can pose a direct threat to grade control structures that are not sufficiently keyed into the banks. Bank erosion that cuts around a constructed grade control structure can re-initiate incision. There should be enough roughness built into the stream valley to prevent incision from getting around the structure. Because of its size, wood is an ideal material for creating complex grade control structures that extend beyond the channel to reinforce banks and floodplain areas that may be subject to erosion (Figure 4-31). However, single log weirs should be avoided; they are subject to undercutting and have no redundancy should the log fail. The more logs used, the stronger the structure and greater the factor of safety. Whether using a step-pool or reinforced riffle design, it is important to minimize the magnitude of individual drops and thus create broad crested structures (Figure 4-32). This typically increases the cost, but greatly increases the structure's stability and enhances fish passage. In steep step-pool or cascade channels this may entail placing wood through the length of the stream.

In montane rivers natural logjams can create steps several meters high and have a dramatic effect on floodplain morphology by creating terrace surfaces with slopes several times lower than the valley grade (Figure 4-33, A and B) (Montgomery and Abbe 2006). Observations from the Queets River in Washington showed how logjams aggraded channels to elevations higher than surfaces that had previously been well above flood stage. The lower slopes between wood steps reflect how the wood is partitioning shear stress and storing sediment that would otherwise route through the reach. In restoration sites where a large portion of the valley can be restored, constructing channel-spanning structures should certainly be considered. Even in a highly constrained urban setting it can be possible to include wood where there is sufficient freeboard.

Figure 4-24. Log Strength Can Be Critical in Headwater Channels Where They Are Subjected to Severe Forces Imposed by Debris Flows



Plot illustrates an example of how large logs need to be to overcome the impact of a large boulder moving at 9 meters (30 feet) per second, as a function of log length (assuming it spans the channel). Plot illustrates that logs 0.5 meter (20 inches) in diameter can withstand this impact for a 10-meter (33-foot) wide channel (Abbe 2000).

Figure 4-25. Wood Stores Sediment thus Reducing Sediment Transport Capacity by Obstructing Flow and Increasing Roughness, Thereby Increasing Sediment Storage Within a Channel[1]

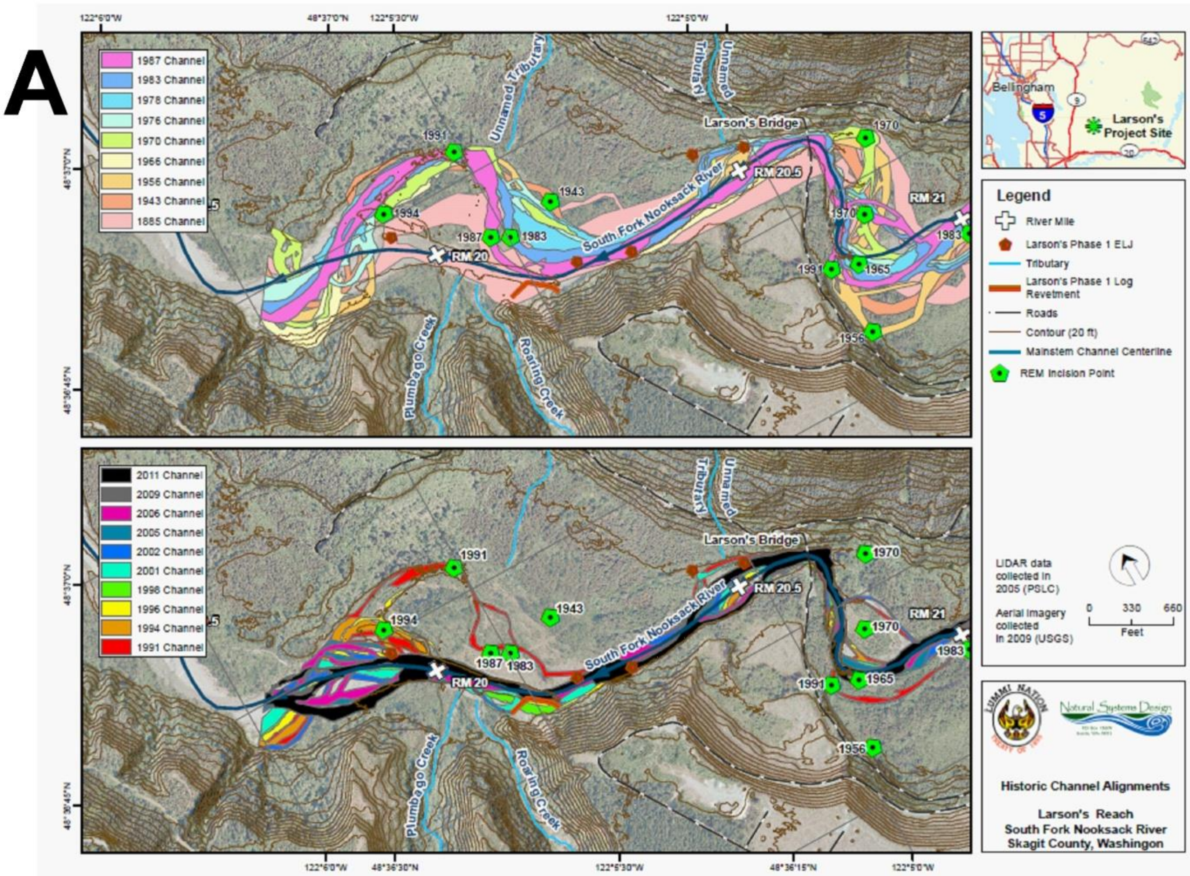
[1] This process can transform a channel from bedrock to alluvium, which not only slows down long-term incision rates, but increases ecological productivity. Logjam sediment storage in Hehe Creek, Oregon Cascades. The logjam stored 1,100 cubic meters of alluvium. Within a year after removal of the logjam, 97% of the sediment had been eroded and the channel reverted to bedrock. The log seen laying on the stream bed in 1977 was suspended 2 meters above the channel in 1978. (Adapted from Baker 1979)

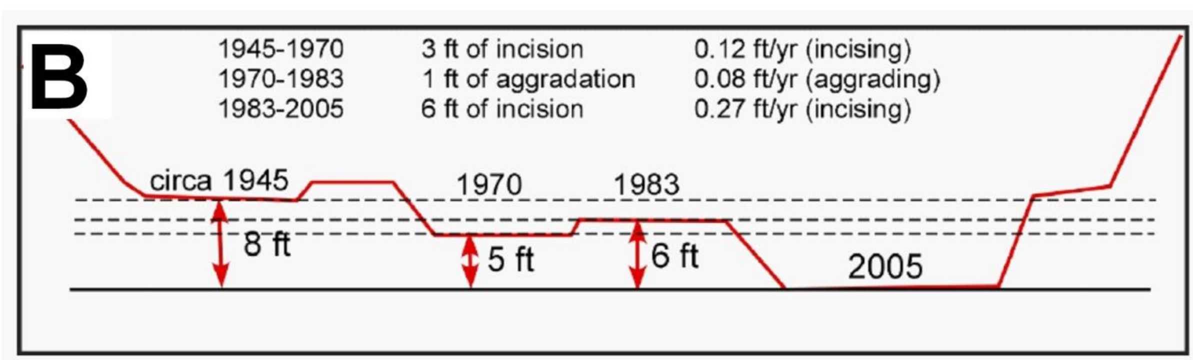
Figure 4-26. (A) Wood in Taylor Creek (Seattle) Is Trapping Sediment and Dissipating Flood Energy[1]; (B) Coal Creek in Nearby Bellevue also Experienced Increased Peak Flows due to Urbanization but Was also Historically Cleared and Lacks Mature Riparian Conditions and Is Undergoing Incision[2]

[1] Taylor Creek lies entirely within the city and has experienced a dramatic increase in peak flows due to urbanization. The 100-year flood flow prior to development now occurs annually. Segments of the creek with mature riparian forests and instream wood have demonstrated resilience to the increased flows unlike segments without trees and wood.

[2] Incision of 3–12 meters (10–40 feet) is common in creeks of the Puget Sound region and requires costly engineering solutions to protect pipelines, bridges, road embankments, and homes.

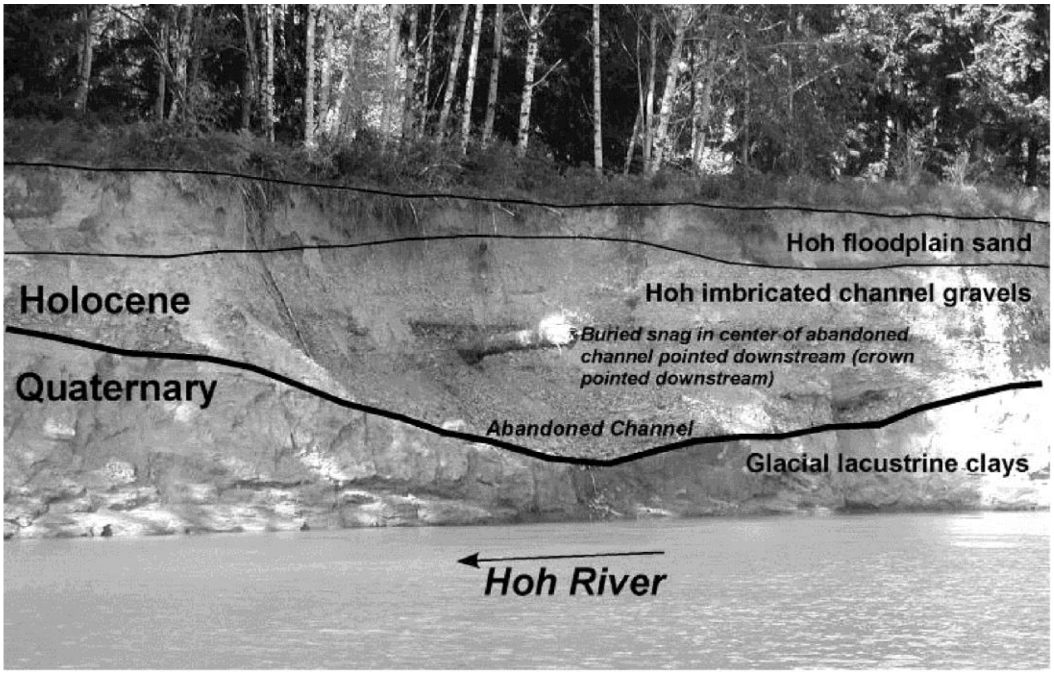
Figure 4-27. Historic Channel Incision in the South Fork Nooksack River, Washington





The river has no dams and this reach has not been channelized; the only disturbances have been channel clearing and clearcut logging of valley bottom and hillslopes. Incision was determined by mapping channel planform (A) and determining elevations of abandoned channel beds (B). Hydraulic modeling shows that channels occupied as recently as the 1980s are no longer inundated in a 100-year flood.

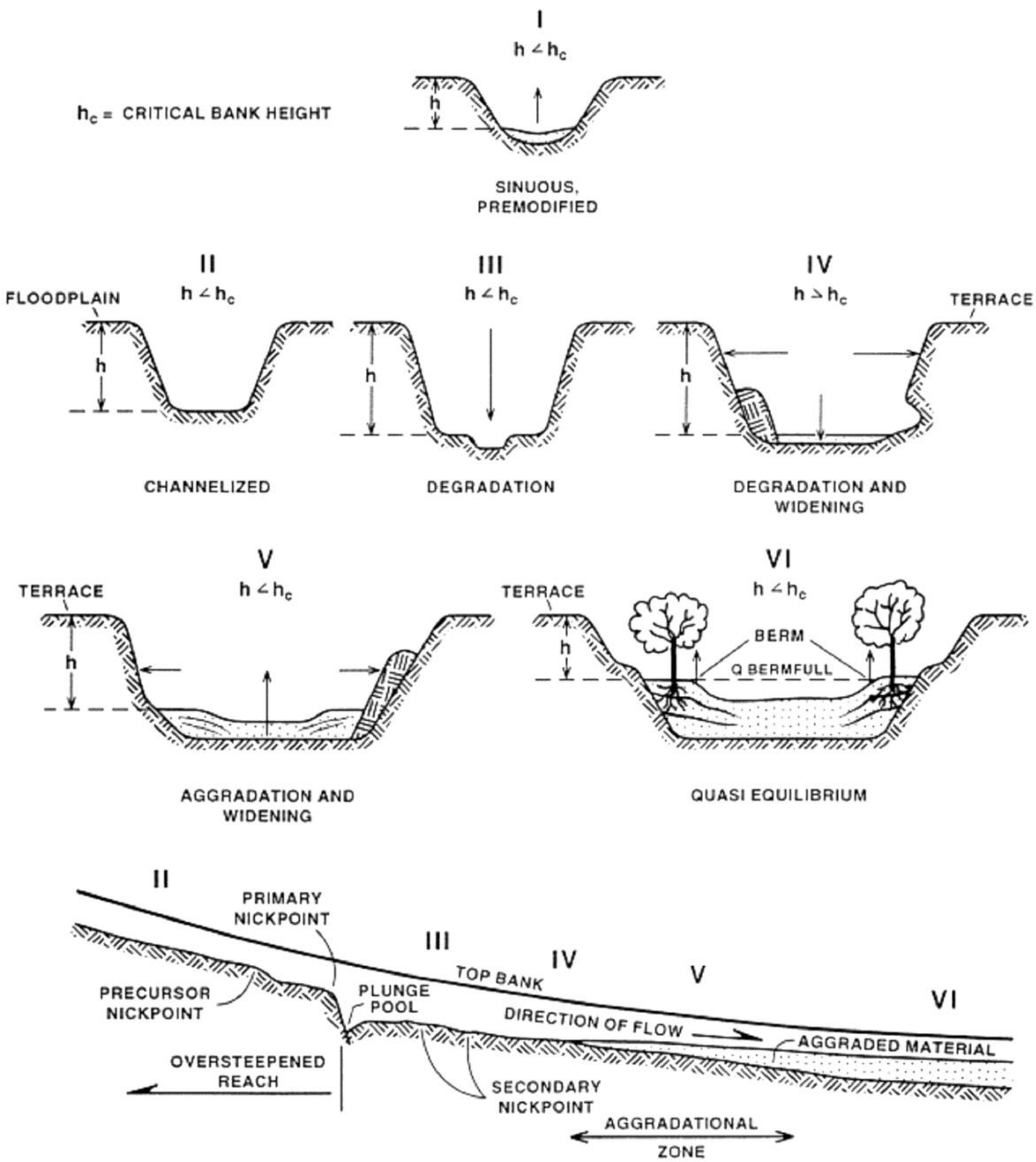
Figure 4-28. Eroding Bank Along the Hoh River, Washington, Showing a Snag Pointing in Flow Direction of a Relic Channel With its Invert Perched Over 2.4 Meters (8 Feet) Above the Current River Bed



The old alluvial floodplain surface is now a terrace due to historic incision of the river.

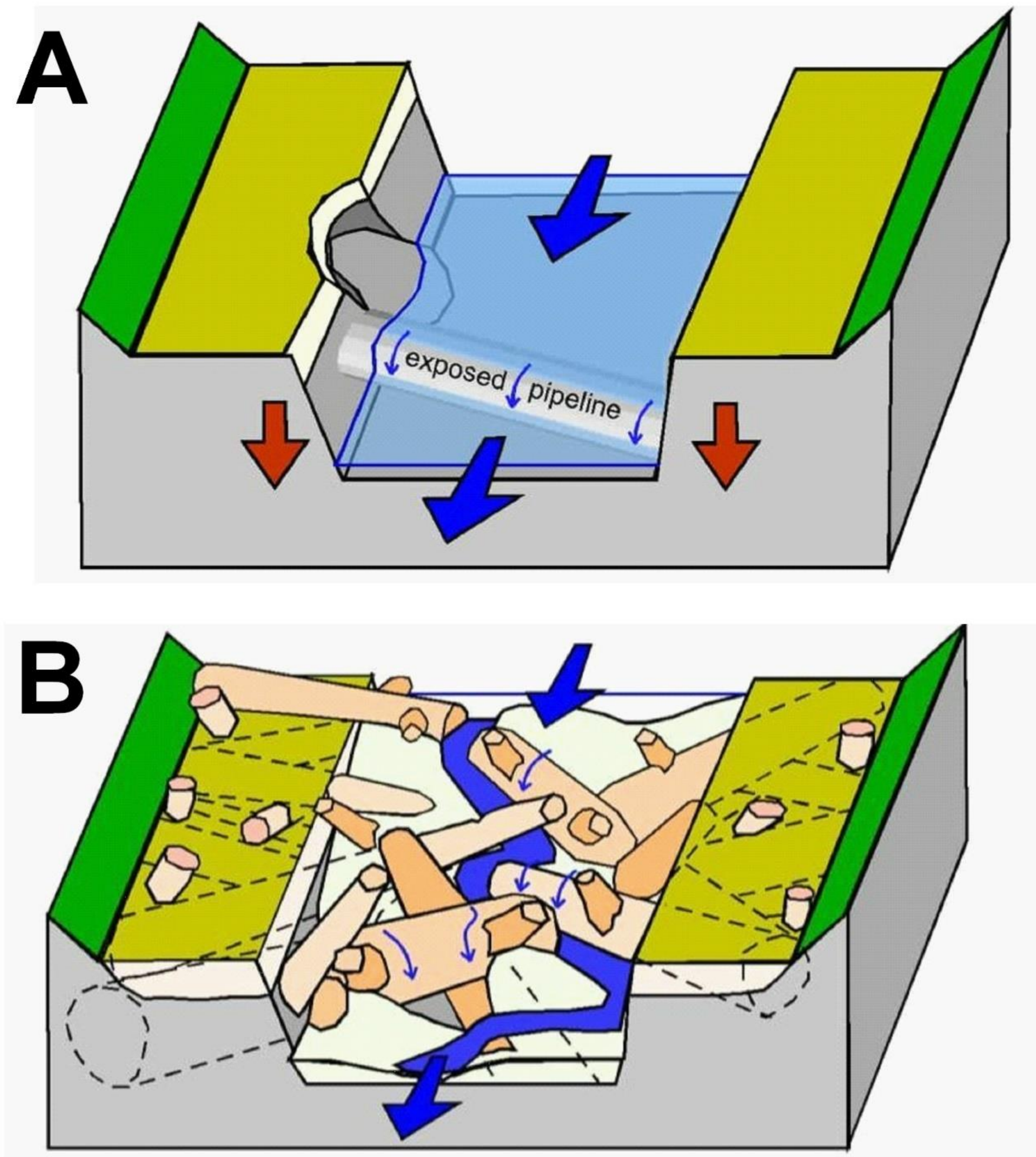
Figure 4-29. A Single 2.5-Meter (8.2-Foot) Diameter Old Growth Douglas Fir (*Pseudotsuga menziesii*) Impounding the Carbon River in Mt. Rainier National Park, Washington

Figure 4-30. Conceptual Channel Evolution Model of Stream Experiencing Incision due to Channelization



Removing wood from a channel increases the effective shear stress available for sediment transport and erosion. A loss of instream wood can trigger long-term incision that is difficult to reverse (from Doyle and Shields 2000, adapted from Simon 1994).

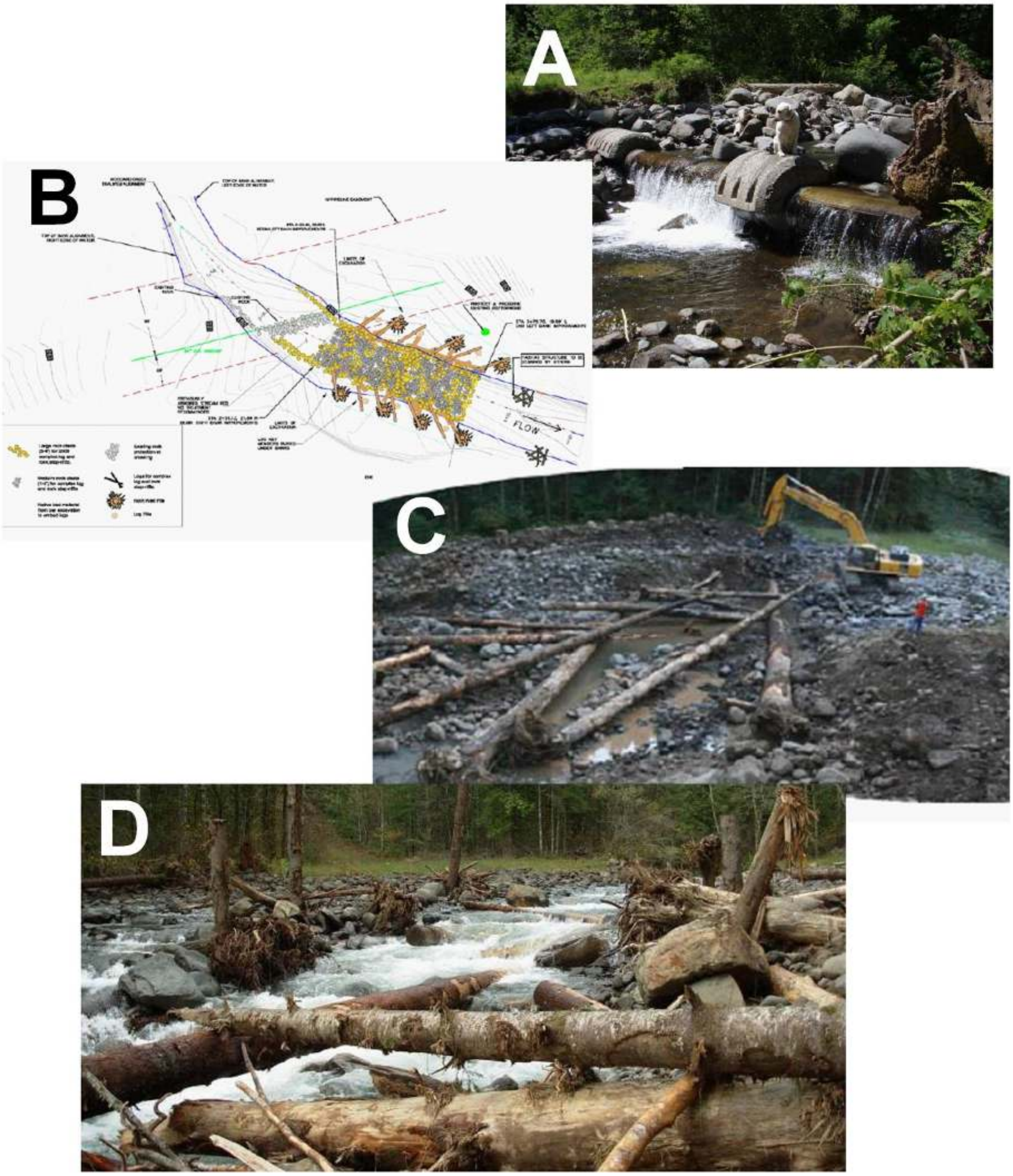
Figure 4-31. Channel Incision Poses a Serious Threat to Infrastructure Such as Pipelines, Bridge Abutments and Piers, Water Intakes, and Road Grades[1]



[1] A geomorphic assessment is essential in evaluating channel incision, determining causal mechanisms, and predicting the consequences. Complex wood assemblages offer a natural means of controlling incision that can also improve fish passage.

The standard of practice is to bury pipeline only 1.5 meters (5 feet) below the streambed), bridge piers, and road embankments (A). Emulating natural wood accumulations, engineered placements can create complex grade control that can reverse channel incision to protect infrastructure while also improving fish passage and floodplain connectivity (B).

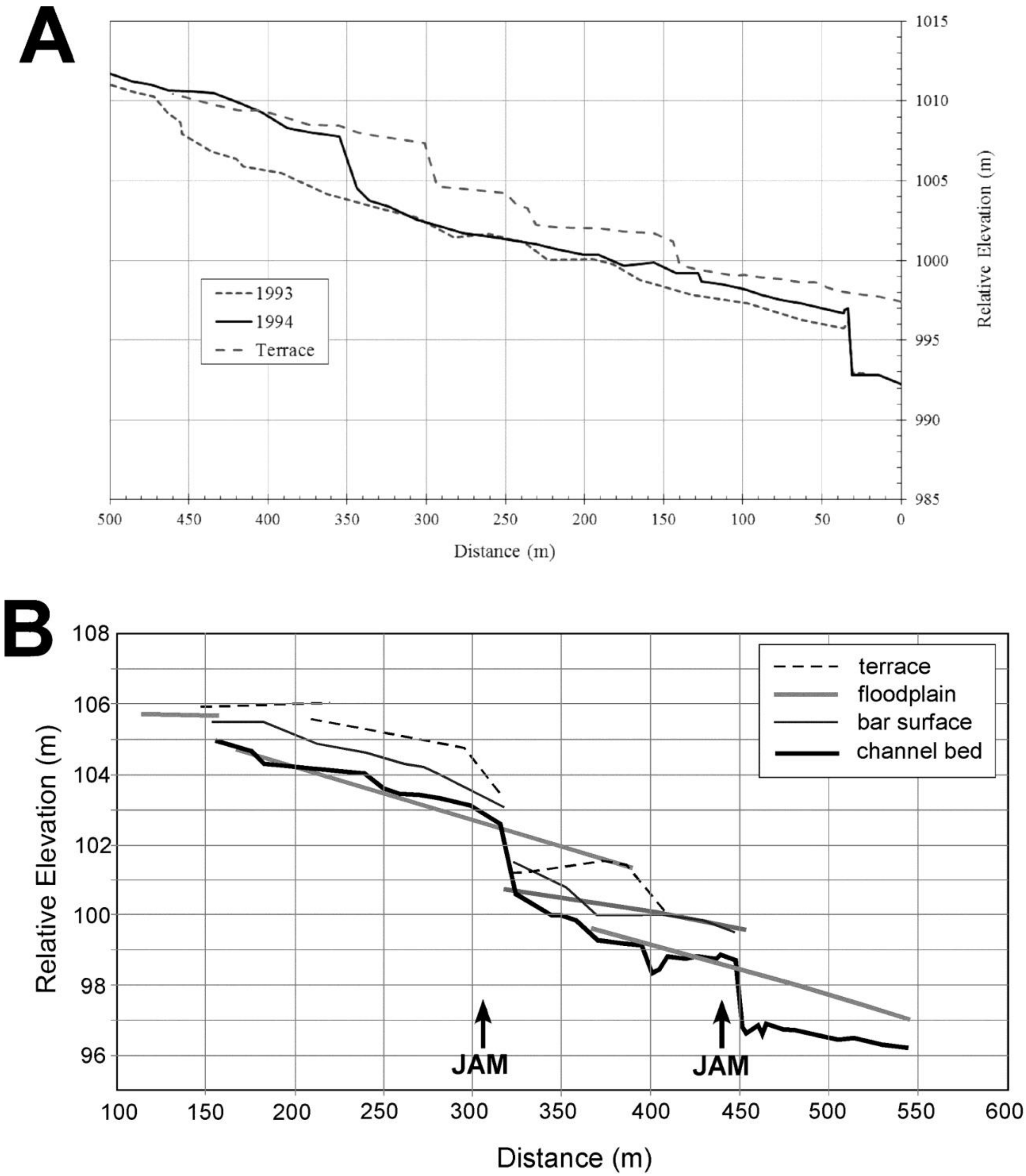
Figure 4-32. Geomorphologists Offer Direct Design Input on the Role of Wood and Bed Material on Channel Morphology that Is Essential in Stream Restoration and Providing Sustainable Solutions for Protecting Infrastructure[1]



Here (Woodward Creek in southwestern Washington), wood and large rock was used to create a cascading channel step to treat incision threatening a gas pipeline and restore fish passage,

The pipeline was exposed in 2007 after the channel incised approximately 2.4 meters (8 feet) (A). To safeguard the pipeline and improve fish passage, a log and rock grade control riffle was designed (B) and constructed in 2008 (C). The bottom photo shows the structure in 2009 after it had been subjected to a 25-year flood (D). This type of approach shows how wood and stream restoration can also benefit infrastructure (Abbe et al. 2009).

Figure 4-33. Natural Logjam Influence on Channel Aggradation and Terrace Construction in 4th Order Alta Creek (A) and 6th Order Mainstem Queets River (B)



Source: Abbe (2000), Abbe and Montgomery (2003), and Montgomery and Abbe (2006).

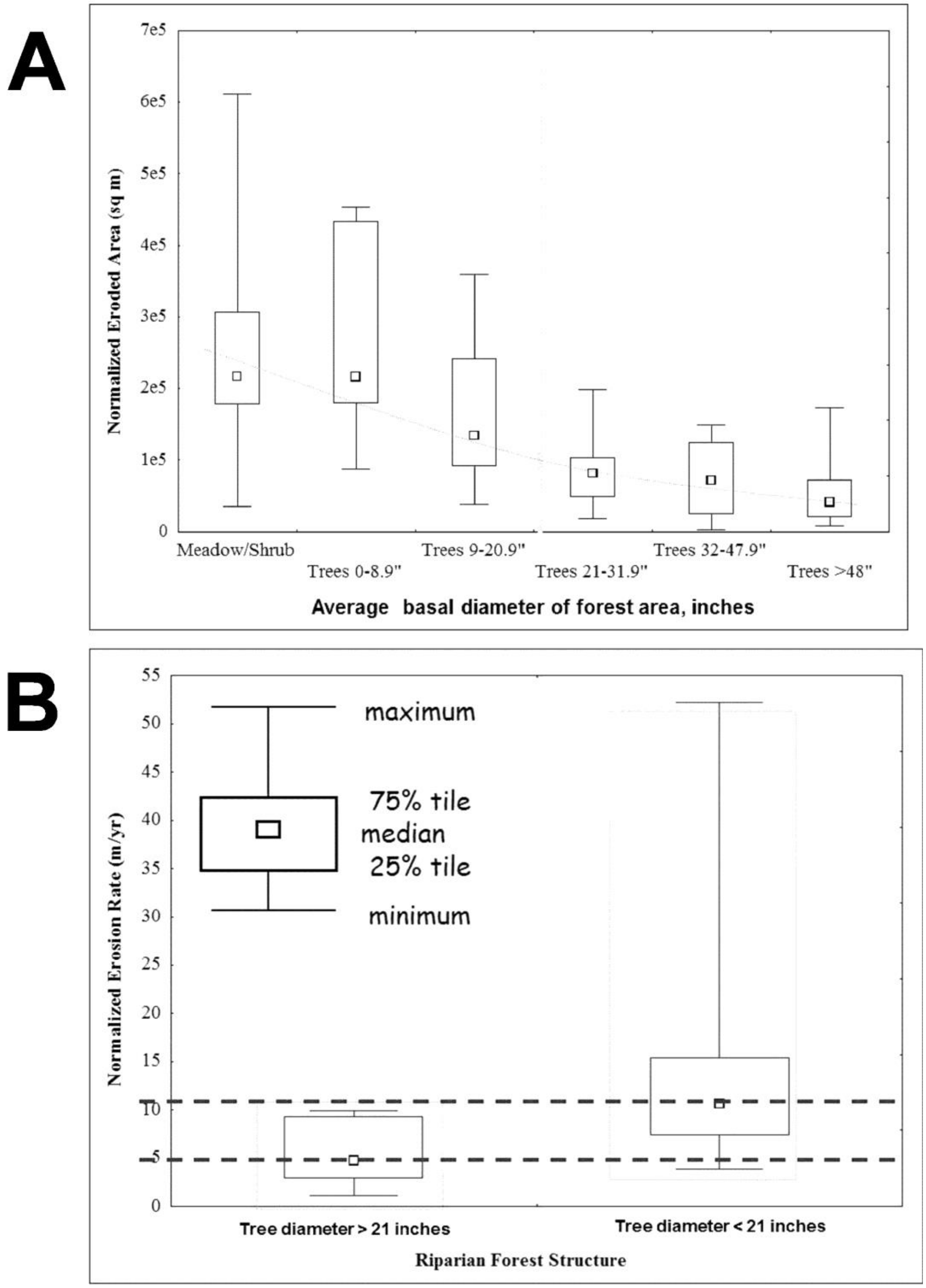
4.2.6 Wood and Bank Erosion

Trees further slow the water and their roots hold the underlying soil together (e.g., Tsukamoto 1987; Sidle 1991) and increase the strength of river banks to resist erosion (Eaton et al. 2004; Eaton 2006; Simon and Collison 2002; Simon et al. 2000; Konsoer 2014). The cohesion provided by riparian vegetation directly influences bank strength and hydraulic geometry, effectively reducing channel width (Eaton et al. 2004; Eaton 2006). When banks erode, fallen trees can form logjams that further diffuse the river's energy and even protect some areas of floodplain from erosion (Abbe et al. 2003a; Konsoer 2014).

Functional wood can play an influential role in the rate of bank erosion along rivers and demonstrates how both the restoration of mature riparian forest buffers and engineered wood placements can be used to protect banks and enhance habitat. A geomorphic analysis of channel migration along the Hoh and Queets rivers of northwestern Washington found that erosion rates were lower in areas with larger trees (Figure 4-34A) (Abbe et al. 2003a). The analysis showed a statistically significant difference between areas with trees less than 53 centimeters (21 inches) in diameter versus those with greater diameters (Figure 4-34B). The median normalized erosion rate for the areas with larger trees was 5 meters (16 feet) per year, and the rate for areas with small trees was 11 meters (36 feet) per year (Abbe et al. 2003a). These differences are consistent with work by Micheli et al. (2003) who found erosion rates along meanders of the Sacramento River in California were twice as high in agricultural areas as they were along riparian forests (forest erosion rates ranged from 2.5–6 meters [8–20 feet] per year versus agricultural rates of 6–11 meters [20–36 feet] per year. The differences in rates found along the Hoh and Queets rivers (Abbe et al. 2003a) are due to the role of key pieces of wood falling into the river as the bank erodes. Stable snags create roughness along the bank that partitions shear stress and deflects flow away from the bank (Figure 4-35A). Small trees are easily flushed downstream by the river and do not retard erosion (Figure 4-35B). The role of large trees is evident in the forest structure of undisturbed rivers where channel migration erodes valley hill slopes. At such sites, logjams form at the toe of the hill slope that redirects the river and halts further erosion (Figure 4-36). Where large trees were removed, erosion tends to proceed, even into hill slopes that rise far above the river (Figure 4-37). An analysis of the Hoh River found almost four times as much land was eroded by channel migration outside Olympic National Park in logged lands versus unlogged areas (Figure 4-38).

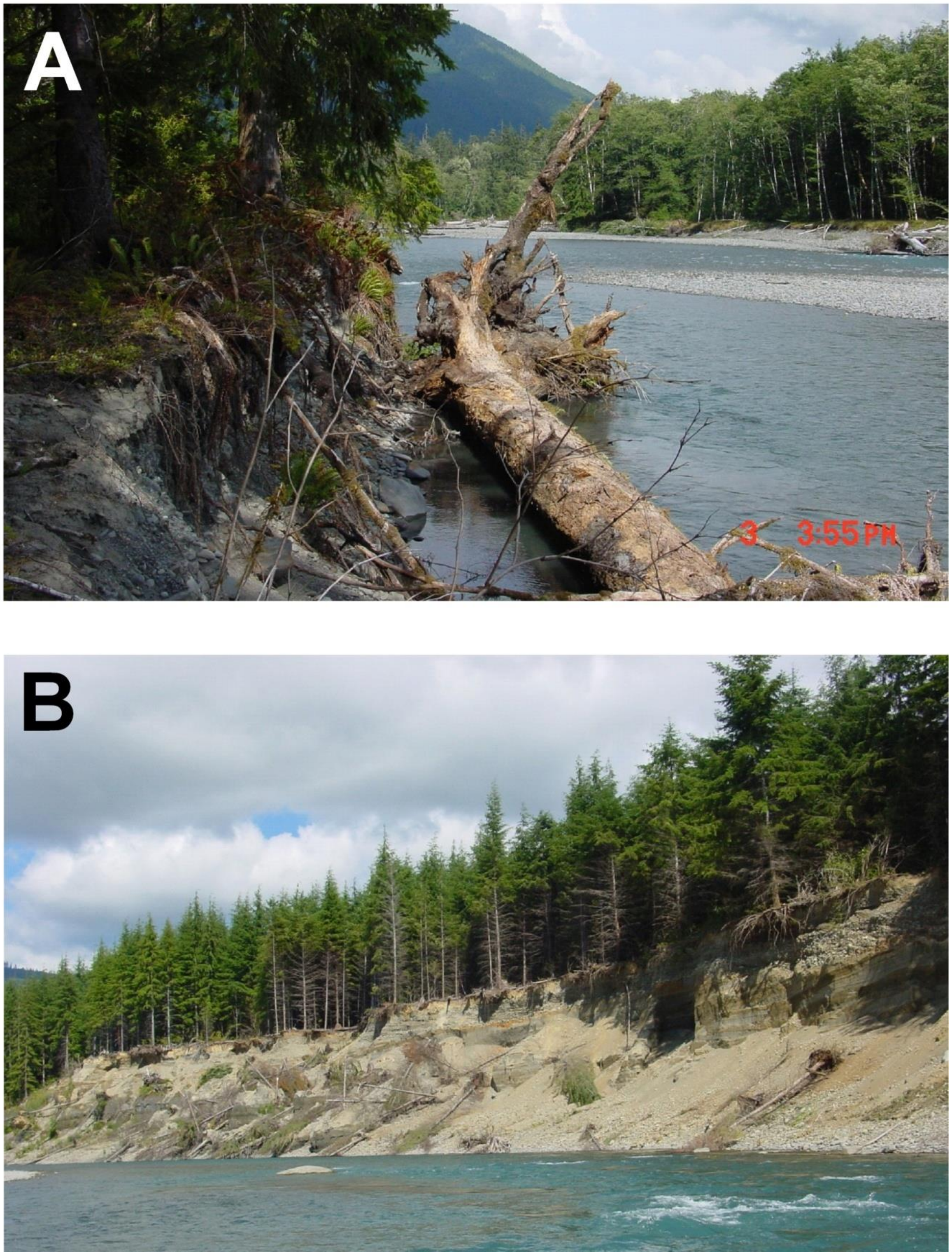
Bank erosion rates along forested banks can be 50 to 90% lower than along unforested banks (Thorne and Furbish 1995; Micheli et al. 2003; Abbe et al. 2003a; Konsoer 2014). Abbe et al. (2003a) found erosion rates were dependent on tree size, which was attributed to larger trees being more likely than smaller trees to form stable roughness elements with a longer residence time along an eroding bank. Konsoer (2014) found that tree snags along a bank were the primary roughness element and responsible for major changes in flow patterns along eroding banks. Flow patterns and erosion rates were compared to two similar meander bends of the Wabash River in Illinois, one with a smooth bank along agricultural land, one along forested land (Figure 4-39). Rougher banks have much more pronounced secondary flow vortices that slow near-bank velocities and push the primary current farther from the bank (Thorne and Furbish 1995; Meile et al. 2011; Konsoer 2014). The smoother bank eroded 17 times faster than the rough bank (Konsoer 2014). Increasing bank roughness increases the width of slower near-bank velocities, reducing shear stresses acting on the bank and creating more refuge and cover for fish. Roughened bank treatments can offer greater erosion protection and fish benefits than traditional methods (Figure 4-40). Complex placements of wood that increase river bank roughness and lower shear stress can be an effective means of bank protection (e.g., Abbe and Brooks 2011; Abbe et al. 2011).

Figure 4-34. (A) Forest Areas With Larger Trees Erode More Slowly Than Areas With Smaller Trees Along the Hoh and Queets Rivers; (B) Breaking Data Into Two Categories greater and less than 53 Centimeters (21 Inches), There Is a Statistically Significant Difference, With Areas With Larger Trees Eroding at less than Half the Rate of Smaller Trees



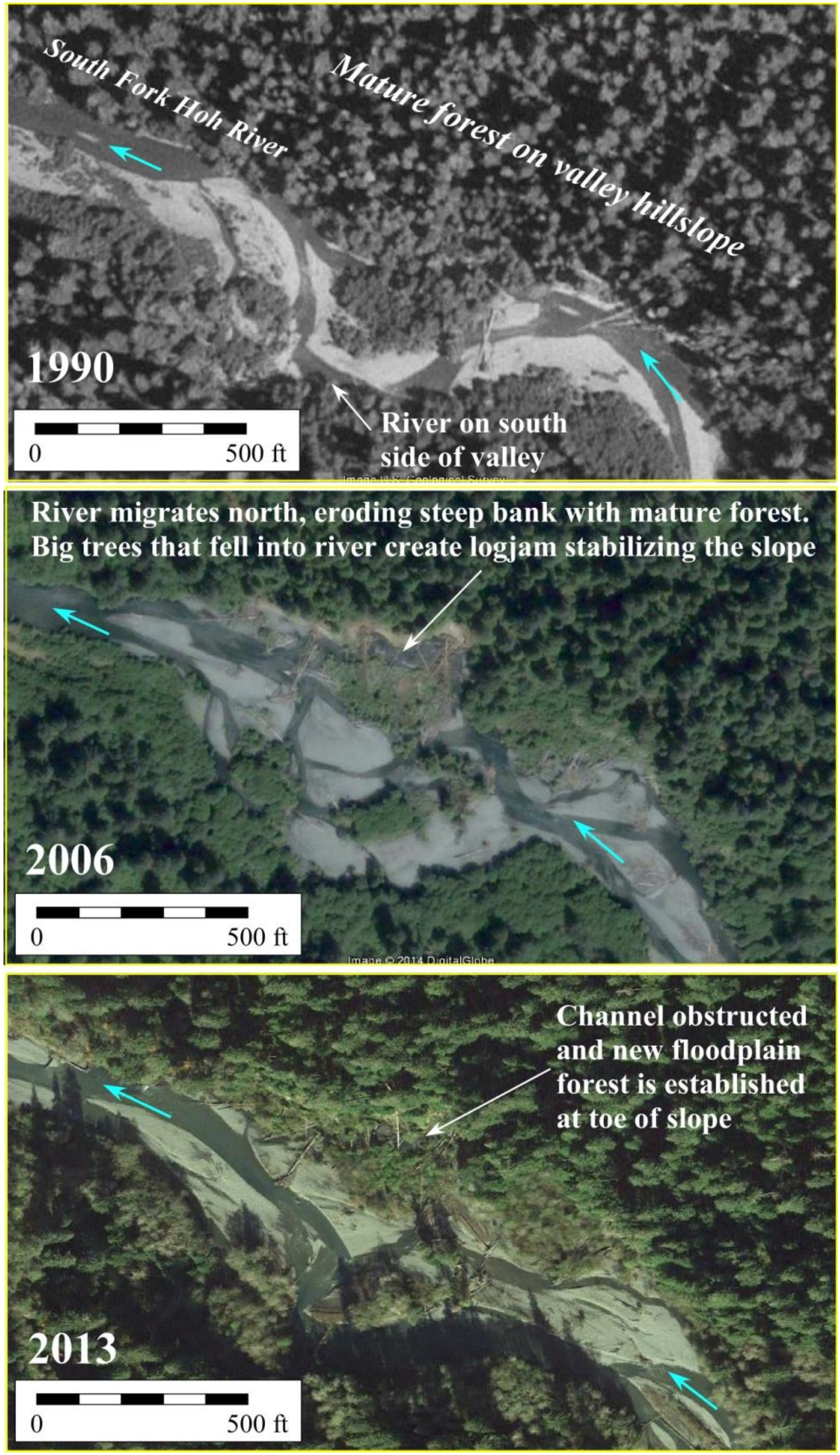
Source: Abbe et al. (2003a).

Figure 4-35. (A) Erosion Into Mature Forests Along the Hoh River Recruits Large Snags That Form Stable Obstructions (Key Pieces) in the Channel That Slow Erosion Rates; (B) Areas of Industrial Forest or Agriculture (Trees Less Than 21 Inches) Erode at Over Twice the Rate



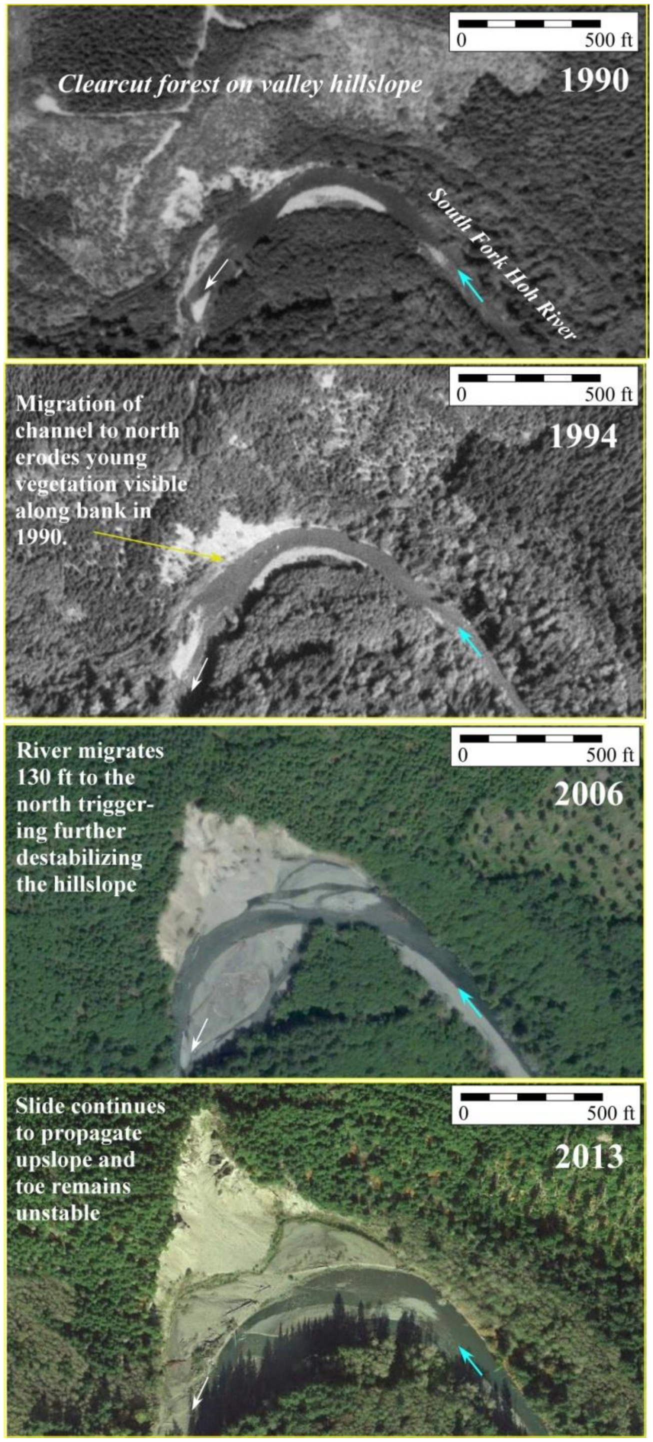
Source: Abbe et al. (2003a).

Figure 4-36. Illustration of How Large Wood Influenced Channel Process and Morphology on the South Fork Hoh River, Washington, from 1993 to 2013



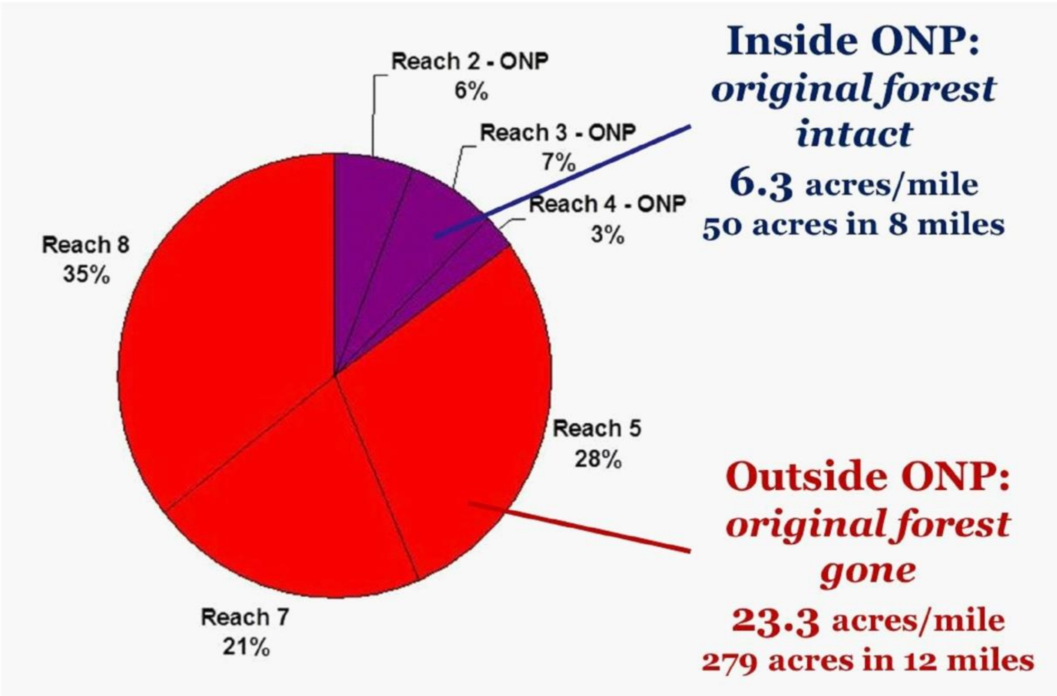
From 1990 to 2006 the river migrated north about 32 meters (106 feet) into mature timber, a rate of about 2.1 meters per year (7 feet per year). This recruited trees that obstructed the channel and halted further erosion. The logjam moved the river south, stabilized the toe of the embankment, and established new floodplain forest.

Figure 4-37. Clearing Mature Riparian Forests Eliminates Functional Wood Recruitment and Alters Processes and Channel Form



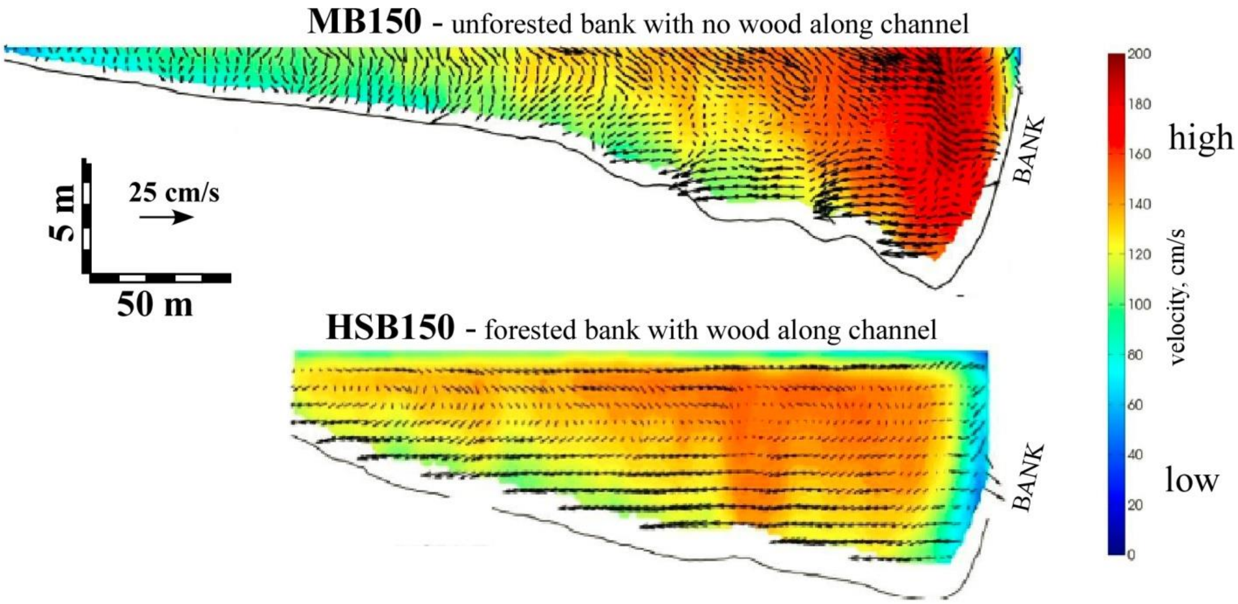
This site in the South Fork Hoh River, Washington (just downstream of the site shown in Figure 4-36), the river migrated about 47 meters (153 feet) to the northwest from 1990 to 2006 into the adjacent valley hillslope that had been clear cut. The average rate was 3 meters per year (10 feet per year). Because the erosion destabilized the hillslope, erosion impacted a much greater area, extending 167 meters (550 feet) into the valley margin. From 1990 to 2013 the rate of head scarp retreat was about 7.3 meters per year (24 feet per year).

Figure 4-38. Outside Olympic National Park Almost All Old Growth Forest Within the River Valley and Adjacent Hillslopes Has Been Cut



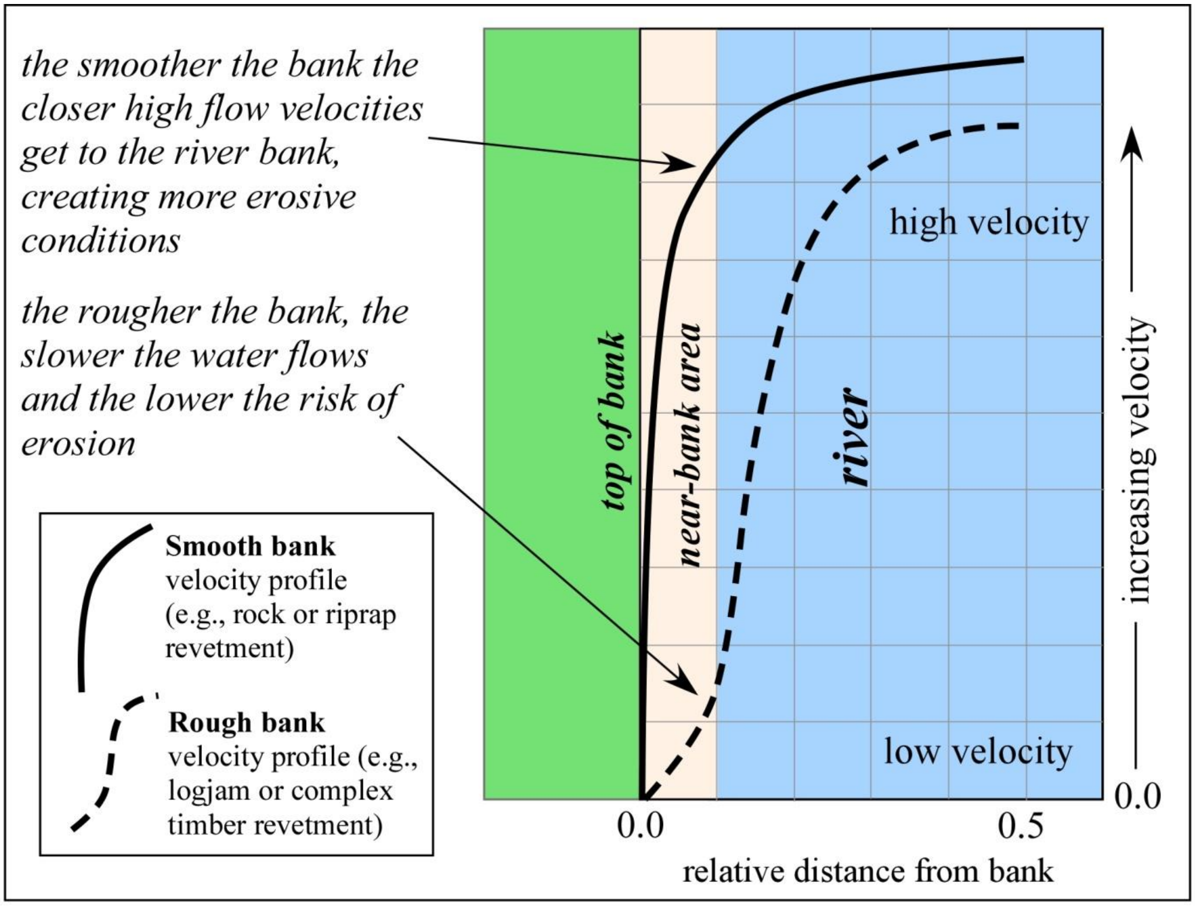
The area outside the park has experienced much more erosion and expansion of historic channel migration zone than the areas within the park (U.S. Bureau of Reclamation 2005).

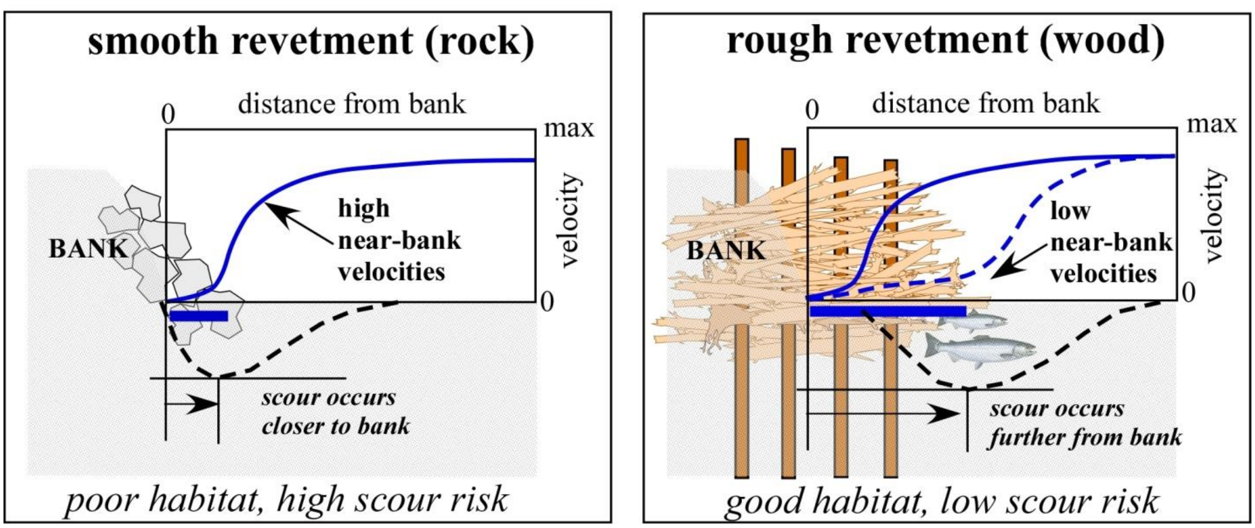
Figure 4-39. Flow Velocity Fields Around Two Bends of the Lower Wabash River, Illinois



Cross-section MB 150 is downstream of meander apex with relatively smooth bank, HSB72 is cross-section in similar location of bend where there are snags along the bank. The roughness created by the snags along HSB72 slows down velocities near the bank. Erosion rates at HSB72 are 17 times less than MB 150 (Konsoer 2014)

Figure 4-40. Illustration of How Rougher Banks Reduce River Velocities Near the Bank





Traditional bank protection tends to create a smooth bank where high flow velocities hug the bank (solid lines above). Where banks are roughened, near-bank velocities are reduced (dashed lines), diminishing the risk of erosion and improving salmon habitat.

4.2.7 Sediment Storage

Sediment storage behind large wood accumulations was clearly illustrated in the patterns of channel erosion that followed wood removal (e.g., Veatch 1906; Guardia 1933; Baker 1979; Sedell and Luchessa 1981; Hickin 1984; Sedell and Frogatt 1984; Hartopo 1991; Barrett 1996; Abbe 2000; Wallerstein and Thorne 2004; Stock et al. 2005; Phillips 2012). Examples of channel incision in large low-gradient rivers include the Cann River in Victoria, Australia (Brooks and Brierly 2004), the Red River of Louisiana (Veatch 1906; Guardia 1933; Triska 1984), and the Colorado River near the town of Matagorda, Texas (Wadsworth 1966; Kanes 1970; Hartopo 1991).

The Cann River is a sand-bedded river draining about 650 square kilometers (250 square miles). After wood removal, the Cann River experienced an 860-fold increase in sediment transport and evacuated a volume of sediment representing 1,500 years of floodplain sedimentation (Brooks and Brierly 2004). These authors estimated that to aggrade the river to its pre-existing state would take 31,000 years, assuming restoration of instream wood and riparian vegetation.

The Red River drains 110,190 square kilometers (43,545 square miles) of Arkansas and Louisiana. Logjams were documented in the earliest records of European exploration, and Native Americans could not recall a time when jams did not block the Red River (Lowrey 1968; Triska 1984; Barrett 1996). After large logjams were removed from 1873–1892, the river experienced 5 meters (16 feet) of incision (Veatch 1906). The river transformed from a network of narrow anabranching channels to a larger single thread channel. Barrett (1996) estimated floodplain sedimentation rates were reduced almost 10-fold from 2.0–3.0 to 0.3–0.4 centimeters per year (0.8–1.2 to 0.1–0.2 inches per year) after logjam removal in the Red River.

The Colorado River of Texas has a drainage area of 110,190 square kilometers (43,545 square miles). The first recorded observation of a large channel-spanning wood accumulation (historically referred to as "rafts") in the lower Colorado River of Texas was by Spanish explorers in 1690 (Clay 1949). Prior to removal of this wood by the U.S. Army in 1927, the shoreline at the river's confluence into Matagorda Bay exhibited no protruding delta. Directly after removing the jam, a pronounced delta began to extend into and eventually across the bay (Wadsworth 1966; Hartopo 1991). Approximately 11 by 81 cubic meters (14 by 106 cubic yards) of sediment was introduced to Matagorda Bay (Gulf of Mexico) over a 29-year period after raft removal (Abbe 2000).

These are examples from relatively large rivers, but the same issues impact streams of all sizes throughout a watershed. In the Puget Sound small streams that were relatively stable for several thousand years have been subject to dramatic incision in the twentieth century following historic logging that removed riparian trees and instream wood (e.g., Baker 1979; Stock et al. 2005), and upland development that increased peak flows (e.g., Booth 1990). Incision sent head cuts and gullies up these drainages (such as Figure 4-26B) and large quantities of sediment downstream that often required construction of expensive sediment retention ponds throughout the region. Restoration of wood can provide a much more economical, environmentally beneficial, and sustainable solution to limit channel incision, reduce erosive power (sediment transport capacity), and trap sediment (e.g., Lester and Wright 2009; Abbe et al. 2009; Abbe and Brooks 2011; Daley 2012).

4.2.8 Water Quality

The ability of large wood to trap sediment is also applicable to other suspended materials in the channel. Ehrman and Lamberti (1992) compared channels with and without large wood, and found that channels with large wood retained water 1.5–1.7 times longer and reduced coarse particulate organic matter (CPOM) transport by 35% when compared to channels without large wood. Similarly, Jacobson et al. (1999) found that large wood trapped CPOM, which was then incorporated into the benthic biomass, creating islands of organic matter in the channel that became focal points for decomposition and secondary production. Because decomposition (Sinsabaugh et al. 1994) and invertebrate grazing (Lampert 1978) of CPOM releases dissolved organic carbon (DOC) into the water, it would follow that CPOM retention would create higher DOC concentrations in the stream.

CROSS-REFERENCE

Wood influences on hydraulics, water levels, substrate, channel morphology, and hyporheic flow has direct implications for water quality, a topic that is also addressed in Chapter 3, *Ecological and Biological Considerations*.

A litter exclusion study by Meyer et al. (1998) at Coweeta, North Carolina, showed that DOC contribution from the in-channel leaf pack contributed 30% of the total export of the stream; the remainder of the DOC was imported into the channel from the landscape. Once in the channel, however, DOC is labile and will likely be taken up quickly in a reach with a high volume of large wood. It has been shown that certain labile dissolved organic compounds are quickly taken up in channels that have flow obstructions (Hall and Meyer 1998; Wiegner et al. 2005). Therefore, it would seem that the presence of large wood and associated CPOM would not significantly impact stream DOC concentrations because there are the counteracting dynamics of DOC export from CPOM decomposition and DOC uptake from large wood–induced water retention.

Water retention from large wood and the presence of CPOM in the channel also play important roles in the fate of nutrients in the stream channel. In a classic paper by Mulholland et al. (1985) it was suggested that leaf litter in streams promotes nutrient retention as the leaf pack acts as a substrate for nutrient-hungry microbes. Additionally, a more recent study by Webster et al. (2000) suggests that litter exclusion decreases phosphorus retention and that large wood exclusion further impedes a stream's natural ability to absorb nutrients. Using solute injection techniques Valett et al. (2002) found that phosphorus uptake in channels with high large wood volumes, frequent debris dams, and fine-grained sediments was significantly greater than in channels in younger forests without these characteristics. Finally, corroborating this finding, Ensign and Doyle (2005) conducted phosphorus injections in streams both before and after the removal of large wood and CPOM in the channels, and found that phosphate uptake decreased by up to 88% after large wood removal. These studies show that large wood increases water retention and provides a substrate for biofilm growth; both these factors contribute to higher phosphorus retention in streams that have large volumes of large wood.

Given these factors, it would seem that the presence of large wood acts to reduce phosphorus and sediment export while having little effect on DOC concentrations other than at sites where wood increases turbulence and plunging flow. The removal of upstream snags, especially those associated with major channel formations (pools, large flow divergences), would exacerbate any potential water quality problems. Of course there would be other ramifications if the reach was de-snagged, including the degradation of fish habitat (Lehane et al. 2002; Mossop and Bradford 2004), reduced carcass retention (Johnston et al. 2004; Minakawa and Gara 2005), lower macro-invertebrate populations (Johnson et al. 2003), and increased risk to downstream infrastructure because logjams trap mobile debris. From a water quality perspective the presence of large wood is clearly beneficial.

4.3 Hydrology

Hydrology is an earth science discipline focused on the properties, origin, circulation, and distribution of water in the environment, including fluxes in streamflow, interflow, and groundwater discharge. Understanding the timing, rate, and mechanism of movement of water through watersheds and its role in geomorphic processes is important for large woody material design as it affects erosion, sedimentation, riparian plant growth, and other key processes. Furthermore, knowledge of how hydrological processes, namely streamflow hydrographs and flood wave dynamics discussed herein, are affected by riparian vegetation and large wood in the channel is important to understanding the tradeoffs between enhanced ecological benefit and altered levels of flood protection.

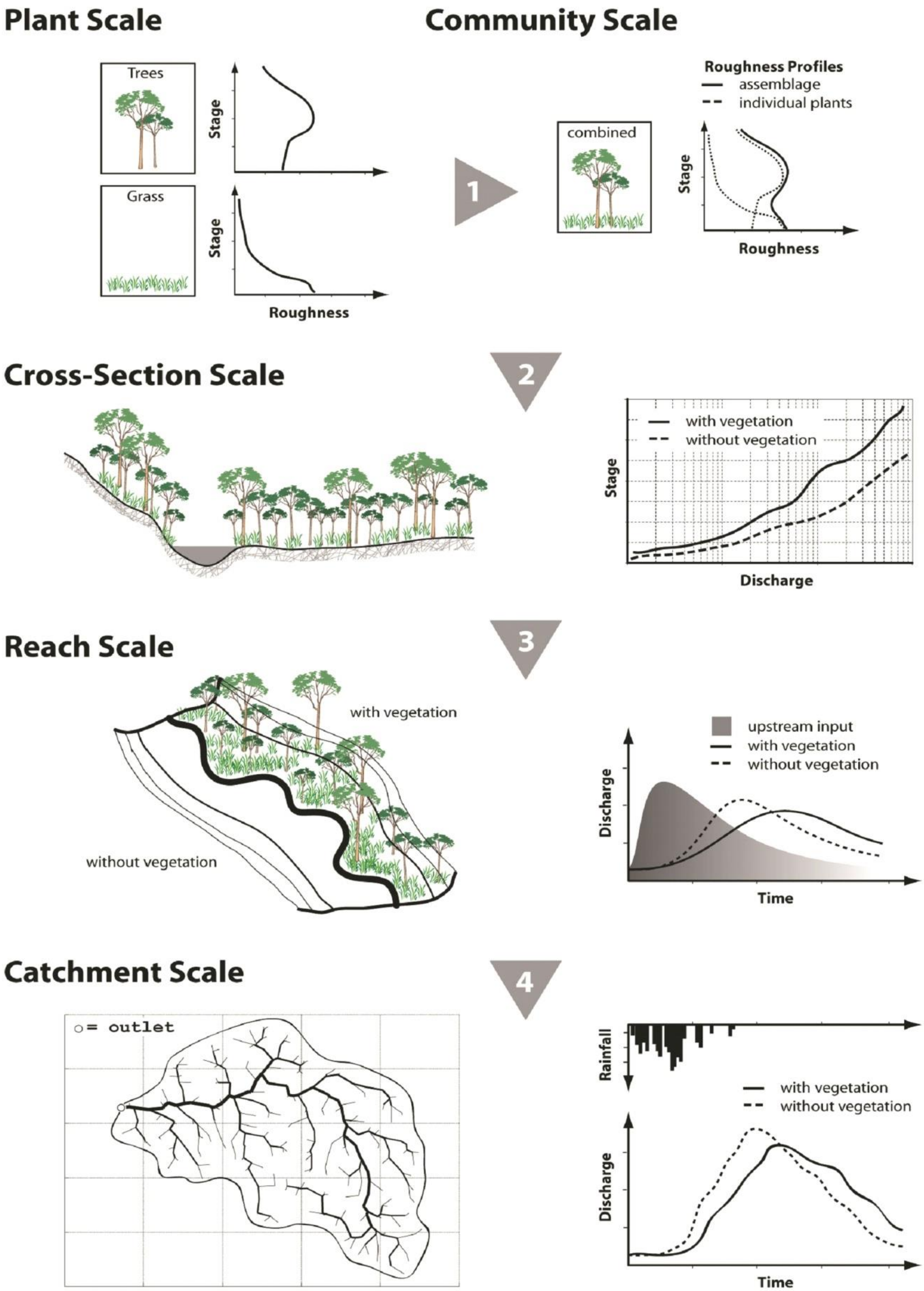
4.3.1 Effects of Riparian Vegetation and Wood on Hydrology

Floods are often described as traveling as a slow-moving wave that increases in size as it travels down the watershed from the addition of many smaller waves derived from the upstream network. Quick traveling small waves typically create a flood wave with a higher peak discharge but shorter duration than slower waves (Anderson 2005, 2006).

Floodplains, riparian vegetation, and large wood in the channel play a key role in flood wave dynamics by storing flood water, at least temporarily, and slowing the pace of the flood wave as it moves down the watershed. Ultimately, the size of the flood wave's peak discharge at a particular location in the watershed is related to how quickly smaller waves from tributaries join together and the volume of water stored during the flood (Anderson 2005, 2006). The effect of riparian vegetation and large wood on flood hydrology depends largely on the scale considered, network geometry, channel morphology, and the flood magnitude.

Large wood and other riparian vegetation (flow obstructions) create a hydraulic "backwater effect" whereby the water level immediately upstream of the obstruction is raised, which in turn raises the level of water upstream of it, and so forth, resulting in a curve of slower and higher water extending upstream from the obstruction. Backwater curves indicate water storage created by the obstruction. Backwater effects typically extend farther upstream in lower slope channels. When the velocity upstream of the obstruction is slowed, then it is not routed downstream as quickly as it otherwise would be, and the water already downstream will drain away as the water level drops (Rutherford et al. 2007). Therefore, an obstruction in the channel has the effect of altering hydrology by slowing a flood wave by increasing storage, depth, and duration of the wave upstream with a decrease in flood depth downstream. As Figure 4-41 illustrates, the effect of individual plants and logs on the flood stage largely depends on biomass, plant flexibility, the level of streamlining and lying down of stems/leaves under flow pressure, and whether the plant is submerged or emergent. Typically, and especially for grasses, willows, and other flexible riparian plants, flow resistance decreases with increasing discharge and stage. However, flow resistance can increase in situations where elevated flood stage results in increased flow through the tree canopy. At the cross-section scale the presence of riparian vegetation results in increased stage levels compared to a condition without riparian vegetation (Figure 4-41). Therefore, placement of wood in the channel and increased riparian vegetation can result in higher water surface elevations along the banks and, in unconstrained reaches, enhanced floodplain connectivity from an increased volume of water spilling out onto the floodplain.

Figure 4-41. Conceptual Diagram of the Effect of Riparian Vegetation on Discharge at the Scale of a Plant, a Cross-Section, a Reach, and a Catchment



Source: Anderson (2006).

GUIDANCE

Riparian vegetation and large wood in a channel network directly influence flood hydrographs (Anderson 2006; Thomas and Nisbet 2006; Rutherford et al. 2007).

- Increase roughness that dissipates flow energy (e.g., stress partitioning).
- Reduce channel and floodplain conveyance
- Diminish flow velocity and the flood peak celerity ,
- increase stage and flood storage which can contribute to attenuating flood waves moving through the watershed, lowering flood stages downstream.

When considered at the reach scale, defined as approximately 10 kilometers (6 miles) in Anderson's (2006) research, the combined backwater effects of increased wood and riparian vegetation result in increased water storage and a slower flood wave celerity (velocity of the wave traveling through the reach) and increased time to peak discharge compared to the no vegetation condition (Figure 4-41). The time rate of flood wave diffusion is greater in the no vegetation condition compared to the densely vegetated channel. Yet, the peak discharge of the flood wave at the end of the reach with vegetation is less than the peak of the wave in the no vegetation reach; thus, the rate of diffusion per channel length with vegetation is equal to or greater than the reach without vegetation (Anderson 2006). This result is explained by differences in flood wave celerity. In Anderson's (2006) research, the hydrograph in reaches void of vegetation generally moves three times faster than with vegetation; thus, diffusion can occur only a third of the time, and at the end of the reach the no-vegetation condition has more discharge than the vegetated condition.

At the catchment scale, the riparian vegetation and large wood have the effect of pushing water out onto floodplains, and delaying and reducing the magnitude of the flood peak but increasing the duration of higher flows (Figure 4-41). Therefore, a tradeoff exists whereby the presence of riparian vegetation and large wood in the channel can lead to increased flood height at the cross-section and into the reach scale versus a delaying of the flood wave and reduction in its peak discharge downstream at the watershed scale. When considered at the watershed scale, the presence of riparian vegetation and large wood actually enhances flood protection for downstream locations compared to a situation devoid of riparian vegetation and large wood (Anderson 2005).

Research has also shown the influence of channel shape on the ability of riparian vegetation and large wood to attenuate flood peaks (see Figure 4-42). In a scenario with a 50-kilometer (31-mile) reach, riparian vegetation and large wood delays the flood wave peak discharge between 5 and 10 hours depending on cross-section shape, with wider and shallower cross-sections with substantial floodplain roughness providing the greatest attenuation and narrower and deep cross-sections the least (Anderson 2006). If the width/depth ratio of the stream is greater than 17, vegetation is not likely to appreciably affect flooding because the cross-section is too wide and shallow (Masterman and Thorne 1992). Also, more flood attenuation is observed in the case of the small input discharge compared to the large input discharge (Figure 4-42).

The following discussion focuses specifically on large wood in the channel without considering the role of riparian vegetation. The backwater effects and flood storage created by multiple wood structures are additive and can result in appreciable flood wave attenuation accompanied by local increases in flood height. Though not uniform to all systems, research has shown that large wood in the channel has a small to insignificant effect on the duration or frequency of large flood events (approximately events greater than the 20-year flood) because much of the flood water is out on the floodplain, but can increase the duration of smaller floods (i.e., 1- to 2-year events) where most of the flow is still contained to the channel (Rutherford et al. 2007). Large wood of a given size will have a greater effect on a small stream.

Figure 4-42. Sample of Simulated Waves Computed for Different Channel Shapes

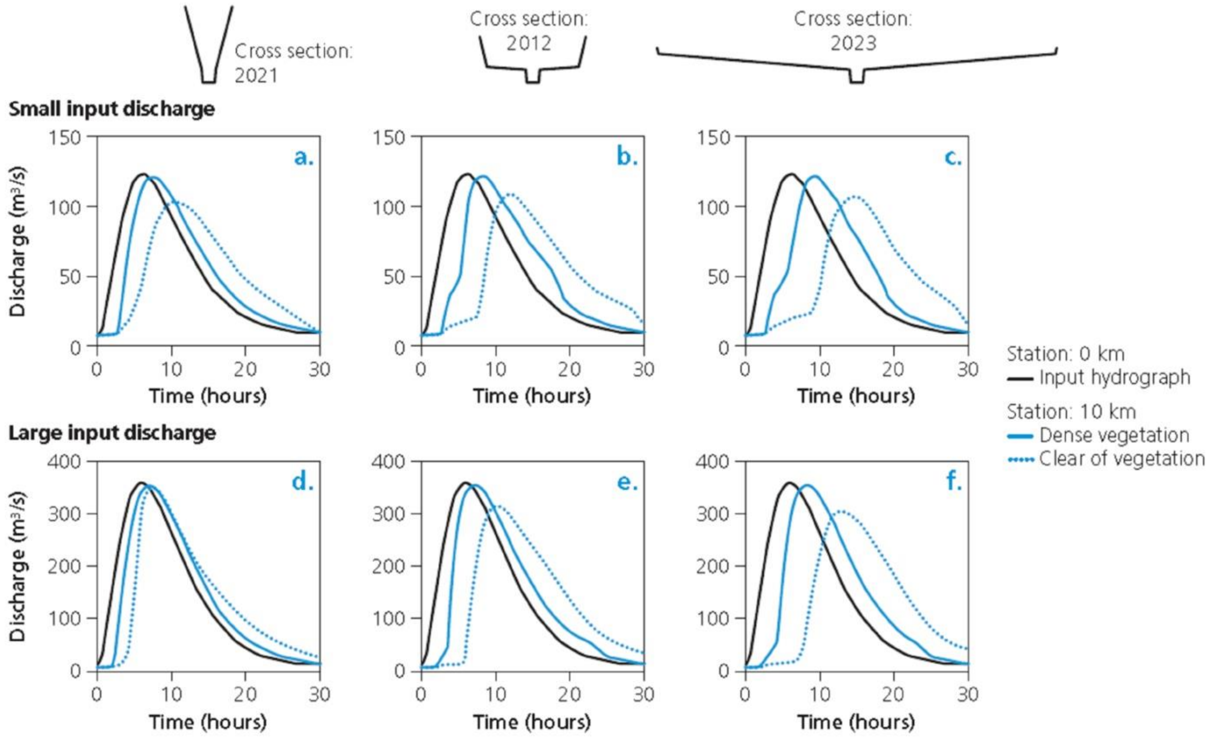


Figure shows the input hydrograph and hydrographs at 10 kilometers (6 miles) downstream of the input hydrograph for channels with vegetation, and clear of vegetation. (From Anderson 2006 as cited in Rutherford et al. 2007).

CAVEAT

Large wood generally will not affect small flood events when the following is true (Rutherford et al. 2007):

- The projected area of the large wood is less than 10% of the area of the cross-section. The projected area is the area of the large wood in a two-dimensional cross-section across the stream. A large wood structure needs to be very large to occupy 10% of the cross-section of a third-order or higher stream.
- The large wood is angled at 40° to the flow (i.e., with the upstream end of the large wood against the bank).
- The large wood is submerged in a backwater at higher flows. That is, the level of the flood could be hydraulically controlled by some feature downstream. For example, a bridge crossing downstream may constrict the flood flow. This constriction will then produce a backwater upstream. If the large wood falls within that backwater, then it will have no hydraulic effect on flow at all during that flood. As the flood level falls, however, the large wood will eventually produce its own shorter backwater. The same principle applies to a backwater produced by large wood: if additional large wood falls within that backwater, it will have no hydraulic effect on flow. A rule of thumb for this effect is that large wood that is five to six diameters upstream of other large wood of similar (or larger) size will not affect flood level, because it will be within the backwater of the existing large wood.
- Several large wood structures in line will not produce any more afflux than a single large wood structure, so long as each structure is located within two times the diameter of the next structure up or downstream. Therefore, up to six structures can be placed parallel to each other in a line. In general, any piece of wood will add little extra afflux (i.e., rise in water level) if it is placed within four log diameters of the next piece.

The research into the effects of large wood on flood hydrology shows that adding wood to the stream in many situations has a negligible effect on the stage or duration of local flooding (Rutherford et al. 2007). However, the local increase in flood stage created by the addition of large wood into the project reach may elevate flood risk for a particular recurrence interval beyond an acceptable level even though a net benefit in flood protection is gained for locations downstream. Hydraulic modeling would need to be performed to fully evaluate the extent to which placement of large wood elevates flood stage at the project site. Similarly, an unsteady flow hydraulic model could be used to also evaluate how placement of the large wood may increase flood wave diffusion and attenuate flooding downstream.

Beyond the question of flood risk, current research is showing how riparian vegetation and the addition of large wood in the channel alters hydrology by slowing water and enhancing hyporheic flow and pushing it out onto floodplains and backwater areas in unconfined reaches where benefits of floodplain connectivity, storage, and recharge and elevation of groundwater levels can be attained.

Geomorphic and Hydrologic Analysis Checklist

Watershed

- Drainage area
- Relief
- Annual and monthly precipitation
- Land cover
- Sediment sources
- Presence of dams or diversions influencing flow, water, and wood

Project Site

- Topography and bathymetry
  - High-resolution digital elevation mapping using LiDAR and ground surveys
- Precipitation and flow data
- Valley
  - Gradient
  - Extent of alluvial valley bottom
  - Extent of active floodplain (e.g., 100- and 500-year flood inundation areas)
  - Presence of relic channels and wetlands
  - Presence of terraces
  - Valley perimeter and geologic composition
  - Infrastructure/development
- Channel
- Gradient
- Unvegetated width
- Sinuosity or total channel length for anabranching systems
- Map presence of side channels or anabranches
- Pool location, frequency, and size
- Grain size distribution of channel substrate, differentiating surface and subsurface in gravel bedded channels
- Bed texture mapping
- Wood
  - Stable snags
    - Location
    - Size

        - Effect (e.g., pool, bar)
    - Logjams
        - Location
        - Size
    - Formative mechanism (e.g., snag, rock, trees, bridge pier)
        - Effect (e.g., pool, bar)
- Infrastructure within floodplain (e.g., bridges, roads)

Historic Change

- Historic documentation
    - Historic accounts and photos
    - Geo-rectified maps and aerial photos
    - Previous studies
- Watershed (e.g., extent of forest clearing, development, dams)
- Hydrology (e.g., are there trends of increasing or decreasing peak and base flows?)
- Floodplain (e.g., how much of floodplain has been disconnected?)
- Original old-growth riparian forest conditions at project site
    - Tree diameters and heights
    - Stem densities
- Channel
- Location, date, and extent of modifications
(e.g., clearing, straightening, levees, revetments, bridges, wood clearing, splash damming, gravel mining)
- Channel patterns
    - Sinuosity, unvegetated width, anabranching
- Incision or aggradation
- Channel migration
- Historic channel change mapped
- Erosion rates computed
    - Is erosion linked to peak flows or floodplain conditions?
- Historic wood loading (from historic evidence or using applicable reference studies)

Problem Definition

- Summarized historic geomorphic change at site
    - Simplification of channel?
    - Shortening of channel length?

  - Floodplain disconnection?
  - Channel incision?
  - How has wood supply and loading changed?
  - How has flow regime changed?
  - How has sediment supply and transport capacity changed?
- Extent of habitat impacts; for example:
  - Total reduction in channel length?
  - Reduction in number of pools?
  - Loss of large riparian trees?
  - Change in substrate?
  - Changes to extent and rate of channel migration?
  - Reduction in flood inundation frequency?
  - Increase in peak flow magnitude and frequency?
  - Alteration of natural flow regime?
  - Increase or reduction in sediment supply?
- Historic and current threats to infrastructure
- Future change prediction under a no-action scenario
- Problem summary

Project Geomorphic Goals Defined

- Full or partial restoration
- Objectives and numerical metrics described; for example:
  - Restore channel gradient
  - Increase sediment storage
  - Increase instream wood quantities
  - Increase number of pools and cover
  - Increase channel length
  - Increase floodplain connectivity (inundation frequency)
  - Protect property or infrastructure
  - Identify area of restored habitats

4.4 Uncertainties and Research Needs

1. Regional descriptions and databases of wood loading, functions, and longevity in streams are lacking throughout the United States, particularly with regards to undisturbed native forests. Much of the present state of knowledge comes primarily come from the Pacific Northwest (Oregon, Washington and Southeast Alaska), and Rocky Mountains (Idaho and Colorado Front Range). Recent work has included the Upper Midwest and New England, but much more is needed. Regions particularly unrepresented include the arid southwest (Nevada, Utah, New Mexico, Arizona, and Southern California), the Sierra Nevada (eastern California), the Great Plains (Eastern Colorado, Kansas, the Dakotas, Nebraska, Missouri), the lower Midwest (Iowa, Illinois, Indiana, Ohio), the South (Arkansas, Oklahoma, Texas, Tennessee, Kentucky, the Carolinas, Georgia, Alabama, Louisiana, and Florida), the Mid-Atlantic (Pennsylvania, Maryland, West Virginia, Virginia), and the Alaskan interior.
2. Better predictive models and empirical databases are needed for predicting pre-European settlement wood loadings for each major ecoregion, or a basis for estimating ecologically appropriate loads for future land use and climatic conditions.
3. Little remains known regarding wood in rivers subject to annual ice cover and break-up. It appears that processes that influence ice floes and ice jam formation also influence wood accumulation. Large wood accumulations are found in many rivers that ice over but are rare in some channels, possibly due to the scouring effect of ice floes.
4. More information is needed regarding the linkages between particular types of wood loading (size, individual pieces, logjam types) to:
    a. the geomorphic functions the wood provides
    b. the characteristics of riparian forests
    c. the disturbance processes responsible for wood recruitment to a channel
5. More data on the porosity and permeability of logjams and how these parameters influence hydraulics in and around a logjam.
6. More quantitative data is needed linking key attributes of wood to unique channel types, and models to predict channel response to particular wood loading scenarios.
7. More quantitative data is needed about water and sediment storage due to wood at both the reach and watershed scales.
8. There has been substantial research recently into how beavers, through building dams of wood debris, alter fluvial processes. The differences and linkages between the characteristics and functions of beaver and non-beaver wood placements need to be described.
9. Key factors influencing wood longevity need to be determined and practical models for predicting wood longevity need to be developed.
10. More experimentation is done to show how other materials such as rock or concrete “snags” can be used to restore wood function with the longevity and stability factor of safety that is being requested in many locations that are constrained by existing development.

11. More studies are needed on the antecedent conditions and hydrograph characteristics (e.g., gradual vs. rapid increase in flow) that influence wood stability and transport.
12. More data is needed on wood stability and transport in deformable channels composed of different sediment gradations.
13. The effect of wood on long-term channel incision and landscape evolution needs further study.
14. More information is needed on the extent to which wood altered fluvial systems within the geological record. There has been significant research into the sedimentology and stratigraphy of fluvial systems that includes information on wood and logjams, but much of this information has never been evaluated in the context of current stream management and restoration. This research may offer valuable insights into not only wood longevity, but also into the long-term influence of wood in fluvial environments.
15. Geological literature and additional research could provide information on wood and its effects through past periods of climate change and major disturbances.
16. More physical and numerical modeling is needed on how the density of different wood placements (from random to fixed orientations) along a channel margin influences bank erosion rates.
17. More modeling is needed for flow separation around different logjam configurations (forming bluff bodies), particularly with regards to turbulence, eddy formation, sediment retention, and scour.
18. More modeling is needed to predict wood transport and deposition under different flood hydrograph scenarios, particularly for the National Flood Insurance Program.
19. Qualitative and quantitative channel evolution models could specifically address wood inputs to managers, stakeholders, and communities guidance on how their streams will look under different management scenarios.
20. Guidance is needed on qualifications expected for professional geologists and others to provide expertise in geomorphology sufficient to stamp design plans and reports.

4.5 Key Points

1. Trees have influenced watershed processes and the morphology of fluvial systems for the last 370 million years of earth history.
2. Trees grow along stream banks in almost every region of the country, including the arid southwest, the Great Plains, the tropics of Hawaii and Puerto Rico, and the Alaska interior.
3. Wood enters streams as whole trees or fragments where it becomes part of the physical matter or sediment comprising the stream bed. Larger or key pieces of wood can form stable obstructions (i.e., snags) close to where they entered the stream or after becoming embedded in the channel farther downstream. Smaller pieces move downstream, some accumulating on obstructions to form logjams, some deposited on floodplains by high flows, and some exiting the system.
4. Wood naturally forms distinct types of accumulations depending on the size and shape of the wood and the channel, the channel gradient, and the channel substrate. Wood accumulations are found in all parts of a channel network from headwater tributaries to the largest rivers. Reach-

scale wood density (quantity per channel area or length) generally tends to diminish in larger channels, but when normalized to channel size, wood loading increases with increasing channel size.

5. The geomorphic effects of wood include, but not limited to, the following.
   a. It adds physical complexity, creating more variation in channel geometry (widths and depths).
   b. It increases pool frequency by creating hydraulic steps, flow deflectors, and flow constrictions.
   c. It partitions shear stress to reduce a stream's energy available for sediment transport, bank erosion, or channel incision.
   d. It traps and stores sediment within a stream valley.
   e. It increases channel length by:
      1) Splitting flow into multiple channels, creating islands and anabranching or anastomosing channel patterns.
      2) Reducing channel radius of curvature and increasing sinuosity.
   f. It increases water elevations locally and on a reach scale; thereby, it can:
      1) Create and sustain ephemeral and perennial side channels and floodplain wetlands.
      2) Increase the frequency of overbank inundation and water storage within the floodplain.
      3) Raise groundwater tables.
      4) Increase growth rates of riparian vegetation.
      5) Increase hyporheic exchange, increasing upwelling and downwelling within the system and influencing water quality and temperature.
6. Wood loading tends to be more evenly distributed throughout the length of smaller channels (those with widths less than or similar to height of riparian trees) and more concentrated in intermittent accumulations (i.e., logjams) in large channels (those with widths greater than tree height).
7. Stream management and restoration should focus on wood function in the fluvial system (how it will influence hydraulics, sediment retention, channel form and dynamics) and only use empirical data/models of regional wood loading for the context of placements.
8. Sediment and wood budgets provide an accounting of material inputs and outputs to a project reach that can provide insight into future evolution of the channel. Practitioners should understand how different project design alternatives will influence sediment and wood budgets.
9. Stable instream wood can reduce the median grain size of channel substrate by reducing the shear stress available for sediment transport. It can increase the residence time of alluvial sediment within its valley and control channel gradient.
10. The loss of functional instream wood can trigger channel incision that may be difficult to reverse. This process disconnects streams from their floodplains, which can severely affect the stream's ecology as well as increase downstream flood peaks and lower base flows.

11. Riparian forests are the primary source of instream wood and thus are an essential element for ensuring that stream restoration is sustained over the long term. Riparian forests also help to limit erosion, provide critical ecosystem functions and diffuse flood peaks moving down a channel network.

12. Stable wood (natural or engineered) can be critical in protecting riparian areas from erosion and thus allowing trees to mature so they can sustain the supply of large key pieces in the system.

13. Wood accumulations along stream banks can be effective in reducing bank erosion rates. Even along large rivers, erosion rates into forested banks are one-half to less than one-tenth those observed along banks without trees or only small trees.

14. Wood longevity/preservation in streams varies widely, depending on the depositional setting. Anaerobic conditions (such as remaining saturated) increase preservation so wood that remains saturated can last for thousands of years or longer. Wood subject to periodic drying will be much more susceptible to decay (i.e., fungal or insects) and be gone in several years.

15. Geomorphologists should provide input on wood longevity and whether some situations warrant the use of other materials (e.g., rock) that can provide the same physical function and retention as small wood in a way that better ensures long-term recovery of the system and the required factors of safety needed for some projects. In situations where other materials are used to provide the hydraulic function wood once provided, it is essential to show how the project will restore the many other functions that wood provides by increasing wood retention (both natural inputs and wood placements).

16. Fluvial geomorphology provides an understanding of the processes that shape and change a stream and thus is essential to all stream management and restoration. Geomorphology should provide every project with an explanation of the following.

    a. What factors influence the morphology and dynamics of the stream?

        1) Hydrology/flow regime

        2) Geology and topography

        3) Sediment (characteristics, supply, transport)

        4) Vegetation

        5) Wood

        6) Watershed disturbance regimes (magnitude and frequency)

    b. What did the stream look like prior to human disturbance?

    c. Did the stream channel move around historically or in its natural state (time period undisturbed by human development)? What is the stream corridor, including its floodplain and channel migration zone? Is there evidence the stream channel cut down (incised) or rose (aggraded), and how has this affected fluvial processes and morphology?

    d. Was the stream ever in a state of dynamic equilibrium; if not, what state of channel evolution is it in?

    e. How much wood was naturally in-channel, and how did wood influence channel morphology, hydraulics, and substrate?

f. What changed and how did the stream respond? How much did the loss of wood contribute to the current state of the stream? What is the present state of the channel evolution?

g. What will happen to the stream if nothing is done?

h. How can wood be used to rehabilitate the stream given the current context of the watershed, changes in flow regime, and sediment supply?

i. What will be the channel's response to wood placement, and what will the benefits and risks be?

j. How will a design respond to channel scour or aggradation? How will it perform if the channel moves away?

k. How will watershed development and climate change influence flow regime, sediment, riparian conditions, and instream wood? How will the project design accommodate and possibly moderate changes?

l. How long will wood placement function as intended within the stream? How long will it take to restore riparian forests to sustain long-term wood functions?

17. Stream management and restoration should include both stable and dynamic wood placements to restore natural processes to channels depleted in wood.

4.6 References

Abbe, T. B. 2000. *Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System*. Ph.D. dissertation. University of Washington, Seattle, WA. 222 pp.

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers: Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, and C. Petroff. 1997. Design of Stable In-Channel Wood Debris Structures for Bank Protection and Habitat Restoration: An Example from the Cowlitz River, WA. Pages 809–816 in S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, F.D. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi, Oxford, MS.

Abbe, T. B., J. Carrasquero, M. McBride, A. Ritchie, M. McHenry, and K. Dublanica. 2003a. *Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington*. Proceedings of the Georgia Basin/Puget Sound 2003 Research Conference, Vancouver, B.C., March 31–April 1, 2003, T. Droscher (ed.). Puget Sound Action Team, Olympia, WA.

Abbe, T. B, A. P. Brooks, and D. R. Montgomery. 2003b. Wood in River Rehabilitation and Management. Pages 367–389 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003c. Integrating Engineered Log Jam Technology into River Rehabilitation. In D. R. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies.

Abbe, T. B., C. Miller, and A. Michael. 2009. *Self-Mitigating Protection for Pipeline Crossings in Degraded Streams: A Case Study from Woodward Creek, Washington.* 9th International Right of Way Symposium. 2009. Portland, OR.

Abbe. T., J. Bjork, A. Zehni, T. Nelson, and J. Park. 2011. New Innovative, Habitat-Creating Bank Protection Method. Pages 2011–2021 in *Proceedings of ASCE World Environmental and Water Resources Congress*.

Abbe. T., M. Ericsson, and L. Embertson, L. 2013. *Geomorphic Assessment of the Larson Reach of the South Fork Nooksack River, NW Washington*. Report submitted to Lummi Indian Nation.

Ahmad, M. 1951. Spacing and Projection of Spurs for Bank Protection. *Civil Engineering and Public Works Review.* March:172–174; April:256–258.

Agee, J. K. 1990. The historical role of fire in Pacific Northwest forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1992. The Historical Role of Fire in Pacific Northwest Forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Wash. D.C.

Anderson, B. 2005. *Will Replanting Vegetation along River Banks Make Floods Worse*? 8th International River Symposium, Brisbane, Australia.

Anderson, D. B. 2006. *Quantifying the Interaction between Riparian Vegetation and Flooding: from Cross-Section to Catchment Scale*. University of Melbourne.

Andrus, C. W., B. A. Long, and H. A. Froehlich. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging: *Canadian Journal of Fish and Aquatic Science* 45:2080–2086.

Arno, S. F., and R. J. Hoff. 1989. Silvics of Whitebark Pine (*Pinus albicaulis*). USDA For. Serv. Gen Tech. Rep. INT-253.

Babakaiff, S., D. Hay, and C. Fromuth. 1997. Rehabilitating Stream Banks. In P. A. Slaney and D. Zaldokas (eds.), *Fish Habitat Rehabilitation Procedures, Watershed Restoration Program*. Ministry of Environment, Lands and Parks, Vancouver, BC.

Baillie, B. R., and T. R. Davies. 2002. Influence of Large Woody Debris on Channel Morphology in Native Forest and Pine Plantation Streams in the Nelson Region, New Zealand. *New Zealand Journal of Marine and Freshwater Research*. 36:763–774.

Baillie, B. R., L. G. Garret, and A. W. Evanson. 2008. Spatial Distribution Influence of LWD in an Old-growth Forest River System, New Zealand. *Forest Ecology and Management* 256:20–27.

Baker, C. O. 1979. *The Impacts of Logjam Removal on Fish Populations and Stream Habitat in Western Oregon.* M.S. Thesis, Oregon State University, Corvallis, OR.

Barker, B. L., R. D. Nelson, and M. S. Wigmosta. 1991. Performance of detention ponds designed according to current standards. *Puget Sound Water Quality Authority, Puget Sound Research '91: Conference Proceedings*. Seattle, Washington.

Barrett, M. L. 1996. Environmental Reconstruction of a 19th-Century Red River Raft Lake: Caddo Lake, Louisiana and Texas. *Gulf Coast Association of Geological Societies Transactions* 46 471–471.

Beechie, T. J., and K. Wyman. 1992. *Stream Habitat Conditions, Unstable Slopes and Status of Roads in Four Small Watersheds of the Skagit River.* Skagit System Cooperative, Fisheries services for the Swinomish Tribal Community, Upper Skagit and Sauk-Suiattle Indian Tribes.

Beets, P. N., I. A. Hood, M. O. Kimberley, G. R. Oliver, S. H. Pearce, and J. F. Gardner. 2008. Coarse Woody Debris Decay Rates for Seven Indigenous Tree Species in the Central North Island of New Zealand. *Forest Ecology and Management* 256:548–557.

Beltaos, S. 1983. River Ice Jams: Theory, Case Studies, and Applications. *Journal of Hydraulic Engineering* 109(10):1338–1359.

Benda, L. and T. W. Cundy. 1990. Predicting Deposition of Debris Flow in Mountain Channels. *Canadian Geotechnical Journal* 27:409–417.

Bilby, R. E. 1984. Removal of Woody Debris May Affect Stream Channel Stability. *Journal of Forestry*, 609–613. October.

Bilby, R. E., and P. A. Bisson. 1998. Function and distribution of large woody debris. Pages 324–346 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management.* New York, Springer.

Bilby, R. E., and G. E. Likens. 1980. Importance of debris dams in the structure and function of stream ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E. and J. W. Ward. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48:2499–2508.

Bilby, R. E., and L. J. Wasserman. 1989. Forest Practices and Riparian Management in Washington State: Data Based Regulation Development. In R. E. Gresswell, B. A. Barton, and J. L. Kershner (eds.), *Practical Approaches to Riparian Management.* U.S. Bureau of Land Management, BLM MT PT 89 001 4351, Billings, Montana.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future. Pages 143–190, in E. O. Salo and T. W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Seattle, Washington.

Boose, E. R., K. E. Chamberlin, and D. R. Foster. 2001. Landscape and Regional Impacts of Hurricanes in New England. *Ecological Monographs* 71:27–48.

Booth, D. B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. *Water Resources Bulletin* 26:407–417.

Booth, D. 1991. Urbanization and the Natural Drainage System: Impacts, Solutions, and Prognoses. *The Northwest Environmental Journal* 7, 93-118.

Booth, D., and L. E. Reinelt. 1993. *Consequences of Urbanization on Aquatic Systems—Measured Effects, Degradation Thresholds, and Corrective Strategies.* Watershed '93, American Water Resources Association, pages 545–550.

Bovee, K. D., T. J. Newcomb, and T. G. Coon. 1994. *Relations Between Habitat Variability and Population Dynamics of Bass in the Huron River, Michigan.* Biological Report 21. National Biological Survey, U.S. Department of the Interior. Washington D.C.

Braudrick, C. A., and G. E. Grant. 2000. When do Logs Move in Rivers? *Water Resources Research* 36(2):571–583.

Brooks, A. P., and G. J. Brierly. 2002. Mediated Equilibrium: The Influence of Riparian Vegetation and Wood on the Long-Term Evolution and Behavior of a Near-Pristine River. *Earth Surface Processes and Landforms* 27:343–367.

Brooks, A., and G. J. Brierly. 2004. Framing Realistic River Rehabilitation Targets in Light of Altered Sediment Supply and Transport Relationships: Lessons from East Gippsland, Australia. *Geomorphology* 58:107–123.

Brooks, A. P., G. J. Brierly, and R. G. Millar. 2003. The Long-Term Control of Vegetation and Woody Debris on Channel and Flood-Plain Evolution: Insights from a Paired Catchment Study in Southeastern Australia. *Geomorphology* 51:7–30.

Brooks, A. P., P. Gehrke, J. D. Jansen, and T. B. Abbe. 2004. Experimental Reintroduction of Woody Debris on the Williams River, NSW: Geomorphic and Ecological Responses. *River Research and Applications* 20:513–536.

Brooks, A. P., T. Howell, T. B. Abbe, and A. H. Arthington. 2006. Confronting Hysteresis: Wood Basin River Rehabilitation in Highly Altered Riverine Landscapes of South-Eastern Australia. *Geomorphology* 79(3/4):395–422.

Brummer, C., T. B. Abbe, J. R. Sampson, and D. R. Montgomery. 2006. Influence of Vertical Channel Change Associated with Wood Accumulations on Delineating Channel Migration Zones, Washington State, USA. *Geomorphology* 80:295–309.

Bryant, M. D. 1980. Evolution of large, Organic Debris after Timber Harvest: Maybeso Creek, 1949 to 1978. USDA Forest Service, General Technical Report, PNW-101.

Bryant, M. D. 1983. The Role and Management of Woody Debris in West Coast Salmonid Nursery Stream. *North American Journal of Fisheries Management* 3(3):322–330.

Bryant, M. D., and J. R. Sedell. 1995. Riparian Forests, Wood in the Water, and Fish Habitat Complexity. Pages 202–224 in N. B. Armantrout and R. J. Wolotira, Jr. (eds.), *Conditions of the*

World's Aquatic Habitats. Proceedings of the World Fisheries Congress Theme 1. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Buffington, J. M., and D. R. Montgomery. 1999a. A Procedure for Classifying Textural Facies in Gravel-Bed Rivers. *Water Resources Research* 35(6):1903-1914.

Buffington, J. M., and D. R. Montgomery. 1999b. Effects of Hydraulic Roughness on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3507–3521.

Buffington, J. M., and D. R. Montgomery. 1999c. Effects of Sediment Supply on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3523–3530.

Clay, C. 1949. The Colorado River Raft. *The Southwestern Historical Quarterly* 102 (4):400–426.

Camp, A., C. Oliver, P. Hessburg, and R. Everett. 1996. Predicting Late-Successional Fire Refugia Pre-Dating European Settlement in the Wenatchee Mountains. USDA PNW, Wenatchee For. Sci. Lab., Univ. of Washington, Seattle. Elsevier Science Publishers B.V. *Forest Ecology and Management* 95:63–77.

Cederholm, C. J., W. J. Scarlett, N. P. and Peterson. 1988. Low-Cost Enhancement Technique for Winter Habitat of Juvenile Coho Salmon. *North American Journal of Fisheries Management* 8:438–441.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997b. Response of Juvenile Coho Salmon and Steelhead to the Placement of Large Woody Debris in a Coastal Washington Stream. *Transactions of the American Fisheries Society*. 118:368–378.

Chambers, J. Q., J. I. Fisher, H. Zeng, E. L. Chapman, D. B. Baker, and G. C. Hurtt. 2007. Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. *Science* 318 (5853):1107.

Chesney, C. 2000. *Functions of Wood in Small, Steep Streams in Eastern Washington: Summary of Results for Project Activity in the Ahtanum, Cowiche, and Tieton Basins*. Washington Department of Natural Resources. Prepared for the Timber/Fish/Wildlife Monitoring Advisory Group and the Northwest Indian Fisheries Commission. TFW Effectiveness Monitoring Report: TFW-MAGl-00-002.

Clay, C. 1949. The Colorado River Raft. *The Southwestern Historical Quarterly* 102 (4):400–426.

Coho, C., and S. J. Burges. 1993. Dam-Break Floods in Low Order Mountain Channels of the PNW. *Water Resources Series Tech Rep no. 138*. Dept. Civil Engineering, Univ. of Washington, Seattle. 68 pp.

Collins, B. D., and A. J. Sheikh. 2005. *Historical Reconstruction, Classification, and Change Analysis of Puget Sound Tidal Marshes*. University of Washington (Seattle, WA) and the Nearshore Habitat Program, Washington State Dept. of Natural Resources, Olympia, WA. See more at: http://www.eopugetsound.org/science-review/3-tidal-wetlands#sthash. T4OyhfFd.dpuf

Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical Changes in the Distribution and Functions of Large Wood in Puget Lowland Rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59:66–76.

Collins, B. D., D. R. Montgomery, and A. J. Sheikh. 2003. Reconstructing the Historical Riverine Landscape of the Puget Lowland. Pages 79–128 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press, Seattle.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Comiti, F., A. Andreoli, M. A. Lenzi, and L. Mao. 2006. Spatial Density and Characteristics of Woody Debris in Five Mountain Rivers of the Dolomites (Italian Alps). *Geomorphology* 78:44–63.

Comiti, F., A. Andreoli, L. Mao, and M. A. Lenzi. 2008. Wood Storage in Three Mountain Streams of the Southern Andes and its Hydro-Morphological Effects. *Earth Surface Processes and Landforms* 33:244–262.

Copeland, R. R. 1983. *Bank Protection Techniques Using Spur Dikes*. Paper No. HL-83-1. Hydraulics Laboratory. U.S. Army Waterways Experiment Station. Vicksburg, MS.

Cordova, J. M., E. J. Rosi-Marshall, A. M. Yamamuro, and G. A. Lamberti. 2007. Quantity, Controls, and Functions of Large Woody Debris in Midwestern USA Streams. *River Research and Applications* 23:21–23.

Costa, J. E. 1984. Physical Geometry of Debris Flows. Pages 268–317 in J. E. Costa and P. J. Fleisher (eds.), *Developments and Applications of Geomorphology*. Springer-Verlag, Berlin.

Cushman, M. J. 1981. *The Influence of Recurrent Snow Avalanches on Vegetation Patterns in the Washington Cascades*. Ph.D. dissertation. University of Washington, Seattle, Washington.

Dacy, G. H. 1921. Pulling the Mississippi's Teeth. *Scientific American* 75(4):60, 70.

Daley, J. S. 2012. *Taming the Hungry Beast: The Effectiveness of Engineered Log Jams in an Incising Gravel Bedded River*. B.S. Honors Thesis, School of Earth and Environmental Science, University of Wollongong, Australia. Available: http://ro.uow.edu.au/thsci/38.

Daniels, M. D., and B. L. Rhoads. 2004. Spatial Pattern of Turbulence Kinetic Energy and Shear Stress in a Meander Bend with Large Woody Debris. Pages 87–97 in S. J. Bennett and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*. American Geophysical Union, Washington D.C.

Dickman, A., and S. Cook. 1989. Fire and Fungus in a Mountain Hemlock Forest. *Canadian Journal of Botany* 67:2005–2016.

Dominguez, L. G., and C. J. Cederholm. 2000. Rehabilitating Stream Channels Using Large Woody Debris with Considerations for Salmonid Life History and Fluvial Geomorphic Processes. Pages 545–563 in E. E. Knudsen. C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser (eds.), *Sustainable Fisheries Management: Pacific Salmon*. Lewis Publishers, New York.

Doyle, M. W., and F. D. Shields, Jr. 2000. Incorporation of Bed Texture into a Channel Evolution Model. *Geomorphology* 34:291–309.

Dunne, T., and L. B. Leopold. 1978. *Water in Environmental Planning*. New York, NY: W.H. Freeman & Co.

Eaton, B. C. 2006. Bank Stability Analysis for Regime Models of Vegetated Gravel Bed Rivers. *Earth Surface Processes and Landforms* 31:1438–1444.

Eaton, B. C., M. Chuch, and R. G. Millar. 2004. Rational Regime Model of Alluvial Channel Morphology and Response. *Earth Surface Processes and Landforms* 29:511–529.

Eaton, B.C., R. C. Millar, and S. Davidson. 2010. Channel Patterns: Braided, Anabranching and Single Thread. *Geomorphology* 120:353–364.

Edmonds, R. L., T. B. Thomas, and K. P. Maybury. 1993. Tree Population Dynamics, Growth, and Mortality in old-Growth Forests in the Western Olympic Mountains, Washington. *Canadian Journal of Forest Research* 23:512–519.

Ehrman, T. P., and G. A. Lamberti. 1992. Hydraulic and Particulate Matter Retention in a 3rd-Order Indiana Stream. *Journal of the North American Benthological Society*. 11:341–349.

Elmore, W., and R. L. Beschta. 1988. The Fallacy of Structures and the Fortitude of Vegetation. *Proc. of Calif. Riparian Systems Conference*. Davis, Calif.

Ensign, S. H., and M. W. Doyle. 2005. In-channel Transient Storage and Associated Nutrient Retention: Evidence from Experimental Manipulations. *Limnology and Oceanography* 50(6):1740–1751.

Erskine, W. D., and A. A. Webb. 2003. Desnagging to Resnagging: New Directions in River Rehabilitation in Southeastern Australia. *River Research and Applications*. 19:233–249.

Fahnestock, G. R. 1976. Fires, Fuel, and Flora as Factors in Wilderness Management: The Pasayten Case. *Tall Timbers Fire Ecology Conf*. 15:33–70.

Fahnestock, G. R., and J. K. Agee. 1983. Biomass Consumption and Smoke Production by Prehistoric and Modern Forest Fires in Western Washington. *Journal of Forestry* 81:653–657.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large Woody Debris, Physical Process, and Riparian Forest Development in Montane River Networks of the Pacific Northwest. *Geomorphology* 13:133–144. Elsevier Science B.V.

Federal Highway Administration (FHWA). 1985. *Design of Spur-Type Streambank Stabilization Structures*. Federal Highway Administration Report No. FHWA/RD-84/101. U.S. Department of Transportation. Washington D.C. 112 pp.

Federal Writers' Project. 1952. *West Virginia A Guide to the Mountain State.* U.S. History Publishers.

Fisher, G. B., F. J. Magilligan, J. M. Kaste, and K. H. Nislow. 2010. Constraining the Timescales of Sediment Sequestration Associated with Large Woody Debris using Cosmogenic 7Be. *Journal of Geophysical Research* 115 (F3), DOI: 10.1029/2009JF001352.

Flynn, K.M., Kirby, W.H., and Hummel, P.R. 2006. *User's Manual for Program PeakFQ Annual Flood-Frequency Analysis Using Bulletin 17B Guidelines*: *U.S. Geological Survey, Techniques and Methods*. Book 4, Chapter B4. 42 pp.

Foster, D. R., and E. R. Boose. 1992. Patterns of Forest Damage Resulting from Catastrophic Wind in Central New England, USA. *Journal of Ecology* 80:79–98.

Fox, M. J. 2001. *A New Look at the Quantities and Volumes of Instream Wood in Forested Basins within Washington State. Master of Science thesis.* College of Forest Resources, University of Washington.

Fox, M. J. 2003. *Spatial Organization, Position, and Source Characteristics of Large Woody Debris in Natural Systems*. Ph.D. dissertation. College of Forest Resources, University of Washington. Seattle, Washington.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Frangi, J. L., and A. E. Lugo. 1991. Hurricane Damage to a Flood Plain Forest in the Luquillo Mountains of Puerto Rico. *Biotropica* 23(4a):324–335.

Franklin, J. F., and C. T. Dyrness. 1973. *Natural Vegetation of Oregon and Washington*. USDA Forest Service. Gen. Tech. Rep. PNW-8.

Gastaldo, R. A., and C. W. Degges. 2007. Sedimentology and Paleontology of a Carboniferous Log Jam. *International Journal of Coal Geology* 69:103–113.

Gastaldo, R. A., and T. M. Demko. 2011. The Relationship Between Continental Landscape Evolution and the plant-Fossil Record: Long Term Hydrologic Controls on Preservation. Pages 249–285 in P. A. Allison and D. J. Bottjer (eds.)*, Taphonomy: Process and Bias Through Time*. *Aims & Scope Topics in Geobiology Volume 32*. Springer Netherlands.

Gibling, M. R., A. R. Bashforth, H. J. Falcon-Lang, J. P. Allen, and C. R. Fielding. 2010. Log Jams and Flood Sediment Buildup Caused Channel Abandonment and Avulsion in the Pennsylvanian of Atlantic Canada. *Journal of Sedimentary Research* 80:268–287.

Gippel, C. J. 1995. Environmental Hydraulics of Large Woody Debris in Streams and Rivers. *Journal of Environmental Engineering* 121:388–395.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1992. *The Hydraulic Basis of Snag Management*. Center for Environmental Applied Hydrology, University of Melbourne, Melbourne, Victoria, Australia, 115 pp.

Gippel, C. J., I. C. O'Neill, B. L. Finlayson, and I. Schnatz, I. 1994. *Hydraulic Guidelines for Reintroduction and Management of Large Woody Debris in Degraded Lowland Rivers*. Pages 225–239 in Proceedings of the Conference on Habitat Hydraulics. International Association for Hydraulic Research.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1996. Distribution and Hydraulic Significance of Large Woody Debris in a Lowland Australian River. *Hydrobiologia* 318:179–194.

Gotvald, A. J., N. A. Barth, A. G. Veilleux, and C. Parrett. 2012. *Methods for Determining Magnitude and Frequency of Floods in California, Based on Data Through Water Year 2006.* U.S. Geological Survey Scientific Investigations Report 2012–5113. Available: http://pubs.usgs.gov/sir/2012/5113/.

Graf, W. L. 1975. The impact of Suburbanization on Fluvial Morphology. *Water Resources Research* 11:690–692.

Graham, R., and K. Cromack. 1982. Mass, Nutrient Content, and Decay Rate of Dead Boles in Rain Forests of Olympic National Park. *Canadian Journal of Forest Research* 12(3):511–521.

Grant, G. E., and F. J. Swanson. 1995. Morphology and Processes of Valley Floors in Mountain Streams, western Cascades, Oregon. Pages 83–101 in J. D. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock (eds.). *Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph 89*. American Geophysical Union, Washington DC.

Grant, G. E., M. J. Crozier, and F. J. Swanson. 1984. An Approach to Evaluating Off-Site Effects of Timber Harvest Activities on Channel Morphology. *Proceedings of the Symposium on the Effects of Forest and Land Use on Erosion and Slope Stability. Environment and Policy Institute, E-West Center, University of Hawaii, Honolulu* 177–186.

Gray, D. H. 1974. Reinforcement and Stabilization of Soil by Vegetation. *Journal of Geotechnical Engineering*, 100(GT6):695–699.

Gray, D. H. and D. Barker. 2004. Root-soil Mechanics and Interactions. Pages 113–123 in S. J. Bennett and A. Simon (eds.). *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*, American Geophysical Union, Washington D.C.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An Ecosystem Perspective of Riparian Zones. *BioScience* 41(8):540–551.

Grette, G. B. 1985. The role of Large Organic Debris in Juvenile Salmonid Rearing Habitat in Small Streams. MS thesis, University of Washington, Seattle, WA.

Grimm, W. C. 1967. *Familiar Trees of America*. New York: Harper & Row.

Grizzel, J. D., and N. Wolff. 1998. Occurrence of Windthrow in Forest Buffer Strips and its Effect on Small Streams in Northwest Washington. *Northwest Science* 72:214–223.

Guardia, J. E. 1933. Some Results of the Log Jams in the Red River. *The Bulletin of the Geographical Society of Philadelphia* 31(3):103–114.

Gurnell, A. M., G. E. Petts, N. Harris, J. V. Ward, K. Tockner, P. J. Edwards, and J. Kollman. 2000. Large Wood Retention in River Channels: The Case of the Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms* 25:255–275.

Guyette, R. P., and M. Stambaugh. 2003. The Age and Density of Ancient and Modern Oak Wood in Streams and Sediments. *The International Association of Wood Anatomists (IAWA) Journal* 24:345–353.

Guyette, R. P., D. C. Dey, and M. C. Stambaugh 2008. The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits. *Ecosystems* 11:643–653.

Hall, R. O., and J. L. Meyer. 1998. The Trophic Significance of Bacteria in a Detritus-Based Stream Food Web. *Ecology* 79:1995–2012.

Hammer, T. R. 1972. Stream Channel Enlargement due to Urbanization. *Water Resources Research* 8:1530–1540.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986.

Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

Harrod, R. 2000. Ecologist with the Wenatchee National Forest Service, Wenatchee, WA. Personal Communication.

Hartopo, 1991. The *Effect of Raft Removal and Dam Construction on the Lower Colorado River, Texas*. Unpublished M.S. Thesis, Texas A & M University.

Harvey, M. D, D. S. Biedenharn, and P. Combs. 1988. Adjustments of Red River Following Removal of the Great Raft in 1873 [abs.]. *Eos, Transactions of the American Geophysical Union* 69(18):567.

Hauer, F. R. 1989. Organic Matter Transport and Retention in a Blackwater Stream Recovering from Flow Augmentation and Thermal Discharge. *Regulated Rivers: Research and Management* 4:371–380.

Hazard, J. T. 1948. *Our Living Forests, the Story of Their Preservation and Multiple Use*. Seattle, WA: Superior Publishing.

Hedman, C. W., D. H. Van Lear, and W. T. Swank. 1996. In-stream LWD Loading and Riparian Forest Serial Stage Associations in the Southern Appalachian Mountains. *Canadian Journal of Forest Research* 26(7):1218–1227.

Henderson, J. 1996. Unpublished Data Regarding Tree Height vs. Age for Two Common Plant Association Groups. USDA Forest Service, Pacific Northwest Region, Mount Lake Terrace, WA.

Henderson, J. A., R. D. Lesher, D. H. Peter and D. C. Shaw. 1992. *Field Guide to the Forested Plant Associations of the Mt. Baker-Snoqualmie National Forest*. USDA Forest Service, Pacific Northwest Region. Tech paper R6 ECOL TP 028-91. Hershey, K. 1995. *Characteristics of Forests at Spotted Owl Nest Sites in the Pacific Northwest.* M.S. thesis, Oregon State University, Corvallis.Hewitt, E. R. 1934. *Hewitt's Handbook of Stream Improvement.* The Marchbanks Press, New York.

Hickin E. J. 1984. Vegetation and River Channel Dynamics. *Canadian Geographer* 28(2):111–126.

Hilderbrand, R. H., A. D. Lemly, C. A. Dollof, and K. L. Harpster. 1997. Effects of Large Woody Debris Placement on Stream Channels and Benthic Macroinvertebrates. *Canadian Journal of Fisheries and Aquatic Sciences* 54:931–939.

Hollis, G. E. 1975. The Effects of Urbanization on Floods of Different Recurrence Intervals. *Water Resources Research* 11:431–435.

Holstine, C. 1992. *An Historical Overview of the Wenatchee National Forest, Washington*. Rep. 100-80. Archaeological and historical Services. Eastern Washington University, Cheney.

Horner, R. R., D. B. Booth, A. Azous, and C. W. 1997. Watershed Determinants of Ecosystem Functioning. Pages 251–274 in L. A. Roesner (ed.), *Effects of Watershed Development and Management on Aquatic Ecosystems*, American Society of Civil Engineers, New York, NY.

House, R. A., and P. L. Boehne. 1986. Effects of Instream Structures on Salmonid Habitat and Populations in Tobe Creek, Oregon. *North American Journal of Fisheries Management* 6:283–295.

Hyatt, T. L., and R. J. Naiman. 2001. The Residence Time of Large Woody Debris in the Queets River, Washington, USA. *Ecological Applications* 11(1):191–202.

Hygelund, B., and M. Manga. 2003. Field Measurements of Drag Coefficients for Model Large Woody Debris. *Geomorphology* 51:175–185.

Ikeya, H. 1981. A Method for Designation Forested Areas in Danger of Debris Flows. In E*rosion and Sediment Transport in Pacific Rim Steeplands.* Edited by T. R. H. Davies and A. J. Pearce. *International Association of Hydrological Sciences, Publication* 132:576–588.

Interagency Advisory Committee on Water Data (IACWD). 1982. *Guidelines for Determining Flood Flow Frequency*. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia. 183 p.

Jacobson, P. J., K. M. Jacobson, P. L. Angermeier, and D. S. Cherry. 1999. Transport, Retention, and Ecological Significance of Woody Debris within a Large Ephemeral River. *Journal of the North American Benthological Society* 18:429–444.

James, L. D. 1965. Using a Digital Computer to Estimate the Effects of Urban Development on flood Peaks. *Water Resources Research* 1:223–234.

Jenkins, M. J., and E. G. Hebertson. 1998. *Using Vegetative Analysis to Determine the Extent and Frequency of Avalanches in Little Cottonwood Canyon, Utah.* Department of Forest Resources, Utah State University. WestWide Avalanche Network, UT.

Johnson, L. B., D. H. Breneman, and C. Richards. 2003. Macroinvertebrate Community Structure and Function Associated with Large Wood in Low Gradient Streams. *River Research and Applications* 19:199–218.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian Forest Disturbances by a Mountain Flood—The Influence of Floated Wood. *Hydrological Processes* 14:3031–3050.

Johnston, N. T., E. A. MacIsaac, P. J. Tschaplinski, and K. J. Hall. 2004. Effects of the Abundance of Spawning Sockeye Salmon (*Oncorhynchus nerka*) on Nutrients and Algal Biomass in Forested Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 61:384–403.

Kanes, W. H. 1970. Facies and Development of the Colorado River Delta in Texas. Pages 78–106 in J. P. Morgan and R. H. Shaver (eds.), *Deltaic Sedimentation Modern and Ancient*. Special Publication No.15. Society of Economic Paleontologists and Mineralogists. Tulsa, Oklahoma.

Kauffman, J. B., R. L. Beschta, N. Otting, and D. Lytjen. 1997. An Ecological Perspective of Riparian and Stream Restoration in the Western United States. *Fisheries (Bethesda)* 22:12–24.

Keeton, W. S., C. E. Kraft, and D. R. Warren. 2007. Mature and Old-Growth Riparian Forests: Structure, Dynamics and Effects on Adirondack Stream Habitats. *Ecological Applications* 17:852–868.

Keller, E. A. and A. MacDonald. 1995. River Channel Change: The Role of Large Woody Debris. Pages 217–236 in A. Gurnell and G. Petts (eds.), *Changing River Channels*. John Wiley and Sons, Chichester. 217-235.

Keller, E. A., and F. J. Swanson. 1979. Effects of Large Organic Material on Channel Form and Fluvial Processes. *Earth Surface Processes* 4:361–380.

Keller, E. A., and T. Tally. 1979. Effects of Large Organic Debris on Channel Form and Fluvial Processes in the Coastal Redwood Environment. Pages 169–197 in D. D. Rhodes and G. P. Williams (eds.), *Adjustments of the Fluvial System.* Proceedings of the 10th Annual Binghamton Geomorphology Symposium. Kendal-Hunt. Dubuque, IA.

Kennard, P., G. Pess, T. Beechie, B. Bilby, and D. Berg. 1998. Riparian-in-a-Box: A Manager's Tool to Predict the Impacts of Riparian Management on Fish Habitat. Pages 483-490. in M. K. Brewin and D. M. A. Monita (eds.), *Forest-Fish Conference: Land Management Practices Affecting Aquatic Ecosystems*. Proceedings of Forest-fish conference, May 1-4, 1996, Calgary, Alberta. Natural Resources Canada. North For. Cent., Edmonton, Alberta Inf. Rep. NOR-X-356.

Klingeman, P. C., S. M. Kehe, and Y. A. Owusu. 1984. *Streambank Erosion Protection and Channel Scour Manipulation Using Rockfill Dikes and Gabions*. Water Resources Research Institute, Oregon State University. Salem, OR.

Konsoer, K. M. 2014. *Influence of Riparian Vegetation on Near-Bank Flow Structure and Rates of Erosion on a Large Meandering River.* Ph.D. Dissertation, University of Illinois, Urbana-Champaign. 236 p.

Kraft, C. E., and D. R. Warren. 2003. Development of Spatial Pattern in Large Woody Debris and Debris Dams in Streams. *Geomorphology* 51:127–139.

Krause, C., and C. Roghair. 2014. *Inventory of Large Wood in the Upper Chattooga River Watershed, 2007–2013*. U.S. Forest Service Southern Research Station, Center for Aquatic Technology Transfer. Blacksburg, VA.

Lampert, W. 1978. Release of Dissolved Organic-Carbon by Grazing Zooplankton. *Limnology and Oceanography* 23(4):831–834.

Langbien, W. B., and S. B. Schumm. 1958. Yield of Sediment in Relation to Mean Annual Precipitation. *American Geophysical Union Transactions* 39:1076–1084.

Latterell, J. J., and R. J. Naiman. 2007. Sources and Dynamics of Large Logs In a Temperate Floodplain River. *Ecological Applications* 17:1127–1141.

Latterell, J. J., J. S. Bechtold, T. C. O'Keefe, R. Van Pelt, and R. J. Naiman. 2006. Dynamic Patch Mosaics and Channel Movement in an Unconfined River Valley of the Olympic Mountains *Freshwater Biology* 51(3):523–544*.*

Lehane, B. M., P. S. Giller, J. O'Halloran, C. Smith, J. Murphy. 2002. Experimental Provision of Large Woody Debris in Streams as a Trout Management Technique. *Aquatic Conservation-Marine and Freshwater Ecosystems* 12:289–311.

Leopold, L. B. 1973. River Channel Change with Time: An Example. *Geological Society of America Bulletin* 84:1845–1860.Lester, R. E., and W. Wright. 2009. Reintroducing Wood to Streams in Agricultural Landscapes: Changes in Velocity Profile, Stage and Erosion Rates. *River Research and Applications* 25(4):276–392.

Li, R., and H. W. Shen. 1973. Effect of Tall Vegetation on Flow and Sediment. *Journal of the Hydraulic Division, ASCE* 99(5):793–814.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of Large Woody Debris in Streams in Old-Growth Douglas-Fir Forests. *Canadian Journal of Forest Research* 17:150–156.

Lisle, T. 1995. Effects of Coarse Woody Debris and its Removal on a Channel Affected by the 1980 Eruption of Mount St. Helens, Washington*. Water Resources Research* 31:1797–1808.

Lowrey, W. M. 1968. The Red. Pages 53–73 in E. A. Davis, *The Rivers and Bayous of Louisiana*. Louisiana Education Research Association, Baton Rouge, LA.

Luchetti, G. and R. Fuerstenberg. 1993. Management of Coho Salmon Habitat in Urbanizing :andscapes of King County, Washington, USA. Pages 308–317 In L. Berg and P. Delaney (eds.), *Proceedings of the 1992 Coho Salmon Workshop.* Canada Department of Fisheries and Oceans, Vancouver, B.C., Canada.

Lunetta, R. S., B. L. Cosentino, D. R. Montgomery, E. M. Beamer, and T. J. Beechie. 1997. GIS-Based Evaluation of Salmon Habitat in the Pacific Northwest. *Photogrammetric Engineering & Remote Sensing* 63(10):1219–1229.

Lyell, C. 1830. *Principles of Geology*, Volume I. London, UK: John Murray. Published in 1990 by University of Chicago Press. Chicago, IL.

Magilligan, F. J., K. H. Nislov, G. B. Fisher, J. Wright, G. Mackey, and M. Laser 2008. The Geomorphic Function and Characteristics of Large Woody Debris in Low Gradient Rivers, Coastal Maine, USA. *Geomorphology* 97:467–482.Makaske, B., D. G. Smith, and H. J. Berendsen. 2002. Avulsions, Channel Evolution and Floodplain Sedimentation Rates of the Anastomosing Upper Columbia River, British Columbia, Canada. *Sedimentology* 49(5):1049–1071.

Manga, M., and J. W. Kirchner. 2000. Stress Partitioning in Streams by Large Woody Debris. *Water Resources Research* 36:2373–2379.

Manners, R. W., M. W. Doyle, and M. J. Small. 2007. Structure and Hydraulics of Natural Woody Debris Jams. *Water Resources Research* 43, doi:10.1029/2006WR004910.

Manners, R. B. and Doyle, M. W. 2008. A Mechanistic Model of Woody Debris Jam Evolution and its Application to Wood-based Restoration and Management. *River Research and Applications* 24:1104-1123.

Martin, D. J., and L. E. Benda. 2001. Patterns of Instream Wood Recruitment and Transport at the Watershed Scale. *Transactions of the American Fisheries Society* 130:940–958.

Maser, C. and J. R. Sedell, J.R. 1994. *From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans.* St. Lucie Press. 200 pp.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (eds.). 1988. *From the Forest to the Sea: A Story of Fallen Trees*. General Tech. Report PNW-GTR-229. USFS. 153 pp.

Masterman, R., and C. R. Thorne. 1992. Predicting Influence of Bank Vegetation on Channel Capacity. *Journal of Hydraulic Engineering* 118:1052–1058.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source Distances for Coarse Woody Debris Entering Small Streams in Western Oregon and Washington. *Canadian Journal of Forest Research* 20:326–330.

McHenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the Quantity and Characteristics of LWD in Streams of the Olympic Peninsula, Washington, USA (1982-1993). *Canadian Journal of Fisheries and Aquatic Sciences* 55(6):1395–1407.

Means, J. E., K. Cromack Jr., and P. C. MacMillan, 1986, Comparison of Decomposition Models Using Wood Density of Douglas-Fir Logs. *Canadian Journal of Forestry Research* 15:1092–1098.

Meile, T., J. Boillat, and A. Schleiss. 2011. Flow Resistance Caused by Large-Scale Bank Roughness in a Channel. *Journal of Hydraulic Engineering* 137(12):1588–1597.

Melillo, J. M., R. J. Naiman, J. D. Aber, and K. N. Eshleman. 1983. The Influence of Substrate Quality and Stream Size on Wood Decomposition Dynamics. *Oecolgia (Berlin)* 58:281–285.

Meyer, J. L., J. B. Wallace, and S. L. Eggert. 1998. Leaf Litter as a Source of Dissolved Organic Carbon in Streams. *Ecosystems* 1:240–249.

Micheli, E. R., J. W. Kirchner, and E. W. Larsen. 2003. Quantifying the Effect of Riparian Forest Versus Agricultural Vegetation on River Meander Migrations Rates, Central Sacramento River, California, USA. *River Research and Applications* 19:1–12.

Millward, A. A., C. E. Kraft, and D. R. Warren. 2010. Ice Storm Damage Greater Along the Terrestrial-Aquatic Interface in Forested Landscapes. *Ecosystems* 13:249–260.

Minakawa, N., and R. I. Gara. 2005. Spatial and Temporal Distribution of Coho Salmon Carcasses in a Stream in the Pacific Northwest, USA. *Hydrobiologia* 539:163–166.

Minore, D. 1979. The Wild Huckleberries of Oregon and Washington: A Dwindling Resource. *USDA Forest Service Research Paper 143*.

Montgomery, D. R. 1999. Process Domains and the River Continuum. *Journal of the American Water Resources Association* 35:397–410.

Montgomery, D. R., and T. B. Abbe. 2006. Influence of Logjam-Formed Hard Points on the Formation of Valley-Bottom Landforms in an Old-Growth Forest Valley, Queets River, Washington, USA. *Quaternary Research* 65:147–155.

Montgomery, D. R., and J. M. Buffington. 1993. *Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition*. TFW-SH10-93-002. Washington State Timber, Fish & Wildlife.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-Reach Morphology in Mountain Drainage Basins. *Geological Society of America Bulletin* 109:596–611.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995b. Pool Spacing in Forest Channels. *Water Resources Research* 31:1097–1105.

Montgomery, D. R., T. Abbe, N. P. Peterson, J. M. Buffington, K. M. Schmidt, and J. D. Stock 1996b. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Morris, A. E. L., P. C. Goebel, and B. J. Palik. 2010. Spatial Distribution of Large Wood Jams in Streams Related to Stream-Valley Geomorphology and Forest Age in Northern Michigan. *River Research and Applications* 26:835–847.

Moscrip, A. L., and D. R. Montgomery. 1997. Urbanization, Flood Frequency, and Salmon Abundance in Puget Lowland Streams. *Journal of the American Water Resources Association* 33(6):1289–1297.

Mossop, B., and M. J. Bradford. 2004. Importance of Large Woody Debris for Juvenile Chinook Salmon Habitat in Small Boreal Forest Streams in the Upper Yukon River Basin, Canada. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 34:1955–1966.

Moulin, B., E. R. Schenk, and C. R. Hupp. 2011. Distribution and Characterization of In-channel Large Wood in Relation to Geomorphic Patterns on a Low-gradient River. *Earth Surface Processes and Landforms* 36:1137–1151.

Muir, J. 1878. Forests of California, the New Sequoia. *Harper's New Monthly Magazine* LVII (CCCXLII):813–827.

Mulholland, P. J., J. D. Newbold, J. W> Elwood, L. A. Ferren, and J. R. Webster. 1985. Phosphorus Spiraling in a Woodland Stream - Seasonal-Variations. *Ecology* 66:1012–1023.

Murphy, M. L. 1995. Forestry Impacts on Freshwater Habitat of Anadromous Salmonids in the Pacific Northwest and Alaska—Requirements for Protection and Restoration. *U.S. Department of Commerce Coastal Ocean Program, NOAA. Decision Analysis Series No. 7*, 156 pp.

Murphy, M. L., and K. V. Koski. 1989. Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. *North American Journal of Fisheries Management* 9(4):427–436.

Mutz, M., E. Kalbus, and S. Meinecke. 2007. Effect of Instream Wood on Vertical Water Flux in Low-Energy Sand Bed Flume Experiments. *Water Resources Research* 43:W10424.

Naiman, R. J., T. J. Beechie, L. E. Benda, P. A. Bisson, L. H. MacDonald, M. D. O'Conner, P. L. Olsen, and E. A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. Pages 127–188 in R. J. Naiman (ed.), *Watershed Management: Balancing Sustainability and Environmental Change*. Springer: New York.

Naiman, R. J., K. L. Fetherston, S. McKay, and J. Chen. 1998. Riparian Forests. Pages 289-323 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag: New York.

Naiman R. J., S. E. Bunn, and C. Nilsson. 2002b. Legitimizing Fluvial Ecosystems as Users of Water. *Environmental Management* 30:455–467.

National Marine Fisheries Service. 1996. *Making Endangered Species Act Determinations of Effect for Individual or Grouped Actions at the Watershed Scale*. Environmental and Technical Services Division, Habitat Conservation Branch.

Nichols, R. A. and S. G. Sprague. 2003. The Use of Long-Line Cabled Logs for Stream Bank Rehabilitation. Pages 422–442 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press: Seattle.

Nickelson, T. E., M. F. Solazzi, S. L. Johnson, and J. D. Rodgers. 1992. Effectiveness of Selected Stream Improvement Techniques to Created Suitable Summer and Winter Rearing Habitat for Juvenile Coho Salmon (*Oncorhynchus kisutch*) in Oregon Coastal Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 49:790–794.

North American Forest Commission. 2011. *Forests of North America*. Vector Digital Data. Food and Agriculture Organization of the United Nations. Commission for Environmental Cooperation. Montreal, Quebec, CA.

O'Connor, J. E., M. A. Jones, and T. L. Haluska. 2003. Flood Plain and Channel Dynamics of the Quinault and Queets Rivers, Washington, U.S.A. *Geomorphology* 51:31–59.

Oliver, C. D. 1980/1981. Forest Development in North America Following Major Disturbances. *Forest Ecology and Management* 3:153–168.

Oregon Department of Forestry. 1995. *A Guide to Placing Large Wood in Streams*. Salem, OR, Forest Practices Section. 13 pp.

Palik, B., S. W. Golladay, P. C. Goebel, and B. W. Taylor. 1998. Geomorphic Variation in Riparian Tree Mortality and Stream Coarse Woody Debris Recruitment from Record Flooding in a Coastal Plain Stream. *Ecoscience* 5:551–560.Pariset, E., R. Hausser, and A. Gagnon. 1966. Formation of Ice Covers and Ice Jams in Rivers. *Journal of the Hydraulics Division* 92(6):1–24.

Parrish, R. M. and P. B. Jenkins. 2012. *Natural Log Jams in the White River: Lessons for Geomimetic Design of Engineered Log Jams*. U.S. Fish and Wildlife Service, Leavenworth, WA.

Paukert, C. P., and A. S. Makinster. 2008. Longitudinal Patterns in Flathead Catfish Relative Abundance and Length at Age Within a Large River: effects of an urban gradient. *River Research and Applications*. Available: www.interscience.wiley.com. DOI: 10.1002/rra.1089.

Petts, G. E., A. L. Roux, and H. Moller (eds.). 1989. *Historical Changes of Large Alluvial Rivers, Western Europe*. Chichester: John Wiley.

Phillips, J. D. 2012. Log-jams and Avulsions in the San Antonio River Delta, Texas. *Earth Surface Processes and Landforms* 37:936–950.

Phillips, J. D., and L. Park. 2009. Forest Blowdown Impacts of Hurricane Rita on Fluvial Systems. *Earth Surface Processes and Landforms* 34:1069–1081.

Piégay, H., A. and R. A. Marston. 1998. Distribution of Coarse Woody Debris Along the Concave Bank of a Meandering River (the Ain River, France). *Physical Geography* 19(4):318–340.

Piégay, H., A. Thevenet, and A. Citterio. 1999. Input, Storage and Distribution of LWD Along a Mountain River Continuum, the Drôme River, France. *Catena* 35:19–39.

Pollock, M. M., and T. J. Beechie. 2014. Does Riparian Forest Restoration Thinning Enhance Biodiversity? The Ecological Importance of Large Wood. *JAWRA Journal of the American Water Resources Association* 50(3):543–559. Online publication date: June 1, 2014.

Pollock, M. M., R. J. Naiman, and T. A. Hanley. 1998. Plant Species Richness in Riparian Wetlands—A Test of Biodiversity Theory. *Ecology* 79:94–105.

Power, M. E., and W. E. Dietrich. 2002. Food Webs in River Networks. *Ecological Research* 17:451–471.

Power, M. E., A. Sun, G. Parker, W. E. Dietrich, and J. T. Wootton. 1995. Hydraulic Food Chain Models. *BioScience* 45:159–167.

Prowse, T. D. 2001. River Ice Ecology. 1: Hydrologic, Geomorphic, and Water Quality Aspects. *Journal of Cold Regions Engineering* 15(1):1–16.

Quinault Indian Nation (QIN). 2008. *Salmon Habitat Restoration Plan for the Upper Quinault River.* Quinault Indian Nation Department of Fisheries. Taholah, Washington. Prepared by T. Abbe and others.

Ralph, S. C., G. C. Poole, L. L. Conquest, and R. J. Naiman. 1991. Stream Channel Morphology and Woody Debris in Logged and Unlogged Basins of Western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51:37–51.

Rapp, C., and T. Abbe. 2003. *A Framework for Delineating Channel Migration Zones*. Washington State Department of Ecology Publication Number 03-06-027. Final Draft.

Raup, H. M. 1957. Vegetation Adjustment to the Instability of Sites. *Proceedings and Papers of the 6th Technical Meeting of the International Union for Conservation of Nature and Natural Resources*. Edinburgh. Pages 36–48.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991. Rehabilitating and Modifying Stream Habitats. Pages 519–557 in *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication* 19.

Reid, L. M., and S. Hilton. 1998. Buffering the Buffer. Pages 71–80 in R. R. Ziemer (ed.), *Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story*; held May 6, 1998, in Ukiah, California. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-168.

Richards, K. 1982. *Rivers: Form and Process in Alluvial Channels.* New York: Methuen. 382 pp.

Richmond, A. D., and K. D. Faush. 1995. Characteristics and Function of LWD in Subalpine Rocky Mountains Streams in Northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Riley, S. C. and K. D. Fausch. 1995. Trout Population Response to Habitat Enhancement in Six Northern Colorado Streams. *Canadian Journal of Fisheries and Aquatic Sciences*. 52:34–53.

Robert, A. 1997. Characteristics of Velocity Profiles Along Riffle-Pool Sequences and Estimates of Bed Shear Stresses. *Geomorphology* 19:89–98.

Robison, E. G. and R. L. Beschta. 1990. Identifying Trees in Riparian Areas that can Provide Coarse Woody Debris to Streams. *Forest Science* 36:790–801.

Roni, P., and T. P. Quinn. 2001. Density and Size of Juvenile Salmonids in Response to Placement of Large Woody Debris in Western Oregon and Washington Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 58:282–292.

Roni, P., M. Liermann, and A. Steel. 2003. Monitoring and Evaluating Fish Response to Instream Restoration. In D. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies. University of Washington Press: Seattle.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2014a. Wood Placement in River Restoration: Fact, Fiction, and Future Direction. *Canadian Journal of Fisheries and Aquatic Sciences* 72(3):466–478.

Rosgen, D., and H. L. Silvey. 1996. *Applied River Morphology. Wildland Hydrology*. Pagosa Springs, CO.

Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream Channel Configuration, Landform, and Riparian Forest Structure in the Cascade Mountains, Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 57:699–707.

Ruffner, E. H. 1886. *The Practice of the Improvement of the Non-Tidal Rivers of the United States, with an Examination of the Results Thereof*. New York, NY: John Wiley and Sons.

Russell, I. C. 1898. *Rivers of North America*. New York: G.P. Putnams Sons. 327 pp.

Rutherford, I., B. Anderson, and A. Ladson. 2007. Managing the Effects of Riparian Vegetation on Flooding. In S. Lovett and P. Price (eds.), *Principles for Riparian Lands Management*. Land & Water Australia, Canberra.

Sauer, V. B. 1974. *Flood Characteristics of Oklahoma Streams Techniques for Calculating Magnitude and Frequency of Floods in Oklahoma, with Compilations of Flood Data Through 1971.* U.S. Geological Survey Water-Resources Investigations Report 73–52. 307 p.

Sauer, V. B., and D. P. Turnipseed. 2010. *Stage Measurement at Gaging Stations: U.S. Geological Survey Techniques and Methods Book 3*, Chapter A7.

Sear, D. A., C. E. Millington, D. R. Kitts, and R. Jeffries. 2010. Logjam Controls on Channel:Floodplain Interactions in Wooded Catchments and Their Role in the Formation of Multi-Channel Patterns. *Geomorphology* 116:305–319.

Schenk, E. R., J. W. McCargo, B. Moulin, C. R. Hupp, and J. M. Richter. 2014a. The Influence of Logjams on Largemouth Bass (*Micropterus salmoides*) Concentrations on the Lower Roanoke River, a Large Sand-bed River. *River Research and Applications*. www.wileyonlinelibrary.com, DOI: 10.1002/rra.2779

Schenk, E. R., B. Moulin, C. R. Hupp, J. M. Richter. 2014b. Large Wood Budget and Transport Dynamics on a Large River Using Radio Telemetry. *Earth Surface Processes and Landforms* 39:487–498.

Scherer, R. 2004. Decomposition and Longevity of In-Stream Woody Debris: A Review of Literature from North America. Pages 127–133 in *Forest Land–Fish Conference–Ecosystem Stewardship through Collaboration*. Proceedings of Forest-Land-Fish Conference II.

Schumm, S. A. 1999. Causes and Controls of Channel Incision. Pages 19–34 in S. E. Darby and A. Simon (eds.), *Incised River Channels.* Chichester, UK: Wiley.

Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. *Incised Channels: Morphology, Dynamics and Control.* Water Resources Publication. Littleton, CO.

Sedell, J. R., and J. L. Frogatt. 1984. Importance of Streamside Forests to Large Rivers: The Isolation of the Willamette River, Oregon, U.S.A., from its Floodplain by Snagging and Streamside Forest Removal. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1828–1834.

Sedell, J. R., and K. J. Luchessa. 1981. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. Symposium *on Acquisition and Utilization of Aquatic Habitat Inventory Information*. October 23–28, Portland, OR.

Sedell, J. R., F. H. Everest, and F. J. Swanson. 1982. Fish Habitat and Streamside Management: Past and Present. Pages 244–255 in *Proceedings of the 1981 Convention of the Society of American Foresters, September 27–30, 1981*. Society of American Foresters, Publication 82–01, Bethesda, Maryland.

Shields, F. D., Jr., and C. V. Alonso. 2012. Assessment of Flow Forces on Large Wood in Rivers. *Water Resources Research* 48(4):W04156.

Shields, F. D., Jr., and C. J. Gippel. 1995. Prediction of Effects of Woody Debris Removal on Flow Resistance. *Journal of Hydraulic Engineering* 121 (4):341–354.

Shields, F. D., Jr., and R. H. Smith. 1992. Effects of Large Woody Debris Removal on Physical Characteristics of a Sand Bedded River. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:145–163.

Sidle, R. C. 1991. A Conceptual Model of Changes in Root Cohesion in Response to Vegetation Management. *Journal of Environmental Quality* 20:43–52.

Simon, A. 1989. A Model of Channel Response in Disturbed Alluvial Channels. *Earth Surface Processes and Landforms* 14:11–26.

Simon, A. 1994. *Gradation Processes and Channel Evolution in Modified West Tennessee Streams: Process, Response and Form*. U.S. Geological Survey Professional Paper 1470. Washington D.C.

Simon, A., and A. J. C. Collison. 2002. Quantifying the Mechanical and Hydrological Effects of Riparian Vegetation on Stream-Bank Stability. *Earth Surface Processes and Landforms* 27(5):527–546.

Simon, A., and M. Rinaldi. 2006. Disturbance, Stream Incision, and Channel Evolution: The Roles of Excess Transport Capacity and Boundary Materials in Controlling Channel Response. *Geomorphology* 79:361–383.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen. 2000. Bank and Near-Bank Processes in an Incised Channel. *Geomorphology* 35(3):193–217.

Singer, S., and M. L. Swanson. 1983. *The Soquel Creek Storm Damage Recovery Plan with Recommendations for Reduction of Geologic Hazards in Soquel Village, Santa Cruz County, California.* Unpublished USDA Soil Conservation Service report to the Santa Cruz County Board of Supervisors.

Sinsabaugh, R. L., M. P. Osgood, and S. Findlay. 1994. Enzymatic Models for Estimating Decomposition Rates of Particulate Detritus. *Journal of the North American Benthological Society*. 13:160–169.

Smith, D. G. 1979. Effects of Channel Enlargement by River Ice Processes on Bankfull Discharge in Alberta, Canada. *Water Resources Research*, 15(2):469–475.

Smith, D. G., and C.M. Pearce. 2000. River Ice and its Role in Limiting Woodland Development on a Sandy Braid-Plain, Milk River, Montana. *Wetlands,* 20(2):232–250.

Smith, D. G., and D. M. Reynolds. 1983. Tree Scars to Determine the Frequency and Stage of High Magnitude River Ice Drives and Jams, Red Deer, Alberta. *Canadian Water Resources Journal* 8(3):77–94.

Smith, J. D.. 2004. The Role of Riparian Shrubs in Preventing Floodplain Unraveling Along the Clark Fork of the Columbia River in the Deer Lodge Valley, Montana. Pages 71–85 in S. J. Bennett. and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*. American Geophysical Union, Washington, D.C.

Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of Increasing Winter Rearing Habitat on Abundance of Salmonids in Two Coastal Oregon Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 57:906–914.

Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of Log Decay in Old-Growth Douglas-Fir Forests, *Canadian Journal of Forest Research* 17:1585–1595.

Spänhoff, B., C. Alecke, and E. Irmgard Meyer. 2001. Simple Method for Rating the Decay Stages of Submerged Woody Debris. *Journal of the North American Benthological Society* 20(3):385–394.

Spies, T. A., and J. F. Franklin. 1991. The Structure of Natural Young, Mature, and Old-Growth Douglas Fir Forests in Oregon and Washington. Pages 91–109 in L. F. Ruggiero, K. B. Aubrey, A. B. Carey, and M. H. Huff (technical coordinators), *Wildlife and Vegetation of Unmanaged Douglas Fir Forests*. USDA Forest Service. General Technical Report PNW-GTR-285.

Stahle, D. W., M. K. Cleaveland, R. D. Griffin, M. D. Spond, F. K. Fye, R. B. Culpepper, and D. Patton. 2006. Decadal Drought Effects on Endangered Woodpecker Habitat. *Eos, Transactions American Geophysical Union* 87(12):121–125.

Stewart, T. L., and J. F. Martin. 2005. Energy Model to Predict Suspended Load Deposition Induced by Woody Debris: Case Study. *Journal of Hydraulic Engineering-ASCE* 131:1011–1016.

Stock, J. D., D. R. Montgomery, B. D. Collins, W. E. Dietrich, and L. Sklar. 2005. Field Measurements of Incision Rates Following Bedrock Exposure: Implications for Process Controls on the Long Profiles of Valleys Cut by Rivers and Debris Flows. *Geological Society of America Bulletin* 117(11/12):174–194.

Subramanya, K., 2008. *Engineering Hydrology*. New York: McGraw-Hill. 434 pp.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land-Water Interactions: The Riparian Zone. Pages 267–291 on R. L. Edmonds (ed.), *Analysis of Coniferous Forest Ecosystems in the Western United States*. US/IBP Synthesis Series, Hutchinson Ross Publishing Company: Stroudsburg, PA.

Swanson, F. J., T. K. Kranz, N. Caine, and R. G. Woodmansee. 1988. Landform Effects on Ecosystem Patterns and Processes. *BioScience* 38:92–98.

Tappeiner, J. C., D. Huffman, D. Marshall, T. A. Spies, and J. D. Bailey. 1997. *Density, Ages, and Growth Rates in Old-Growth and Young-Growth Forests in Coastal Oregon*. Paper 3166 of the Forest Research Laboratory, Oregon State University, Corvallis.

Thomas, H., and T. R. Nisbet. 2006. An Assessment of the Impact of Flood Plain Woodland on Flood Flows. *Water and the Environment Journal* 21(2):114–126.

Tarzwell, C. M. 1936. Experimental Evidence of the Value of Trout Stream Improvements. *Transactions of the American Fisheries Society* 66:177–187.

Thompson, D. M. 2002. Long-term Effect of Instream Habitat-improvement Structures on Channel Morphology along the Blackledge and Salmon Rivers, Connecticut, USA. *Environmental Management* 29(1):250–265.

Thompson, D. M. 2005. The History of the Use and Effectiveness of Instream Structures in the United States. *Geological Society of America Reviews in Engineering Geology* XVI:35–50.

Thorne, S. D., and D. J. Furbish. 1995. Influences of Coarse Bank Roughness on Flow Within a Sharply Curved River Bend. *Geomorphology* 12(3):241–257.

Triska, F. J. 1984. Role of Large Wood in Modifying Channel Morphology and Riparian Areas of a Large Lowland River under Pristine Conditions: A Historical Case Study. *Verhandlungen-InternationaleVereinigung für Theorelifche und Angewandte Limnologie* 22:1876–1892.

Tsukamoto, Y. 1987. Evaluation of the Effect of Tree Roots on Slope Stability. *Bulletin of the Experimental Forests*. 23:65–124.

Turnipseed, D. P., and V. B. Sauer. 2010. *Discharge Measurements at Gaging Stations: U.S. Geological Survey Techniques and Methods Book 3*, Chapter A8, U.S. Geological Survey.

U.S. Bureau of Reclamation. 2005. *Watershed Conditions and Seasonal Variability for Select Streams within WRIA 20, Olympic Peninsula, Washington*. Available: http://www.ecy.wa.gov/programs/eap/wrias/planning/docs/opendraft_wria20_final4.pdf.

Valett, H. M., C. L. Crenshaw, and P. F. Wagner. 2002. Stream Nutrient Uptake, Forest Succession, and Biogeochemical Theory. *Ecology* 83:2888–2901.Van Cleef, J. S. 1885. How to Restore Our Trout Streams. *Transactions of the American Fisheries Society* 14:50–55.

Van Sickle, J., and S. V. Gregory. 1990. Modeling Inputs of Large Woody Debris to Streams from Falling Trees. *Canadian Journal of Forest Research* 20(10):1593–1601.

Veatch, A. C. 1906. Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas. Washington D.C. *United States Geological Survey Professional Paper* 46.

Veilleux, A. G., T. A. Cohn, K. M. Flynn, R. R. Mason, and P. R. Hummel, P.R. 2013. *Fact Sheet 2013-3108: Estimating Magnitude and Frequency of Floods Using the PeakFQ 7.0 Program*. 2327-6932, U.S. Geological Survey.

Viessman, W. J., and G. L. Lewis. 2003. *Introduction to Hydrology.* Prentice Hall. 612 pp.Wadsworth, A. H., Jr. 1966. Historical Deltation of the Colorado River, Texas. Pages 99–105 in *Deltas in Their Geologic Framework.* American Association of Petroleum Geologists.

Wallace, J. B., and A .C. Benke. 1984. Quantification of Wood Habitat in Subtropical Coastal Plain Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 41:1643–1652.

Wallerstein, N. P., and C. R. Thorne. 2004. Influence of Large Woody Debris on Morphological Evolution of Incised, Sand-Bed Channels. *Geomorphology* 57:53–73.

Washington Forest Practices Board. 1997. *Board Manual: Standard Methodology for Conducting Watershed Analysis.* Under Chapter 222-22 WAC. Version 4.0. Olympia, Washington.Webster, J. R., and 9 others. 2000. Effects of Litter Exclusion and Wood Removal on Phosphorus and Nitrogen Retention in a Forest Stream. *Verhandlungen der Internationale Vereinigung für Limnologie* 27:1337–1340.

Webster, J. R., J. A. Stanford, J. L. Chaffin, and Field Ecology Class. 2002. Large Wood Jam in a Fourth Order Rocky Mountain Stream. *Verhandlungen der Internationale Vereinigung für Limnologie* 28:1–4.

Western Wood Products Association (WWPA). 1995. *Ponderosa Pine Species Facts*. Available: www.wwpa.org/ppine.htm.

Whitney, G. G. 1996. *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present.* Cambridge University Press: Cambridge, UK.

Wiegner, T. N., L. A. Kaplan, J. D. Newbold, and P. H. Ostrom. 2005. Contribution of Dissolved Organic C to Stream Metabolism: A Mesocosm Study Using C-13-Enriched Tree-Tissue Leachate. *Journal of the North American Benthological Society* 24:48–67.

Wilcock, P. R., A. F. Barta, C. C. Shea, G. M. Kondolf, W. V. Graham Matthew, and J. Pitlick. 1996. Observations of Flow and Sediment Entrainment on a Large Gravel-Bed River. *Water Resources Research* 32:2897–2909.

Wilford, D., Maloney, D., Schwab, J., and Geertsema, M. 1998. Tributary Alluvial Fans. *B.C. Ministry of Forests Extension Note* 30.

Wiltshire, P. E. J., and P. D. Moore. 1983, Paleovegetation and Paleohydrology in Upland Britain. Pages 433–451 in K. J. Gregory (ed.), *Background to Paleohydrology*. John Wiley: Chichester, UK.

Wohl, E. E. 2001. *Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range*. New Haven, CT: Yale University Press.

Wohl, E. 2013. Floodplains and Wood. *Earth-Science Reviews* 123:194–212.

Wohl E., D. A. Cenderelli, K. A. Dwire, S. E. Ryan-Burkett, M. K. Young, and K. D. Fausch. 2010. Large in-Stream Wood Studies: A Call for Common Metrics. *Earth Surface Processes and Landforms* 35:618–625.

Wohl, E., L. E. Polvi, and D. Cadol. 2011. Wood Distribution Along Streams Draining Old-Growth Forests in Congaree National Park, South Carolina, USA. *Geomorphology* 126:108–120.

Wolff, H. H. 1916. The Design of a Drift Barrier Across the White River, near Auburn, Washington. *Transactions of the American Society of Civil Engineers* 16:2061–2085.

Zeng, H., J. Q. Chambers, R. I. Negron-Juarez, G. C. Hurtt, D. B. Baker, and M. D Powell. 2009. Impacts of Tropical Cyclones on U.S. Forest Tree Mortality and Carbon Flux from 1851 to 2000. *Proceedings of the National Academy of Sciences* 106(19), 7888–7892.

Zobel, D. B., A. McKee, G. M. Hawk, and C. T. Dyrness. 1976. Relationships of Environment to Composition, Structure, and Diversity of Forest Communities of the Central Western Cascades of Oregon. *Ecological Monographs* 46:135–156.

Chapter 5

WATERSHED-SCALE AND LONG-TERM CONSIDERATIONS

Photo credit: Ken DeCamp

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5.1 Introduction and Purpose

River restoration has received valid criticism for focusing on active, engineered, and structure-driven approaches (Bernhardt et al. 2007; Kondolf 2000) that incur high financial costs, significant risks of failure, and uncertain biotic responses relative to more passive or assisted restoration methods. The relatively high cost profile alone of these active techniques means that they cannot address the high degree and wide distribution of riverine alteration and damage in the United States and elsewhere. As true in most forms of restoration, but even more so because of the normally shorter lifespans of placed wood (compared to stone) and its interactions with mobile wood elements, large wood-based projects must anticipate various forms of and alterations to background load inputs. While weighing or integrating active, assisted, or passive techniques can be challenging, it is particularly important with wood-based projects.

Addressing these points requires focusing on large-scale and long-term issues with wood supply and dynamics, including: basin-scale large wood recruitment and supply issues, wood management at reservoirs and re-operations for wood recruitment and routing, effects of climate change, effects of stochastic flooding and storms on pulsed colluvial and alluvial recruitment of wood, planning and infrastructure design for large wood conveyance during peak flows, and large wood management and utilization in flood response.

5.2 Corridor and Basin Management Concepts

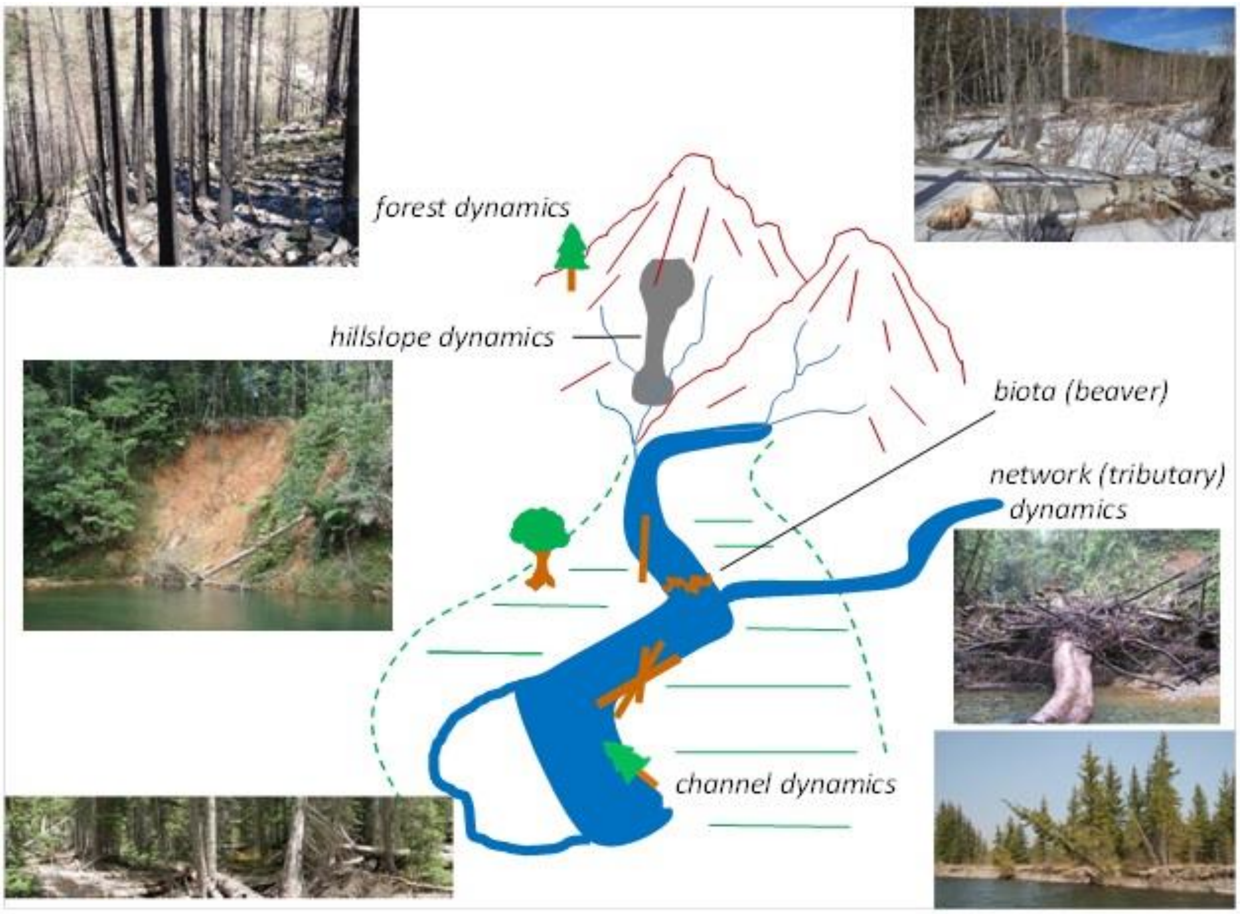
Much of the need for this manual stems from the truncation of wood supply to U.S. rivers by large-scale forest clearing and development. There has also been elimination, reduction, or fragmentation of supply and transport processes by transportation infrastructure, channel armoring, leveeing, and dam construction. Alteration to wood supply has been particularly acute for large trees that form the key elements that create relatively stable features (depending on channel dimensions relative to wood dimensions). In many areas of the country wood supply, both in terms of overall volume and, increasingly, recruitment of large, key-sized material, is only now becoming available to the fluvial system at landscape and sub-landscape scales, and restoration needs to focus increasingly on the ability of stream crossings and related infrastructure to convey that material. However, an approximation of normative supply will not occur without a geographically, economically, and politically broader acceptance of the value of riparian and stream corridors as supply zones for wood, zones of desirable physical dynamism (as currently documented by geomorphic channel migration and geotechnical hazard zone delineation (e.g. FEMA 1999), and areas for flood storage, recreation, and concentrated ecosystem services and values.

5.3 Flood Dynamics and Response

5.3.1 Pulsed Stochastic Inputs as a Large Wood Recruitment Mechanism

Recruitment of wood to channels and floodplains is highly variable through time and space within an individual drainage basin and between drainage basins. Forest dynamics, hillslope dynamics, river-network dynamics, biota, and channel dynamics interact to govern mechanisms, rates, and quantities of wood recruitment (Figure 5-1). Forest dynamics include individual tree mortality and mass mortality caused by fires, insects, and blow downs (Gregory et al. 1993; Marcus et al. 2011; Wohl 2013a). Hillslope dynamics primarily refers to slope instability in the form of avalanches, landslides, and debris flows that introduce wood to valley bottoms (May and Gresswell 2003a, b; Comiti et al. 2006; Wohl et al. 2009; Rigon et al. 2012). River-network dynamics describes tributary inputs of wood to a main valley (Benda et al. 2003a). Biota refers primarily to beavers, which are capable of recruiting wood to streams by chewing down trees (Kreutzweiser et al. 2005). Channel dynamics includes bank erosion that undermines and recruits trees, and floodplain erosion that exhumes buried wood and returns it to the active channel (Downs and Simon 2001; Kukulak et al. 2002; Wyżga and Zawiejska 2005; Guyette et al. 2008).

Figure 5-1. Influences on Wood Recruitment to River Corridors



Inset photographs illustrate (clockwise starting from upper right) beaver-felled trees in Colorado; a logjam at the mouth of a tributary along the Upper Rio Chagres, Panama; trees leaning over the Snake River in Wyoming as a result of bank erosion; abundant downed wood and secondary channels in Colorado; a small landslide along the Upper Rio Chagres; and standing dead trees following a forest fire in Colorado. (Photographs by Ellen Wohl)

CASE STUDIES

Episodic Mass Large Wood Recruitment

Blowdown along Glacier Creek, Colorado (Wohl 2013a): On November 21, 2011, a microburst knocked down trees over a 33-hectare (82-acre) area along Glacier Creek in Rocky Mountain National Park with old-growth subalpine spruce-fir forest. Many of the trees remained partly attached to the bank via rootwads partly anchored in the soil. Other trees formed a bridge, with the trunk above peak-flow water levels but large branches oriented down into the channel. During the next 2 years, these relatively stable downed trees acted as key pieces for new logjams by trapping smaller wood in transport down the creek. Jam frequency along this portion of Glacier Creek increased from approximately 1 jam per 100 meters (330 feet) to 1 jam per 54 meters (177 feet) by July 2013. The ratio of tree length (averaging 16 meters [53 feet]) to channel width (averaging 12 meters [39 feet]) allowed downed trees to effectively block a significant portion of the channel and form in situ log jams.

Trees blown down across Glacier Creek (at left). Small landslide along tributary to Rio Chagres (at right) has created a large jam at the tributary junction. The mainstem flow is right to left. Person at upper left of jam for scale.

Landsliding in the Upper Rio Chagres, Panama (Wohl et al. 2009): The Upper Rio Chagres drains 414 square kilometers (160 square miles) of mountainous terrain covered by old-growth rainforest in central Panama. An intense convective storm on July 10, 2007, created widespread rainfall over the basin that triggered flooding and numerous landslides. Transport capacity is very high within the Chagres catchment, where peak unit discharge can reach 41 cubic meters per second per square kilometer. However, landslides introduced such large masses of wood that enormous logjams formed at sites of reduced transport capacity such as tributary junctions or bends on the main channel. Trees in the watershed can attain a height of 30 meters (90 feet) and a diameter of 2.2 meters (7.2 feet), and key pieces in these jams were greater than 20 meters (66 feet) in length. The ratio of piece length to channel width averaged 0.1–0.2 at sites of jam formation. Although some of the jams stored substantial volumes of sediment upstream (1,100–8,200 cubic meters [1,440–10,725 cubic yards]), the jams broke apart and disappeared within 3 years due to the combined effects of subsequent high flows and extremely fast rates of wood decay.

Low frequency, episodic processes such as fire, landslides, or channel avulsion, in particular, can create relatively large inputs of sediment and wood to river networks. Understanding of geomorphic process domain can provide understanding of where within a landscape these processes are likely to occur, as well as the magnitude and frequency of associated wood recruitment. Geomorphic process domains are spatially distinct portions of the landscape that reflect spatial variability in geomorphic processes and temporal patterns of disturbances that influence ecosystem structure and dynamics (Montgomery 1999). Ecologists define a disturbance 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). A flood is an obvious example of a disturbance in a river environment. Disturbance regime refers to the spatial pattern and statistical distribution of disturbances in terms of magnitude, frequency, and duration of associated changes in the physical environment (Montgomery 1999).

5.3.1.1 Retention of Pulsed Large Wood Inputs

Large, pulsed inputs of sediment and wood to a channel can remain in place, translate downstream as a relatively discrete mass, or diffuse along a greater channel length with time, although studies published thus far focus on downstream movement of sediment pulses rather than wood (e.g., Lisle et al. 2001; Sklar et al. 2009). The retention of wood following individual or mass recruitment also varies through time and space as a function of valley geometry, existing wood loads at the time of recruitment, discharges of water and sediment, and channel characteristics.

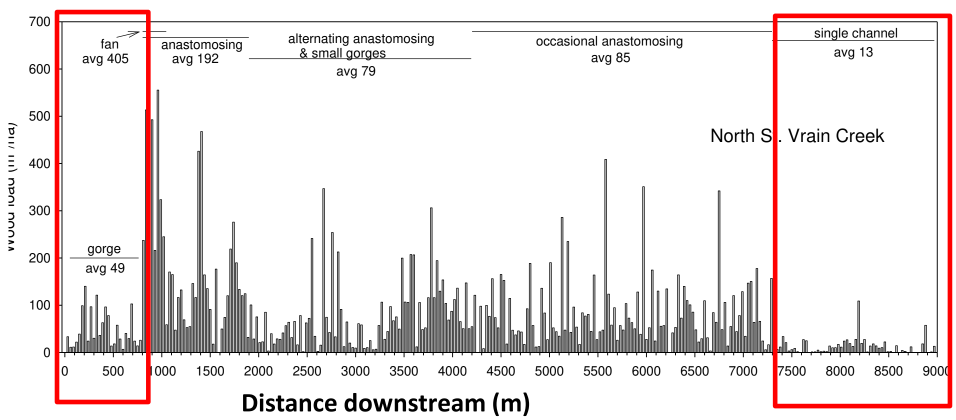
The most relevant aspects of valley geometry are the ratio of active channel width to valley-bottom width and the channel gradient. These typically correlate: a valley bottom that is much wider than the active channel commonly has a relatively low gradient, whereas steeper valley segments have narrowly confined active channels. Steep, narrow channels may have limited transport capacity because of large ratios of wood piece length to channel width. Physical experiments in flumes (Braudrick and Grant 2000; Welber et al. 2013) and field studies (Haga et al. 2002; Warren and Kraft 2008; Merten et al. 2010) indicate that wood transport scales with the ratios of piece length/channel width and piece diameter/flow depth. As these ratios increase, wood mobility declines. Depth increases rapidly with discharge in narrow reaches, however, as do hydraulic forces acting on wood, so that narrower, steeper valley segments may retain less wood than otherwise comparable wider, lower gradient segments (Wohl 2011b; Wohl and Cadol 2011). The presence of a floodplain in a wider valley segment facilitates overbank flows that limit increases in depth and velocity during higher discharges. Shallower, slower overbank flows can also carry wood onto the floodplain, increasing wood retention within the valley segment.

Existing wood loads at the time of pulsed recruitment are important because they can create congestion within the channel and floodplain, forming obstacles in the form of immobile ramped pieces or logjams that trap wood in transport (Bocchiola et al. 2006; Moulin et al. 2011; Wohl and Beckman 2014a). Even if all wood pieces are mobile, the volume of wood in transport relative to channel dimensions can create different modes of transport. Braudrick et al. (1997) observed congested, semi-congested, and uncongested wood transport during physical experiments in a flume. During uncongested transport, logs move without piece-to-piece interactions, whereas logs interact with one another during semi-congested transport and move as a single mass during congested transport. Wood can move farther during congested transport (Bocchiola et al. 2008). During a 10-year study of the mobility of individual wood pieces within mountainous channels in the Colorado Front Range, Wohl and Goode (2008) found that pieces within jams typically had longer residence times than isolated pieces.

CASE STUDIES

Case Studies of Spatial Distribution of Large Wood

Longitudinal Segregation and Aggregation of Large Wood (Kraft and Warren 2003; Morris et al. 2010): Two years after extensive wood deposition from an ice storm in the eastern Adirondack Mountains of New York, Neighbor *K* statistics indicated that individual pieces of wood were aggregated at spatial extents ranging from 0 to 40 meters (0 to 131 feet) and were segregated (regularly spaced) at distances ranging from 100 to 300 meters (328 to 984 feet) along channels draining 6 to 130 square kilometers (2 to 50 square miles). Mean channel widths varied from 4 to 13 meters (13 to 43 feet). Spatial segregation of jams occurred in response to stream features that created stable accumulation points.



North St. Vrain Creek, Colorado (Wohl and Cadol 2011): A longitudinally continuous survey of instream wood distribution along 9 kilometers (5.6 miles) of North St. Vrain Creek included diverse stand ages of riparian forest and valley geometry. The surveyed portion of the creek drains 15 to 82 square kilometers (6 to 32 square miles). Channel width varies from 7 to 20 meters (23 to 66 feet) and tree heights are typically less than 20 meters (66 feet). Individual wood pieces are highly aggregated at length scales of 1 to 150 meters (3.3 to 492 feet). Local valley and channel geometry exert a stronger influence on longitudinal patterns of wood distribution than since either the last forest disturbance or progressive downstream trends associated with increasing drainage area. Wood loads and average jam size are greater in valley segments with greater valley-bottom width and lower gradient. Red highlights in the figure above indicate relatively steep, narrow portions of the channel, which have lower wood loads.

Sediment discharge influences wood retention and redistribution along a channel by influencing processes such as abrasion, breakage, and burial of wood pieces (Webb and Erskine 2003; Young et al. 2006; Merten et al. 2013). Although few data exist for abrasion rates for instream wood, observations suggest that abrasion can significantly erode logs close to the streambed in channels with high rates of flux for sand-sized and coarser particles (Spänhoff and Meyer 2004). Weakened wood pieces can be broken by hydraulic forces or by the impact of very coarse sediment, although, again, no data are available on rates or magnitudes of these processes. Burial can protect wood from hydraulic forces and abrasion, but can also promote wood decay if the wood is buried in anoxic conditions.

Water discharge influences wood retention and redistribution by creating hydraulic forces that can mobilize wood, as well as sufficient transport capacity to keep the wood moving. Discharge-stage relationships within a channel are likely to create numerous thresholds at which differently sized and oriented pieces of wood are mobilized (MacVicar and Piégay 2012; Kramer and Wohl 2014; Schenk et al. 2014a), although few studies address this phenomenon.

Channel characteristics that influence wood mobility include what Braudrick and Grant (2001) referred to as *debris roughness*. A rough channel, in this context, is one with at least some large clasts that protrude well above the bed and in some cases above the water surface. These clasts can effectively trap wood in transport (Figure 5-2). Bends in the channel and downstream variations in channel width can also enhance wood retention. Wood can be preferentially deposited either on point bars at the inside of bends (Daniels and Rhoads 2004) or along the top of the bank/edge of the floodplain along the outside of bends (Piégay 1993; Johnson et al. 2000) (Figure 5-3).

The few stochastic models of instream wood loads through time reflect the influences on large wood retention of these disparate mechanisms (e.g., Meleason et al. 2007). The model of Eaton et al. (2012), for example, includes parameters for wood piece dimension, channel and flow dimensions, wood load, and wood decay and breakage. Conceptual models of instream wood loads can also implicitly incorporate factors that influence recruitment and retention. Based on four field sites in Costa Rica and Panama, Wohl et al. (2012) differentiate a steady-state end-member with gradual recruitment of wood through individual tree fall that creates relatively consistent wood load through time and minimal development of logjams, and an episodic end-member in which episodic mass recruitment via landslides or blowdowns results in formation of transient logjams, so that wood loads are highly spatially and temporally variable.

In summary, the ability of any river segment to retain pulsed stochastic inputs of large wood reflects the pre-event wood load, the presence of channel and valley features that can enhance wood storage (e.g., large protruding clasts, meander bends, abrupt expansions or constrictions, floodplains), and the sequence of water and sediment fluxes following large wood recruitment. Marcus et al. (2002) described river segments as being either supply-limited or transport-limited with respect to wood. Wohl and Jaeger (2009) built on this idea to develop a conceptual model of wood distribution throughout a network. Lower order streams are transport-limited for wood and have high loads of randomly distributed wood pieces (Figure 5-4). Moderate order streams have sufficient transport capacity to move wood into jams that form at sites with local limitations on transport capacity, such as abrupt channel expansions or bends. Higher order streams are supply-limited for wood and have lower wood loads. The specific portions of a network that fit into these three general categories will depend on factors such as peak discharge per unit drainage area, rates of downstream increase in channel width, and the size and abundance of wood pieces recruited to the channel. Subsequent research supports the idea that smaller watersheds can be transport-limited for wood (Fremier et al. 2010).

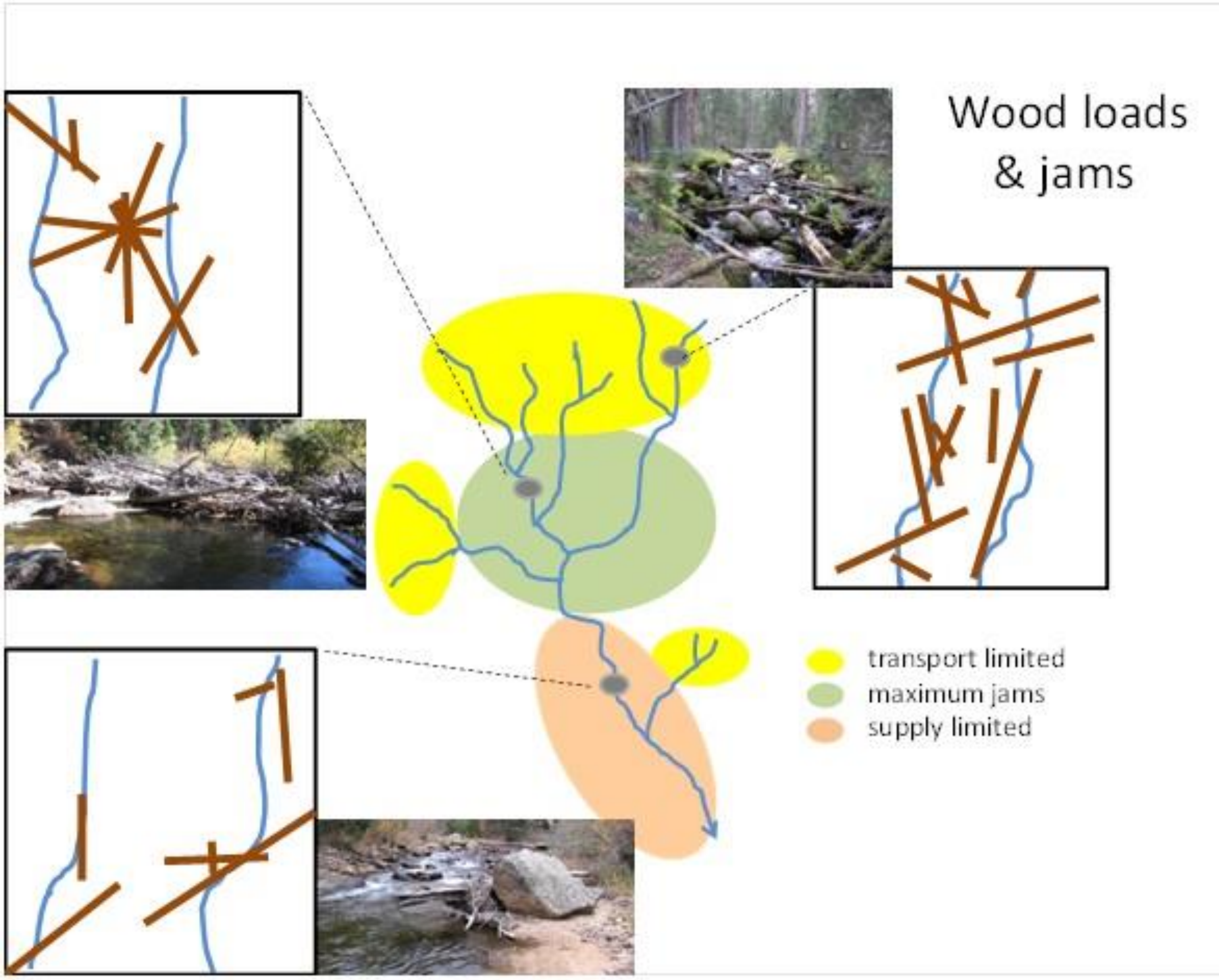
Figure 5-2. Examples of Protruding Boulders Helping to Trap Wood along Streams

Upper left is on North St. Vrain Creek in Colorado and lower right is along Atlas Creek in Canada. In each case, the yellow arrow indicates flow direction. (Photographs by Ellen Wohl)

Figure 5-3. Wood Deposited Along the Top of Bank at the Outside of a Meander Bend on the Dall River in Central Alaska

Yellow arrow indicates flow direction.

Figure 5-4. Conceptual Illustration of Downstream Trends in Total Wood Load and Logjams along a River Network



After Wohl and Jaeger (2009: Figure 7).

5.3.1.2 The Role of Floods

Floods are likely to be the critical intervals for large wood management. Floods can result in greater wood recruitment, particularly rainfall-generated floods that destabilize hillslopes and promote mass wood recruitment. Floods can also result in substantially higher rates of wood transport. Videos posted on the internet of flash floods in environments as diverse as Costa Rica and Nevada indicate that these floods can have a leading front of coarse wood, analogous to the coarse sediment concentrated on the leading edge of many debris flows. By generating much greater hydraulic forces and transport capacity, floods can also limit the stability of deliberately introduced wood such as ELJs. During a flood, wood can also form temporary debris dams that, when they break, release a surge of water and sediment downstream (Mao and Comiti 2010).

Flood duration may be as important as flood magnitude in governing the balance between wood recruitment and transport. Successive rainfall-generated floods within the Upper Rio Chagres drainage of Panama had very different effects on instream wood load because of differences in duration (see *Case Study* above).

A flood in July 2007 resulted from intense rainfall that triggered widespread landsliding within the catchment, resulting in the formation of channel-spanning logjams, each of which trapped a large volume of sediment and organic matter upstream (Wohl et al. 2009). A flood in December 2010 also resulted from intense rainfall that triggered dozens of landslides and even greater wood recruitment to the river network. The 2010 flood, however, lasted 2 days rather than the 5 hours of the 2007 flood, and the enormous volumes of wood recruited during the longer flood were transported through the river network and into Lake Alhajuela, the reservoir behind Madden Dam (Wohl and Ogden 2013).

Depending on the levels of wood recruitment versus transport, hydraulic roughness levels after a flood can increase, decrease, or remain relatively constant. Roughness is likely to increase if the flood leaves large amounts of wood within the channel and across the floodplain. This is one of the rationales commonly used for removing all wood immediately after a flood. As exemplified by the September 2013 floods along the Colorado Front Range, recruitment of wood into river corridors is viewed as moving communities out of compliance with FEMA requirements to return river corridors to pre-flood conditions in order to qualify for federal financial assistance. Roughness is likely to decrease after a flood if the net effect is removal of pre-existing wood naturally present in the channel or deliberately placed there as part of river restoration. Roughness may not change significantly after a flood if existing wood is transported downstream but new wood is deposited during the waning stages of the flood.

CASE STUDY

Case Study of Flood Large Wood Recruitment and Retention

Jökulhlaup Flooding and Logjams along Dinwoody Creek, Wind River Range of Wyoming (Oswald and Wohl 2008): A jökulhlaup (glacier outburst flood) from Grasshopper Glacier in September 2003 created anomalously high flows along snowmelt-dominated Dinwoody Creek. High flows resulted in extensive bank erosion and large amounts of large wood recruitment. Recruited trees formed channel-spanning logjams at longitudinal intervals of tens to hundreds of meters. Channel aggradation upstream from each jam facilitated extensive overbank flooding and floodplain deposition. Logjams likely persist for decades in this relatively dry region, and floodplain stratigraphy indicates repeated episodic overbank deposition of the type observed following the 2003 flood.

Logjams formed along Dinwoody Creek (right) and 1 meter (3.3 feet) of overbank deposition (left) facilitated by log jams.

GUIDANCE

Effects of Individual Pieces of Wood and Accumulations Within Channels

- Increase hydraulic resistance; the magnitude of this effect depends on the abundance and spatial distribution of wood relative to channel width, flow depth, and other sources of hydraulic resistance (e.g., grains, bedforms, bends) (Shields and Smith 1992; Manga and Kirchner 2000; Mutz 2003; Daniels and Rhoads 2007; Manners et al. 2007; Dunkerley 2014).
- Create local flow separation, with associated scour of the bed and banks, storage of finer sediment and particulate organic matter, and enhanced diversity of aquatic habitat (Carlson et al. 1990; Nakamura and Swanson 1993; Smith et al. 1993; Thompson 1995; Hart 2002; Brooks et al. 2003; Faustini and Jones 2003; Ryan et al. 2014).
- Increase pool volume and fish abundance (Richmond and Fausch 1995; Buffington et al. 2002; Senter and Pasternack 2010; Schenk et al. 2014b).
- Increase hyporheic exchange (Lautz et al. 2006; Hester and Doyle 2008; Lautz and Fanelli 2008; Wondzell et al. 2009; Sawyer et al. 2011).
- Increase nutrient retention and uptake (Buckley and Triska 1978; Bilby and Likens 1980; Munn and Meyer 1990; Raikow et al. 1995; Beckman and Wohl 2014).
- Alter bedform dimensions (e.g., wood can result in taller and more widely spaced steps in step-pool channels) (Curran and Wohl 2003; MacFarlane and Wohl 2003).
- Alter substrate type, as in studies from the Pacific Northwest documenting forced alluvial reaches that would likely have a bedrock bed if no wood were present to trap sediment (Montgomery et al. 1995a.
- Initiate and stabilize bars and alter channel planform (Gurnell et al. 2012; Mikuś et al. 2013).
- Create sufficient obstruction to flow to increase bank erosion, channel avulsion, and channel-floodplain connectivity (Harwood and Brown 1993; Jeffries et al. 2003; Montgomery and Abbe 2006; Sear et al. 2010; Wohl 2011b; Phillips 2012; Umazano et al. 2014).

Effects of Individual Pieces of Wood and Accumulations Within Channels on Floodplains

- Create preferred habitat for organisms, including macroinvertebrates during periods of flooding (Benke 2001) and small mammals and birds during other periods (Harmon et al. 1986).
- Provide germination sites for riparian plants, particularly species that disperse via hydrochory (water transport of propagules) (Pettit et al. 2005; Pettit and Naiman 2006).
- Enhance nutrient storage and uptake (Naiman et al. 2010).
- Provide more erosionally resistant "hard points" within the floodplain that influence rates of bank erosion and lateral channel migration, as well as the age and species diversity of riparian forests (Montgomery and Abbe 2006; Collins et al. 2012).

5.3.1.3 Geomorphic and Ecological Effects of Pulsed Inputs of Large Wood

Many of the geomorphic and ecological effects associated with pulsed inputs of wood to a river corridor are the same as those associated with gradual recruitment of individual wood pieces.

Wood that remains within a river corridor has the net effect of creating a more physically heterogeneous environment that can increase biodiversity because of habitat abundance and diversity. By helping to retain nutrients, wood can also increase animal production (Huryn and Wallace 1987; Gowan and Fausch 1996; Nagayama et al. 2012) and improve water quality. These well-documented effects can provide a strong rationale for retaining or re-introducing wood to river corridors. With the exception of unmanaged rivers flowing through old-growth forest, it is reasonable to assume that any river within the United States historically had much greater wood loads within the river corridor than are present today (Wohl 2014).

5.3.2 Large-Scale and Long-Term Considerations

The existence of diverse sources of variability in large wood recruitment and retention, either within a limited river segment or across a river network, implies that "snapshot" assessments of wood load and wood mobility within a river at a moment in time can be misleading. It is more appropriate to think about wood in the context of a wood budget (Benda and Sias 2003) that varies through time and space, and in terms of a historical or natural range of variability. Natural range of variability (NRV) describes the range of temporal and spatial variations in river parameters such as flow regime, channel geometry, or wood load (Wohl 2011c). Wood loadings depend on the recruitment, storage, and transport of wood; and a budget may be constructed using an approximation of the following (Martin and Benda 2001).

Equation 5-1:

$$\Delta S = (I\Delta x - O\Delta x + Q_i - Q_O - D)\Delta t$$

where ΔS is a change in storage within a channel with a length of Δx over the time interval Δt; I is lateral wood recruitment, O is loss of wood from the active channel to overbank deposition during flood events, abandonment of jams, and burial; D is in situ decay; and Q_i and Q_o are fluvial transport of wood into and out of the segment. Large compilations of field data on relatively unmanaged rivers within a region can be used to constrain NRV for instream wood, but these have only been published for relatively small rivers in the Pacific Northwest (Fox and Bolton 2007) and the Colorado Front Range (Wohl 2011a). In the absence of quantitative data, numerical simulations may be used (Gregory et al. 2003b), although existing models are predominantly region specific (e.g., Beechie et al. 2000; Bragg 2000; Welty et al. 2002; Eaton et al. 2012).

Although development of wood budgets must start with an evaluation of the NRV of wood loadings in a watershed, or for a region, one must evaluate the numerous management activities and policies that have in the past, or will in the future, impact the spatial and temporal distribution of wood in a watershed. As the natural range provides an idea of how much wood may be recruited and stored within a river system, a consideration of management actions will help to identify the limitations. For example, infrastructure or safety considerations often require the removal of large pulses of wood (e.g., Benda et al. 2003b) (*also see Chapter 7, Risk Considerations*). The following discussion covers two impacts on stream systems: dams and land-use/land-cover.

5.3.2.1 Dams

Dams interrupt the movement of water, sediment, and organic matter through a watershed. At the most fundamental level, dams alter a wood budget when the upstream reservoir traps the large wood recruited and transported by the river. Changes to the flow regime and sediment supply downstream, however, also have the potential to greatly impact a river's wood budget. Channel mobility is often reduced and, as a result, the recruitment and regeneration of riparian forests (Scott et al. 1996; Kloehn et al. 2008). Channel pattern and other geomorphic variables can also shift (Walter and Merrits 2008). Lassettre and Piegay (2008) documented an increase in wood recruitment on the Ain River downstream from a dam in response to floodplain afforestation as a result of a change from a braided to meandering channel pattern. Various studies have noted shifts in the composition of the riparian vegetation community (Nilsson and Berggren 2000; Friedman et al. 2005). For example, cottonwood-dominated forests have declined along many western rivers, at least in part because of dams (Rood and Mahoney 1990). In some systems, dense stands of shrubby tamarisk took the place of cottonwood (Merritt and Poff 2010). These changes can exacerbate reductions in channel mobility (Dean et al. 2011; Manners et al. 2014) but may also alter the potential for the recruitment of jam-forming logs or the wood storage capacity on the floodplains.

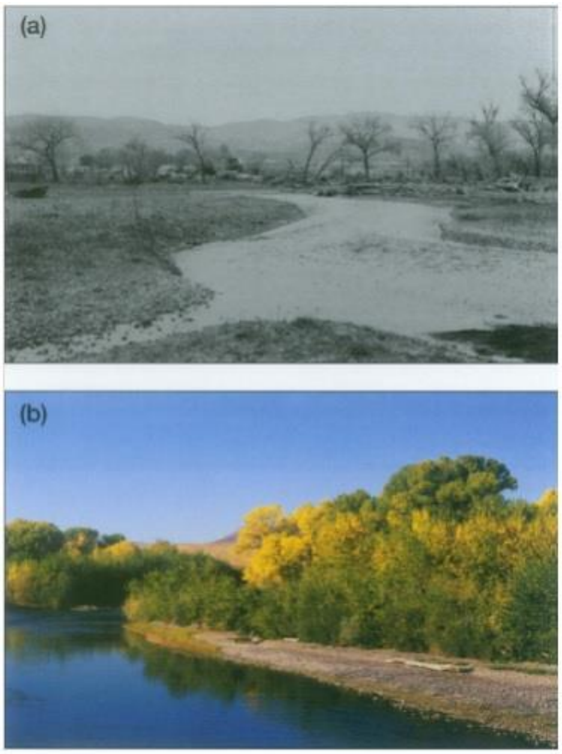
The magnitude and length-scale of the impact of a dam on the wood budget varies greatly and depends on the type of dam (i.e., its intended purpose) (Magilligan and Nislow 2005), the hydroclimatic region (Graf 1999), and the geologic setting (Grant et al. 2003; Schmidt and Wilcock 2008). In the western mountains and plains regions of the U.S., dams generally have a more profound impact on the hydrologic regime (Graf 1999); however, the direction of these changes is relatively constant across dam sites and include an increase in the minimum flows and a decrease in maximum flows (Magilligan and Nislow 2005). Inputs from tributaries, or changes in the geomorphic character of the downstream channel, can offset the impact of a dam (Williams and Wolman 1984; Schmidt and Wilcock 2008; Draut et al. 2011). One must also consider where within the watershed the dam is located with respect to the dominant controls on wood recruitment and transport (see Figures 5-1 and 5-4). The direct impact of these downstream changes on a wood budget have rarely been quantified.

There has been a growing movement to remove dams (Doyle et al. 2003). Motivations for removal include an aging infrastructure, public safety, and an enhanced environmental awareness of the importance of free-flowing rivers (Pohl 2002). To date, removals have predominately occurred on smaller dams, but in recent years large dams have been removed (Major et al. 2012; East et al. 2014) and many more removals are planned (e.g., Gosnell and Kelly 2010). The majority of the removals have occurred in the northeastern region of the United States, where there is a high density of dams. Various organizations have begun to track removals, and the associated dialogue (e.g., American Rivers, www.americanrivers.org/initiatives/dams and the Clearinghouse for Dam Removal, a collaboration of California Universities, http://library.ucr.edu/wrca/collections/cdri/).

Dam removals have the potential to greatly affect the wood budget, both in the short term, as the flux of sediment and wood that accumulated within the reservoir passes downstream, and the long term, as the river responds to the new, more natural flow regime and sediment supply. Between 2011 and 2013, two large dams on the Elwha River in Washington State were removed. Prior to the removal, Brenkman et al. (2012) documented that the number of jams below the dams was one to two orders of magnitude less than upstream. East et al. (2014) noted that new wood was present after dam removal, most of which had eroded from within former reservoir deposits. Little additional anecdotal evidence exists on how large wood loadings change after the removal of a dam.

Dam operations are also being re-evaluated in order to meet a growing demand for increasingly limited water supplies (Watts et al. 2011) as well as downstream ecosystem needs (Whiting 2002). Increasingly, new dam operation schemes mimic the natural flow regime, or at least a reduced and/or simplified version of it (Poff and Zimmerman 2010). These flow regimes can restore lateral dynamism that recruits wood but can also reintroduce natural processes that may push a wood budget closer to its natural range. For example, the restoration of flow patterns to match the seed release and germination needs of native riparian plant species on regulated rivers in Alberta, Canada and Nevada promoted new recruitment of cottonwood and willow (Rood et al. 2003) (Figure 5-5). Furthermore, some dam operators have now modified their management practices to include downstream placement or disposal for wood deposited in reservoir impoundments.

Figure 5-5. Impact that Reoperation of Dams, to Include More Natural Elements of the Hydrograph, Can Have on a Riparian Ecosystem



Photos show the Truckee River in 1977 (a) with only relatively old stands of cottonwood and no new recruitment and in 1997 (b) after a series of years (1987 and 1995) with flood hydrographs that met the recruitment needs of cottonwood and willow. Photos were taken from approximately the same location, however, not matched exactly because of a shift in the channel. (Figure taken from Rood et al. 2003.)

5.3.2.2 Land-use/Land-cover

The mosaic of land-uses and land-covers within a watershed impacts the timing, rate, and spatial distribution of biophysical fluxes into a river channel. The focus herein is on two regions within a watershed: (1) the river corridor, including the hillslope adjacent to the channel or floodplain, the floodplain, and the channel bank—important for the direct contribution of wood to a channel; and (2) the larger watershed—important for determining the flow regime and sediment supply, and indirectly critical for the wood budget and long-term health of a river system.

In evaluating the impact of land-use/land-cover within the river corridor on the wood budget, it is necessary to remain conscientious of the dominant recruitment mechanisms. For example, in steep landscapes and in headwater reaches, bank erosion is limited and landslides deliver the majority of wood to the channel (May and Gresswell 2003a, b). In other settings, landslides are not important (Kasprak et al. 2012), and instead wood recruitment depends on bank erosion or tree-fall in proximity to the channel. For this latter scenario, hillslope land-use and management history is not as important to consider. Instead, the state of the river bank and floodplain, including any past engineering actions, are important.

Numerous studies have quantified the impact of forest management history on wood loadings and shown repeatedly that old-growth forests generally have greater jam frequency or wood volume than previously cleared ones (Bilby and Ward 1991; Collins and Montgomery 2002; Collins et al. 2002; Warren et al. 2009). Forest management in the western United States has also included fire suppression and fuels management, resulting in the alteration of fire regimes (Dwire and Kauffman 2003). Prior to European settlement, fire was the most important disturbance process in many of these western systems, and represents an important mechanism for wood delivery (Naiman et al. 2000). Changes to the fire regime, therefore, altered the frequency and magnitude of wood recruitment processes.

Human development of a river corridor impacts the wood budget in a number of ways. Conversion of forested hillslopes or floodplains removes the local wood source, although where a riparian buffer is maintained, this impact may be mitigated (Robison and Beschta 1990). Even a single Forest Service road paralleling a channel in a well-forested watershed can significantly reduce wood supply (Meredith et al. 2014). Engineering actions that stabilize banks in order to protect infrastructure and valuable crop land reduce recruitment potential (Angradi et al. 2004) and make streams more efficient at transporting wood, reducing storage potential. Roads reduce the infiltration capacity on the road surface itself and intercept surface flow and throughflow by cutslopes, resulting in increased surface runoff and leading to periodic mass failure from the adjacent hillslopes (Wemple and Jones 2003; Arnáez et al. 2004; Goode et al. 2012), potentially increasing recruitment rates.

Removal of forests also reduces the infiltration capacity of the landscape (Matheussen et al. 2000). With the addition of urban or suburban infrastructure and roads, the entire drainage network can shift. Often, the hydrograph becomes “flashier,” with a more rapid storm to stream signal, increased flood peak magnitude, and reduced base flows. River channels, as a result, can incise and become disconnected from their floodplains (Walsh and Roy 2005).

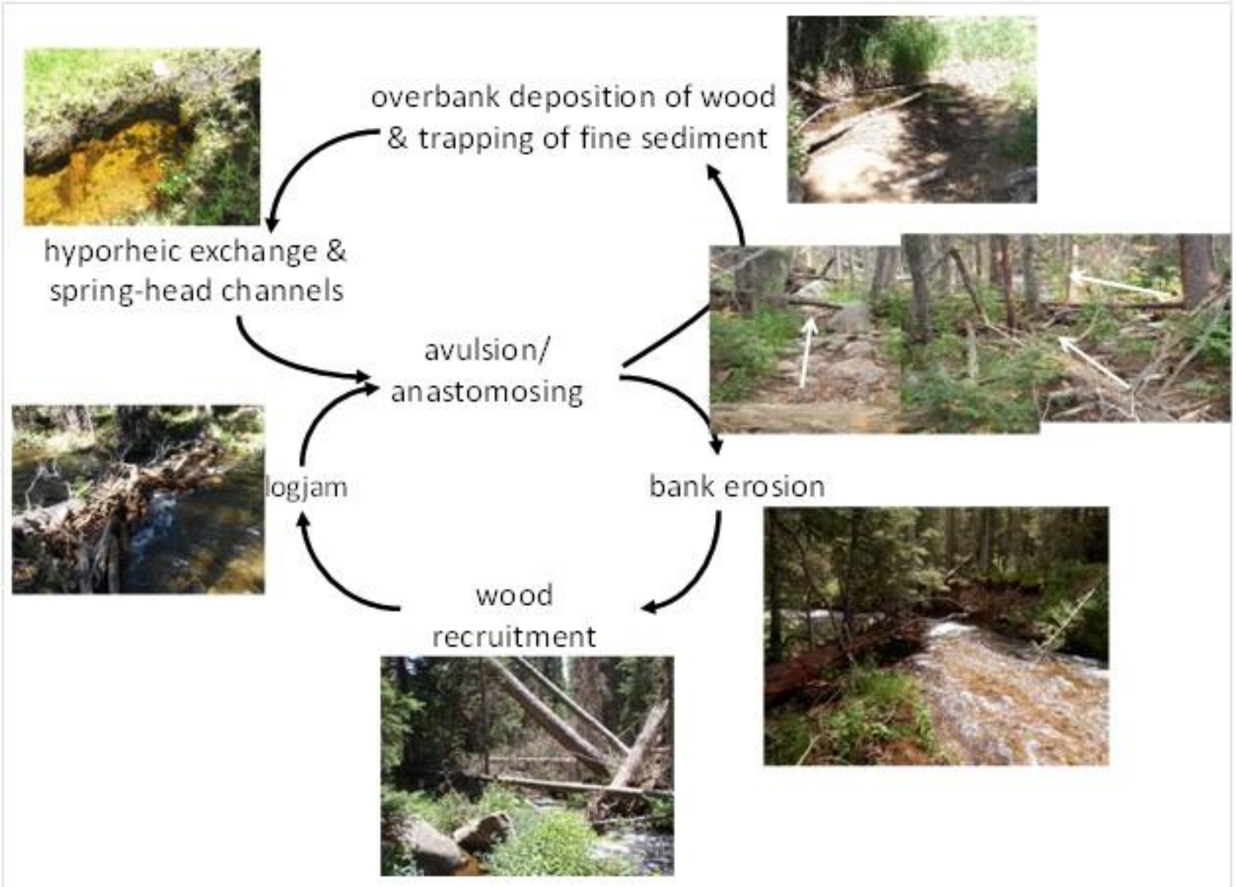
The Puget Sound region of Washington provides a good example of how changes in land-use can alter a wood budget. Urbanization increased the proportion of the basin May et al. (1997) studied from 0% to 60%, reducing the volume of large wood from approximately 1,200 cubic meters per kilometer to near zero, and the number of pieces declined by 75% (May et al. 1997).

Land-uses and land-cover are continually shifting, especially in the western United States The USGS undertook a study of land changes across the United States between 1973 and 2000. Currently, only the results from the Western region have been published and tell a story of losses in forest cover as a result of logging, fire, urbanization, and other land uses (Sleeter et al. 2012). The study highlights the fact that these trends were highly variable and will likely continue to as a result of changing climate, population trends, and local sociopolitical pressures.

5.3.2.3 Thresholds and Alternate Stable States

In ecosystems where wood decays relatively slowly and hydrologic variability is limited—mostly cold-temperate and boreal regions—the limited studies that have considered the existence of alternate stable states suggest that river corridors (channel-floodplain systems) can assume alternate stable states in relation to wood load. The slowness of wood decay is important because it means that, despite natural fluctuations in volume of large wood recruitment through time and space, the river corridor always contains some wood. As long as sufficient wood is present to obstruct transport of newly recruited wood, a positive feedback can develop in which stable wood traps wood in transport, enhancing bank erosion, channel avulsion, formation of multiple, subparallel channels, and overbank flows, and thus further increasing wood recruitment and retention (Figure 5-6) (Collins et al. 2012; Wohl and Beckman 2014b). These river corridors can become stabilized in a wood-poor condition if people remove instream and floodplain wood and reduce recruitment through processes such as timber harvest, channelization, inadequate stream crossings, and bank stabilization. River corridors with extremely high peak discharge per unit drainage area and/or high rates of wood decay, such as those in the tropics and subtropics, may have such continually changing wood loads that they never achieve the positive feedbacks that create persistent, wood-rich conditions (Benke and Wallace 1990; Wohl et al. 2009, 2011, 2012).

Figure 5-6. Conceptual Illustration of Wood-Related Feedback



Inset photographs illustrate (clockwise starting from upper right) fine sediment and organic matter deposited along the margin of a stream in the backwater created by a channel-spanning logjam; multiple, subparallel channels (flow direction indicated by white arrows) along the floodplain of North St. Vrain Creek in Colorado; bank erosion opposite a tree that fell into the stream; trees gradually falling into a stream as a result of bank erosion; a channel-spanning logjam; and a spring-head channel fed by hyporheic return flow along the floodplain of Cony Creek in Colorado. (Photographs by Ellen Wohl)

5.4 Large Wood and River Crossing Interaction

The generation, storage, and transport of large wood from trees falling into a river influence channel equilibrium and stability and improves instream habitat (Lassettre and Harris 2001; Brooks et al. 2006b). For example, wood can create stable step-pools in steep mountain channels (Wohl and Merritt 2008); influences hydraulics and slows water on meander bends and can reduce erosion (Daniels and Rhoads 2004); and influences sediment storage, spacing of riffle-pool sequences, and vertical channel stability (Thompson 1995). Also, large wood forms physical holding locations for fish and serves as the base of the aquatic food web (Allan 1995). Consequently, the known benefits of large wood have led to a rise in the use of engineered log jams and other large wood installations to restore instream habitat.

Wholesale woody debris removal following large floods to protect bridges, culverts, and other infrastructure removes an important mechanism for long-term channel bed and bank stability and future instream habitat. Effective river management must strike a balance between the removal of wood that can be problematic and the wood that could be of benefit is left in the channel and on the floodplain. Consideration of the diversity, quantity, retention, and transport of large wood is an important aspect of proper flood recovery.

Removal of large wood is typically performed to increase conveyance for water, sediment, additional large wood, and ice during the next flood to protect infrastructure, buildings, and unmovable improved property where vertical instability and risk of rapid channel migration (i.e., avulsion) exist (Schiff et al. 2014). Common scenarios for removal of large wood include clogged bridges and culverts, filled channels and floodplains, and avulsed channels. Too often wood is removed without addressing the stream crossing characteristics that induced deposition.

Many rivers have a history of bridge and culvert failures and backwater flooding due to large wood jams. Disproportionate or extreme flood damage is often highly correlated to stream crossings. For example 200 state bridges, 280 local bridges, and 960 local culverts were damaged in Vermont alone during Tropical Storm Irene in 2011 (Pealer 2012). Many structure failures are observed to be caused by wood; therefore, many communities shy away from leaving wood in a channel during flood recovery or from implementing wood-based restoration projects. A need exists to understand the budget of large wood at the watershed level, the risk large wood elements and jams pose in rivers, and the important roles large wood plays toward channel stability and habitat. A better understanding of large wood benefits and mitigation will help encourage stream crossing designs for wood conveyance and reduce infrastructure risks while maintaining the important natural functions of large wood.

5.5 Large Wood's Impact on Bridges and Culverts

5.5.1 National Overview

A national survey by the Federal Highway Administration (Diehl 1997) found that floating debris contributed to more than one-third of bridge failures in the United States Roughly two-thirds of bridge failures are attributed to hydraulic problems such as floods and scour, both of which are linked to large wood accumulation and structure clogging. There are approximately 485,000 bridges over water in the United States, with 17,000 listed as being scour critical.

The National Bridge Inspections and Safety programs (initiated in the 1980s after many bridge failures) highlighted the known risks of bridge failure and the level of national investment needed to keep bridges safe. The Federal Highway Administration considers the accumulation of wood at bridges and culverts to be a major safety and maintenance problem.

Guidance exists on the contributions of large wood to scour at bridges and culverts (Bradley et al. 2005; Lagasse et al. 2010; Arneson et al. 2012). Diehl (1997) provides detailed research on the formation of log jams at bridges. Lagasse et al. (2012) identify locations to place structures to limit conflicts with wood.

5.5.1.1 Large Wood and Bridge Scour

The most frequent bridge failure is due to scour at piers or abutments. Large wood accumulations create scour by restricting the waterway cross-sectional area, leading to higher velocities and scour-inducing turbulence. Log jams can also redirect flowing water toward the river bed where vulnerable piles and footings are located.

Bridge failures have been attributed to debris jams against piers that create high lateral forces and induce scour (Wipf et al. 2012). The trapping problems include accumulations at individual bridge piers that increase local pier scour and span-wide channel blockages that increase contraction and local abutment scour. Log jams at bridge piers begin at the water surface and then expand upstream and laterally. The width of pier log jams is often influenced by a few long logs. Some log jams extend from pier to pier while others ultimately fill the entire bridge opening.

Lagasse et al. (2010) details the procedure by which debris contributes to bridge scour based on field data and laboratory tests. Expanded protocols for predicting scour depths at piers and abutments and due to contraction are contained in *Hydraulic Engineering Circular* 18 (Arneson et al. 2012).

5.5.1.2 Large Wood and Hydraulic Capacity

Large wood jams at bridges reduce the cross-sectional flow area and reduce the structure's hydraulic capacity to pass flood flows raising upstream flood levels (i.e., backwatering). Large wood also increases the risk of overtopping and eroding the abutments and embankment.

5.5.1.3 Regional Data

In a recent study of 691 bridge failures in the United States, 52% were hydraulic failures, of which 40% were due to scour that largely originated from large wood accumulation (Cook 2014). In New York, of 92 bridge failures between 1987 and 2011, 20% were due to scour and 28% were due to floods. Hamill (1999) studied bridge failure and found that floods leading to scour and large wood piled against the structure were the most common cause of damages. Large wood and clogging is often cited to contribute to most bridge and culvert damage.

The effects of large wood on structures is likely higher than reported (Agrawal et al. 2007). Sediment, tree branches, large wood, and trash often intermittently block bridge and culvert openings during floods leading to contraction or local scour and eventual structure failure. The clogged structure then releases the accumulated material, and the true cause of the failure may not be properly recorded.

5.5.1.4 Forest Roads

In the Pacific Northwest, Furniss et al. (1998) conducted data collection and evaluations on the performance of logging road culverts with respect to large wood, sediment, flood flow conveyances, and fish passage. Numerous culvert failure mechanisms were identified including debris flows with channel scour and deposition, lodgment of large wood that plugged culverts, sediment deposition from mass flows, and hydraulic exceedance that overtopped roads. Sediment and large wood accounted for over 90% of the failures, while failure due to hydraulic conveyance alone was less than 10% (Table 5-1).

Table 5-1. Culvert Failure Data

Percent of Total	Failure Type
36	Sediment
26	Debris torrent
17	Woody debris
12	Woody debris/sediment
9	Hydraulic exceedance

5.5.1.5 Woody Debris at Dams

Large wood transport to, and accumulation at, dams is a continuing problem because dams block the movement of both bedload and entrained material. Most hydroelectric dams have to use trash racks at turbine intakes and often use floating booms to trap wood.

The increase in removal of obsolete dams over the past 20 years has allowed more wood to move downstream and has also revealed large quantities of wood previously submerged in impoundments. For example, after draining the former Carbonton Dam in North Carolina, an upstream bridge within the impounded area was found to be fully blocked by the submerged large wood. The removal of the Great Works Dam from the Penobscot River in Maine in 2011 exposed tree remnants originating from upstream natural transport and sawed timber that was the product of logging drives in the nineteenth century. Large wood was also observed in the pool upstream of recently removed large dams such as Elwha Dam on the Elwha River, Condit Dam on the White Salmon River in Washington, and Milltown Dam on the Clark Fork River in Montana.

Decisions regarding large wood management at dams and dam removals must rely on site-specific analyses of constraints and opportunities, but it is clear that dropping wood immediately downstream of existing structures can represent a financially and ecologically effective strategy, and that allowing exposed wood to route itself passively following a dam removal can help attenuate sediment pulses and provide valuable habitat complexity.

5.6 Watershed-Scale Risk to Structures

5.6.1 System-scale and Local Large Wood Sources

The primary sources of large pieces of wood in rivers are forested riverbanks, the top of banks, and adjacent floodplain edges (Diehl 1997). Unstable channels that are widening, degrading, or actively migrating are continually undermining their banks and causing trees to fall into the channel from within the meander belt (Williams 1986) or material contribution zones (Smith et al. 2008). Other trees fall due to age, wind, or ice storms. A single alluvial meander bend on the Pomperaug River with a tall failing bank in Southbury, Connecticut, has been observed to contribute trees with intact root masses annually over the past 15 years.

Additional sources include islands such as observed on large rivers with multiple channel paths such as the Connecticut and Penobscot Rivers. Large loads of wood can originate from colluvial inputs from valley wall mass wasting. Landslides in the Catskill Mountains of New York along Stony Clove Creek and Westkill Creek and in the Berkshire Mountains along Cold River and North River were the source of significant quantities of both large wood and sediment. The valley wall erosion originated from large floods that scoured the bottom of the valley wall and the overlying material slide down the slope and into the river.

5.6.2 Wood Transport to Bridges

Trees that fall into or across river channels tend to align parallel to the flow, with the stump at the upstream end. Observations of floating wood in eastern rivers reveals that smaller wood and logs without stumps tend to float with random orientation to the flow and can pass wide bridge spans and large culverts. Montgomery and Piégay (2003) showed that trees with spreading branches tend to form bed snags, while cylindrical-shaped conifers are more readily transported downstream. For narrow streams, the channel width can be used to estimate the log length that can readily be transported downstream (Lagasse et al. 2010).

In smaller streams and during low flows, the stumps on floating logs drag on the river bed, and the tree may become grounded on existing sediment bars. Sediment then accumulates behind the tree, and the shape and depth of the bar changes. Grounded large wood creates channel roughness and hydraulic diversity that improves habitat. As sedimentation takes place and the level of embeddedness increases, grounded wood can remain in place for decades until it decays into smaller pieces or a large flood mobilizes the wood again.

5.6.3 Critical Wood Size

The risk of a large wood blockage is a function of the structure size and alignment, large wood dimensions, channel width, and watershed wood yield (Lagasse et al. 2010). Large tree trunks and branches that are longer than the channel width tend to get caught on the banks or on meander bends and remain in place unless a large flood takes place. Wood that is shorter than the channel width will tend to regularly get transported downstream during frequent floods. If the wood is very small, it will likely be transported through bridges and culverts unless they are very undersized. Undersized structures are common. A review of over 3,000 culverts in Vermont indicated that over 25% of structures were less than half the channel bankfull width (Schiff et al. 2008b). Higher risks are associated with medium-sized wood that is shorter than the channel width and so can readily be transported downstream but is prone to accumulation at undersized structures (Gurnell et al. 2002).

Once a jam begins with blocked key pieces of large wood, smaller brush, leaves, and bedload sediment add to the mass and can clog a structure rapidly. In this way, a small number of large logs near a structure and an abundance of small wood delivered from upstream can lead to structure clogging and failure.

5.6.4 Bed Forms

At the reach scale, wood in rivers influences the shape and size of the channel cross section, pattern, and profile. Pools can be formed upstream of large wood elements or jams that create local dams. Scour holes are common along, under, or just downstream of large wood. Wood also influences sediment bars and flood benches located next to the wetted channel. Wood deposits on floodplains and inside channels affects overbank flows approaching bridges and culverts, while woody debris along the banks affects lateral floodplain connectivity. Excess wood in channels prone to deposition, such as braided and anastomosed stream types (Rosgen and Silvey 1996), can have a strong influence on sediment deposition and flow patterns. Conversely, bedform morphology helps determine stability and transport characteristics of individual and massed wood elements; the ratios of rootwad and crown diameters relative to depth to riffle crests and other bedforms at various flood stages are important determinants.

5.6.5 Floodplain Wood

Large wood can both establish and isolate floodplains from channels. Large deposits of wood of in-channel wood can elevate the channel bed and establish more frequent floodplain connection. In appropriate areas, more floodplain connection is beneficial in spreading floodwaters, depositing sediment, and creating areas for nutrient uptake. Frequent floodplain inundation is also important for diversifying riparian habitat for birds and wildlife that rely on river corridors.

Large wood deposits that increase the inundation frequency of floodplains in developed areas can lead to property and infrastructure damages. During floods they can disconnect secondary channels, raising floodwater levels. During Tropical Storm Irene, wood inputs from landslides on the Cold and Chickley Rivers blocked the channel around the Charlemont Island in the Deerfield River leading to flood damages in the area. Along Bushkill Creek in New York, wood preferentially accumulated along the top of banks during Irene, limiting lateral flows from the channel into the floodplain and confining flood flows within the channel that increased risks downstream.

Those issues noted, wood and woody vegetation on floodplains perform many functions. They trap wood and mobile ice during overbank flows that might otherwise clog stream crossings. They attenuate floodplain flow velocities and, at wide distribution, can reduce the risk of channel avulsions. They induce sediment and propagule deposition of floodplains, creating in many settings optimal conditions for self-revegetation.

Finally, they create microtopographic diversity on floodplains with consequent beneficial effects on habitat diversity.

5.6.6 Spoil Piles

Wood that has been cleared from channels approaching bridges and culverts and disposed of along the banks can interfere with structure hydraulics, confine floodplain flow, encroach on the channel, and create higher scour potential. Large wood that is cut and disposed of along road embankments across floodplains can lead to increased downstream jamming at structures.

CASE STUDY

Wood Recruitment and Structure Damage During Tropical Storm Irene

Tropical Storm Irene moved across eastern New York, western Massachusetts, and Vermont on August 28, 2011, damaging hundreds of miles of highways and hundreds of bridges. The storm caused flooding that inundated entire valley bottoms and caused channel erosion and floodplain enlargement. Landscape changes also included many landslides on forested valley walls that generated high volumes of large wood inputs to channels that blocked bridges and culverts leading to structural failures.

In New York, a 500-year-frequency flood with unit discharges of 860 cubic feet per second per square mile of watershed along Westkill Creek in the Catskill Mountains caused 1.5 meters (5 feet) of bed down-cutting (i.e., degradation) and landslides along 610 meters (2,000 feet) of channel. Large wood clogged structures, bridges failed on Route 42, and sections of the highway were washed away. Large and small wood combined with sediment that obstructed the channel and blocked bridges in the towns of Windham, Maplecrest, and Shandakan. Wood jams contributed to bridge scour and overtopping that damaged numerous structures in the region.

In Massachusetts, four landslides along the Route 2 Mohawk Trail left large wood and debris in the Cold River that contributed to road embankment loss. The wood also caused floodplain blockages along the Deerfield River in Charlemont. The National Guard was mobilized and cleared all of the debris from bridges in Colrain and Buckland.

The upper reaches of Esopus Creek in New York's Catskill Mountains had a unit discharge of 460 cubic feet per second per square mile of watershed. The flood caused channel widening and degradation that generated large volumes of wood from the undermined banks and valley walls. Floodplains were obstructed, channels were jammed, and bridges were blocked and destroyed by scour and overtopped due to wood and sediment loading. Headwater channels such as McKinley Hollow were filled with wood and sediment leading to structure failure and road washout.

A series of three landslides up to 18 meters (60 feet) high along Stony Clove Creek in the Catskill Mountains delivered colluvium and large wood into the channel. Large wood and sediment had to be removed from the downstream channel and bridge at Route 214 in Phoenicia, and the pier at Bridge Street was damaged. Again, all of the large wood was removed from the channel.

5.7 Structure Vulnerability and Design Recommendations

5.7.1 Vulnerability

Bridge and culvert vulnerability to large wood jams and debris is a function of the watershed and channel characteristics and the structure geometry. The debris size and volume depend on the watershed forest type and age and, particularly, the floodplain area within 30.5 meters (100 feet) of the channel.

In high risk areas, the channel banks and floodplain can be inventoried to identify the size and volume of potential wood load. The size of living and downed trees is compared to the channel bankfull width to assess the quantity and size of wood that could be transported. Trees that are longer than the bankfull width are less likely to be transported to structures. Denser, and often older, forests tend to produce more wood at their edges near channels than younger forests in the early stages of succession.

Bridge and culvert clear spans should be compared with the size and amount of potential wood load. Proposed structures should at least span the entire bankfull channel (i.e., structure width >1.0 channel bankfull width) with adequate under clearance for crowns and rootwads.

5.7.2 Increasing Structure Resiliency

Many communities that see natural wood and log jams in rivers express concern about downstream bridges and culverts. Following Tropical Storm Irene, there was a rush to clear every piece of wood out of channels to ensure remaining structures would not clog in the next flood. The flood recovery was marked by a strong reluctance to allow the use of the large volume of wood generated in the flood for restoration purposes such as engineered log jams or bank revetments.

Part of the solution is to increase new structure resiliency by proper sizing to pass wood downstream with reduced risk of blockage and damages. This approach has been shown to be more cost-effective in the long run (Gillespie et al. 2014).

Proper structure sizing includes consideration of transport of water, woody debris, sediment, and ice both in the channel and floodplains.

5.7.3 Improved Bridge and Culvert Design to Pass Large Wood

Removal of large wood and sediment often begins at clogged bridges and culverts following large floods. Material should be removed throughout the entire structure and in the adjacent bankfull channel entering and leaving the structure. The cover over the footings should be reviewed at structures to identify if the structure remains stable following the flood. (See Table 5-2.)

When removing large wood and sediment from bridges and culverts, an acceptable profile needs to be established that will not lead to an erosion face moving upstream (i.e., headcutting) or increase the risk of avulsion. Uniform and gradual slope transitions in and out of the structure should be established.

Replacement of undersized structures that block sediment and large wood should be considered to reduce the risks during future floods (Lassettre and Kondolf 2012).

Table 5-2. Debris Countermeasures for Culverts and Bridges

Measure	Culverts	Bridges
Structural Measures		
Debris Deflector	Structure that deflects the major portion of the debris away from the culvert entrance. Normally "V"-shaped in plan with the apex upstream.	Structure placed upstream of the bridge piers to deflect and guide debris through the bridge opening. Normally V-shaped in plan with the apex upstream.
Debris Rack	Structure placed across the stream channel to collect the debris before it reaches the culvert entrance. Usually vertical and at right angles to the streamflow, but may be skewed with the flow or inclined with the vertical.	
Debris Riser	Closed-type structure placed directly over the culvert inlet to cause deposition of flowing debris and fine detritus before it reaches the culvert inlet. Usually built of metal pipe.	
Debris Crib	Open crib-type structure placed vertically over the culvert inlet in log-cabin fashion to prevent inflow of coarse bed load and light floating debris.	Walls built between open-pile bents to prevent debris lodging between the bents. Typically constructed out of timber or metal material.
Debris Fin	Walls built in the stream channel upstream of the culvert. Purpose is to align the debris with the culvert so that the debris would pass through the culvert without accumulating at the inlet.	Walls built in the stream channel upstream of the bridge to align large floating trees so that their length is parallel to the flow, enabling them to pass under the bridge without incident. Also referred to as a "pier nose extension."
Debris Dam/Basin	Structure placed across well-defined channels to form basin, which impedes the stream flow and provides storage space for deposits of detritus and floating debris.	Structure placed across well-defined channels to form basin, which impedes the streamflow and provides storage space for deposits of detritus and floating debris.
River Training Structures		Structure placed in the river flow to create counter-rotating stream-wise vortices in the wake to modify the near-bed flow pattern to redistribute flow and sediment transport within the channel cross section.
Flood Relief Sections		Overtopping or flow through structure that diverts excess flow and floating debris away from the bridge structure and through the structure.

Measure	Culverts	Bridges
Debris Sweeper		Polyethylene device that is attached to a vertical stainless steel cable or column affixed to the upstream side of the bridge pier. Device travels vertically along the pier as the water surface rises and falls. It is also rotated by the flow, causing the debris to be deflected away from the pier and through the bridge opening.
Booms		Logs or timbers that float on the water surface to collect floating drift. Drift booms require guides or stays to hold them in place laterally.
Design Features		Structural features that can be implemented in the design of a proposed bridge structure. The first feature is freeboard, which is a safety precaution providing additional space between the maximum water surface elevation and the low chord elevation of the bridge. The second feature is related to the type of piers and the location and spacing of the piers. Ideally, the pier should be a solid wall type aligned with the approaching flow. It should also be located and spaced such that the potential for debris accumulation is minimized. The third feature involves the use of special superstructure design, such as thin decks, to prevent or reduce the debris accumulation on the structure when the flood stage rises above the deck. The last feature involves providing adequate access to the structure for emergency and annual maintenance.
Combination Devices	Combination of two or more debris-control structures at one site to handle more than one type of debris and to provide additional insurance against the culvert inlet from becoming clogged.	

Measure	Culverts	Bridges
Nonstructural Measures		
Emergency and Annual Maintenance	Although not always feasible for remote culverts or culverts with small drainage areas, maintenance could be a viable option for larger culverts with fairly large drainage basins. Emergency maintenance could involve removing debris from the culvert entrance and/or an existing debris-control structure. Annual maintenance could involve removing debris from within the culvert, at the culvert entrance, and/or immediately upstream of the culvert, or repairing any existing structural measures.	Emergency maintenance could involve removing debris from the bridge piers and/or abutments; placing riprap near the piers, abutments, or where erosion is occurring due to flow impingement created by the debris accumulation; and/or dredging of the channel bottom. Annual maintenance could involve debris removal and repair to any existing structural measures.
Source: FHWA (2005).		

The hydraulic sizing of bridges and culverts is well established (e.g., FHWA 1985b; VTrans 2001), yet current design guidelines (e.g., UNH 2009; MassDOT 2010) are now turning to geomorphic principles to both naturalize stream crossings and make them less prone to flood damages. Structures commonly fail due to geomorphic incompatibility (Schiff et al. 2008b) such as stream instability (FHWA 2012) and clogging with sediment and large wood (Furniss et al. 1998).

A geomorphic-engineering design approach (Figure 5-7) (Schiff et al. 2014) is recommended to optimize structure size and type so that the river channel form and processes can play out in a more natural way. Structures that are sized at the bankfull channel width or larger are

- Able to convey more water, sediment, large wood, and ice.
- Less prone to clogging.
- Less prone to bridge scour.
- More compatible with a stable channel.
- Able to pass fish and wildlife.

A central theme of the geomorphic-engineering design approach is that bridges and culverts should be sized to operate with a headwater–to-depth ratio less than 1 (i.e., part full) to leave space for sediment and wood. Even with a large volume of historical information indicating that wood and sediment are the primary mechanisms of structure failure, the majority of structure design is still currently done primarily with consideration of only clear-flow hydraulics, leading to recurring public safety, financial, and environmental impacts.

One example of geomorphically based stream crossing design is the USFS stream simulation approach (USFS 2008). Another is presented in the box below.

The potential input of large wood during a flood needs to be evaluated along the channel reach and watershed to know if a structure is prone to clogging. In northern climates, ice can also clog structures. If past flood damages have occurred due to clogging or are suspected due to a high possible wood load during a flood, the bridge or culvert should be designed to fill to 80% of the opening height (i.e., $Hw/D < 0.8$) during clear flow to allow vertical space in the structure to pass sediment, large wood, and ice. Post-flood evaluations of failed structures indicate that structures that were filled or overtopped during a flood were typically damaged due to large wood accumulation and clogging (Furniss et al. 1998) (Figure 5-8).

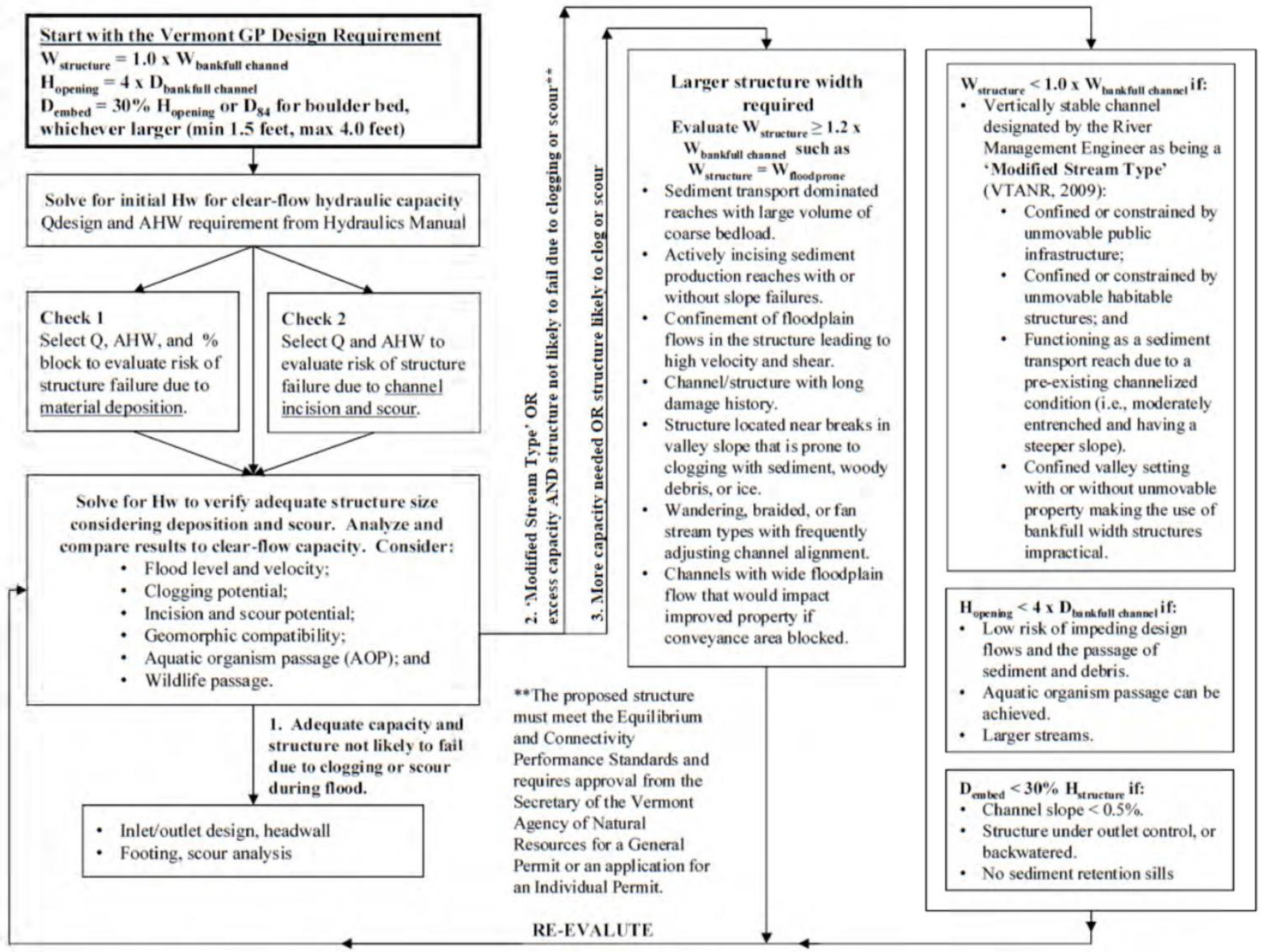
Proper structure design must consider the floodplain setting (i.e., does the channel have broad floodplains or narrow benches?). The floodplain width and frequency of inundation are important to fine tune the structure width to achieve an acceptable flow width during floods. Overflow structures should be considered in broad floodplain settings although structures placed away from the channel and at higher elevations than the banks can be prone to clogging due to slower flow velocities than in the channel.

GUIDANCE

Geomorphic Engineering Design Recommendations Required by the Vermont Stream Alteration General Permit (2013) (Schiff et al. 2014; VTANR 2014).

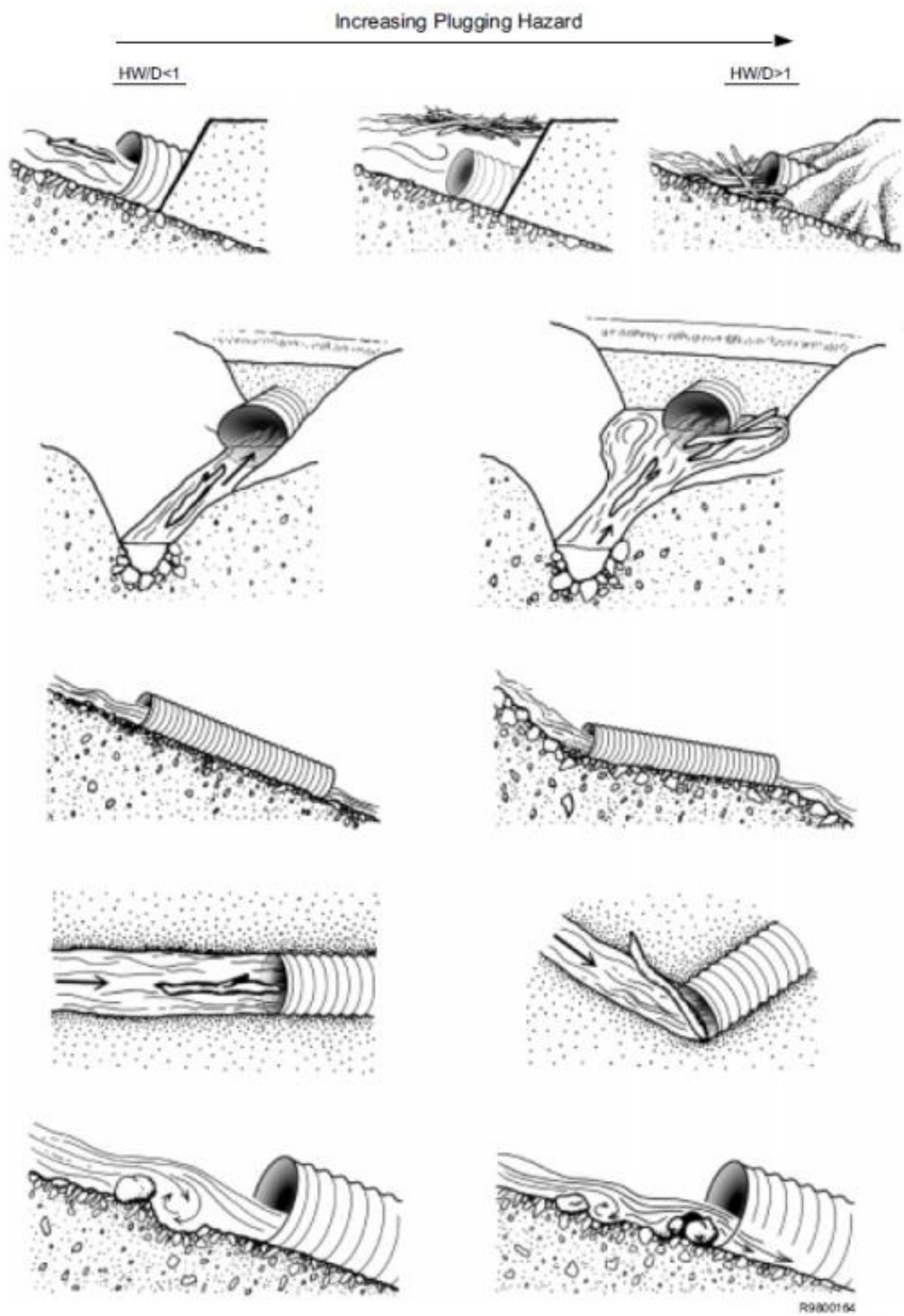
- Wstructure = 1.0 x Wbankfull channel.
- Hopening = 4 x Dbankfull channel.
- Dembed = 30% Hopening or D84 for boulder bed, whichever is larger.
- Match channel profile and create uniform longitudinal transitions at inlet and outlet.
- Structure shall not obstruct aquatic organism passage.
- Evaluate structure for clear-flow hydraulics and perform checks for large wood and sediment deposition and scour.
- Where physical constraints preclude achievement of the 4.0X opening height standard and any potential increase in flooding hazard associated with a reduced opening height will be offset by other factors such as a lower roadway fill height, the minimum opening height shall be > 3.0X the mean bankfull channel depth, as approved by the Secretary of the Vermont Agency of Natural Resources (VTANR), and as specified in the most current version of the Vermont Agency of Transportation (VTrans) *Hydraulics Manual* (2001).
- Where more capacity is needed based on flow, material deposition, or scour, structure width shall be 1.2 x bankfull width or larger (e.g., floodprone width).
- Where channel gradient is 0.5% or less or the structure is under outlet control, depth of embeddedness may be reduced, as approved by the Secretary of the VTANR.
- Retain sediment throughout structure and maintain natural sediment transport.
- Avoid backwatering at inlet and naturalize the movement of large wood and ice.
- Design Q and Hw/Hopening from state hydraulic standards (VTrans 2001).
- Match channel hydraulic conditions for design flood, fish passage, and low flows.
- Align structure parallel to flow in channel.
- Maximize fish and wildlife passage.

Figure 5-7. Geomorphic Engineering Structure Sizing Method



Source: Schiff et al. (2014)

Figure 5-8. Schematic of Culvert Performance at Varying Stages and Alignments



Source: Furniss et al. (1998)

5.7.4 Additional Bridge and Culvert Design Considerations

Traditional debris jam mitigation strategies focus on bridge design, debris source control, and debris shedding/passage at structures. Many debris problems at bridges and culverts can be reduced through proper design of new structures. Specific techniques for new bridges include the following considerations.

Wide Channel Span – Bridge and culverts should span the entire active bankfull channel and minimize hydraulic dead zones behind embankments. Bridge abutments should not be located in the channel. For small channels, single spans of up to 24 meters (80 feet) will eliminate the need for mid-channel piers. Where piers are necessary due to wide channels, each span between piers and between the end abutments and piers should exceed the length of expected logs if possible.

Channel Design – A compound channel cross-section with two or three benches is common for concentrating low and moderate flows to promote wood transport through the structure while maintaining a wide floodplain to allow flow to spread out during large floods and deposit wood across the floodplain. A vegetated floodplain will trap wood away from hydraulic openings at structures.

Overflow Structures – Wet and dry side channels in floodplains should have structures in addition to the main channel that pass under the road embankment. Although prone to clogging unless regular maintenance is performed, overflow structures minimize lateral and converging flows and can reduce the wood load to the primary hydraulic opening. Floodplain equalization culverts can be used to convey floodplain flows away from secondary and tertiary channels, whether wet or dry, and can provide passage for terrestrial, amphibious, and aquatic species at minimal risk to travelers.

Pier Locations Out of Main Flow – If piers are needed, they should not be placed at the channel thalweg in the main flow location of the channel or on the outside of meander bends where debris tends to preferentially accumulate.

Ample Vertical Clearance – Bridges and culverts over rivers with significant wood loads should have ample vertical clearance above the design water profile to pass the material without it hitting the top of the bridge or culvert.

No Pier Skew – Bridges that have an alignment skewed to the river should have piers aligned parallel to the flow.

Scour Protection – Scour protection should be provided at piers and abutments where local scour is anticipated due to the anticipated wood load and size of the structure opening. Replacement structures in high risk areas should have deep footings, piles, or armor to reduce the risk of structure damage.

Debris deflection structures may be used, but they require maintenance to keep clean and in functioning order. Debris deflectors are structures installed upstream of the bridge or culvert to redirect wood and ice away from bridges and culverts. Debris fins are one of the more common devices located on the upstream extension of bridge piers. They consist of a sloping wall or series of piles that are at the leading edge of piers and are parallel to the flow. Freestanding piles or fenders are also used to redirect large wood. Debris racks can be used to block wood accumulation from a structure. Racks are porous steel bar or concrete structures that are inclined or skewed to deflect debris. Proper structure design is preferred over debris trapping structures.

5.8 Floods, Recovery, and Large Wood

Some of the information in this section has been adapted from the Vermont Standard River Management Protocols (Schiff et al. 2014; see http://www.anr.state.vt.us/dec/waterq/rivers).

5.8.1 Large Wood Assessment

After a flood, an evaluation of the load of large wood must be completed within the context of the watershed wood budget of source, transport, and retention. A channel survey or flight to document the size and distribution of channel-spanning jams and smaller deposits should be performed. The following information is typically collected to describe post-flood large wood accumulations:

- Location in or near structure, channel, or floodplain (GPS if possible).
- Photo-documentation.
- Number of pieces and lengths.
- Dimensions, area, and volume (small, medium, or large) (Bradley et al. 2005).
- Embeddedness.
- Prediction of stability.
- Distance and proximity to nearby property and infrastructure.
- The remaining load from accumulated or sources or recent mass failures.

A stream walk and sketch with notes is helpful to document the post-flood large wood load. A tally form can be used to count and size large wood pieces and jams (e.g., Schiff et al. 2008a).

5.8.2 Large Wood Alternatives Analysis

A primary objective of the post-flood assessment is to develop a list of wood retention/removal alternatives to avoid the unwarranted wholesale removal of large wood that is often performed out of habit, fear of future damages, and ease of construction. Large wood removal often leads to long-term channel destabilization due to removal of large elements that provide hydraulic friction, stabilizing bed features and dimensional morphology. Large wood is essential to stabilize both the channel bottom and banks in most channel types.

Removal of large wood also leads to loss of habitat, so limiting wood removal is recommended. Many channels with watersheds having young forests lack regular inputs of large wood; thus, pulses delivered through material contribution zones (Smith et al. 2008) or mass wasting events during floods are critical to long-term habitat formation and maintenance.

RISK
Large wood accumulations should be assessed to see if they pose high, moderate, or low risk during future floods (Homer et al. 2004). Do not default to removing all of the large wood from post-flood channels and floodplains as some likely does not pose a risk during future floods (Table 5-3). If the transport potential of wood is small, the material will remain in place over time and can have a positive effect on habitat and stability with relatively low risk to downstream infrastructure. If large wood is highly mobile, it can lead to high risks downstream and should be removed. Tyler (2011) provides a flow chart for predicting the likelihood of wood transport. When evaluating risk, consider that large wood mobilized in a flood can commonly be deposited on the nearest downstream bar (Bertoldi et al. 2013). Cut large wood on small bars that is likely to be highly mobile into small pieces so it may pass through downstream structures and remain in the ecosystem.

Large jams that could lead to avulsion, bank erosion, or clogging of downstream structures due to sudden release should be removed. Large trees should be stockpiled for future habitat restoration work if storage space is available (NRCS 2007e).

Table 5-3. Large Wood Removal Recommendations

Risk Level	Risk Description	Recommendation
HIGH	Channel-spanning large wood jams with altered flow path and high risk of avulsion. Remobilization of large amounts of wood and downstream structure clogging likely. Structure completely or mostly clogged.	Remove large wood jam.
HIGH TO MODERATE	Large mid channel or bank accumulations of large wood. Flow path may be altered, but risk of avulsion is low. Remobilization of a large amount of large wood and downstream structure clogging likely. Structure partially clogged.	Remove large wood.
MODERATE	Large mid channel or bank accumulations of large wood. Flow path may be altered, but risk of avulsion is low. Remobilization of a large amount of wood is not likely.	Leave large wood in place.
LOW	Bank accumulations of large wood jam or individual embedded pieces of wood in channel. Flow path may be altered, but risk of avulsion is low. Remobilization of large wood not likely.	Leave large wood in place.
Source: Adapted from Homer et al. (2004) and Schiff et al. (2014).		

The combined understanding of the distribution of large wood (e.g., Magilligan et al. 2007), the wood budget, the potential for additional transport to an area, the stability and roughness benefits offered by wood in channels and floodplains, and the concurrent potential risks posed by the accumulations will allow for a proper alternatives analysis. A range of large wood retention and removal alternatives should be considered for design and implementation, and assessment should be in concert with consideration of stream crossing retrofits and replacements to improve wood conveyance.

- All wood left in place if little or no risk to property or infrastructure exists.
- Selective removal of wood upstream of bridges and culverts.
- Selective removal of large wood jams that are not embedded and likely to mobilize and create downstream flood and erosion risks.
- Cutting of larger pieces to allow for safe future passage through structures in the event of transport.
- Removal of all wood from the channel, but all wood left on the floodplain to slow flood flows, catch sediment, and create seed propagule areas.
- Wholesale removal of wood from the channel and floodplain in areas with abundant risk to bridges and culverts, or in channels prone to avulsion into areas with improved property.

5.8.3 Large Wood Flood Recovery Design

GUIDANCE

Goals of Large Wood Retention or Removal

- Reduce flood and erosion risks
- Improved long-term channel stability
- Maintain or improved instream habitat
- Protect water quality

Design Considerations for Large Wood Removal

- Retain standing trees with intact roots on the banks and floodplain.
- Minimize large wood removal to limit channel and ecosystem impacts. Individual pieces, side bar accumulations, or mid-channel accumulations of wood can remain that will not dictate hydraulics or clog structures. Large wood should be retained in the post-flood bankfull channel where possible.
- Remove large or channel-spanning wood jams that alter flow path and increase the chance of avulsions or future clogging of the downstream channel or structures.
- Retain large wood jams with limited risk of full movement such as those wedged on the upstream end of islands or in large stable jams (Ravazzolo et al. 2015). Wood on smaller bars is likely to move in more frequent floods. Jams far from infrastructure can be left in place to decay and disperse material downstream.
- Stockpile cleared trees with diameter >30 centimeters (12 inches) for future use in channel or floodplain stabilization or restoration. Intact root balls are preferred.

Standing and rooted trees in the river corridor should not be removed following a flood. A common misperception exists that these pose uniform and hazardous threats during floods. Standing trees reduce bank erosion and typically decrease flood risks by slowing flow velocity and reducing erosion. They also catch sediment and downed wood and hold it on the floodplain instead of allowing all material to deposit in the channel.

Rootwads and tangles of large trees remaining on the banks should not be excavated. It is usually preferable to cut trees that must be removed 2 to 3 meters (6 to 10 feet) above the base of the trunks to remove only the upper sections. The remaining roots will hold the bank together. Minimize the use of large machinery in the channel and the number of access points to control impacts.

Large wood removal has historically been performed without proper design or consideration of resultant flood and erosion risks. There is a high degree of experience with removal of large wood, but the assessment, alternatives analysis, and design approach identified here will be new to most designers and construction crews. A detailed plan review during a preconstruction meeting and frequent construction oversight at the beginning of the project are essential for proper implementation of large wood removal, retention, or re-utilization.

GUIDANCE

New York Large Wood Removal Guidelines

The New York Department of Environmental Conservation (2014) provides recommendations for post-flood wood management in rivers. They recognize that woody debris such as trees and branches are an important part of healthy stream systems, providing habitat, roughness, energy dissipation, and slowing floodwater. Wood should be left in place unless it endangers infrastructure.

The guidelines state that woody debris and trash can be removed from a stream without an Article 15 Protection of Waters Permit due to lower risks of impacts under the following conditions.

- Fallen trees and debris may be pulled from a stream by vehicles and motorized equipment operating from the top of streambanks using winches, chains, or cables.
- Handheld tools such as chainsaws, axes, hand saws, etc. may be used to cut debris into smaller pieces.
- Downed trees still attached to streambanks should be cut off near their stumps. Do not grub (pull out) tree stumps from banks. Stumps keep streambanks from eroding.
- All trees, brush, and trash removed from a channel should be removed from the floodplain as well. Trash should be properly disposed at a waste management facility. Trees and brush can be used as firewood. To prevent the spread of invasive species such as the emerald ash borer, do not move firewood more than 80 kilometers (50 miles) from its point of origin. DEC has additional information on invasive insects.

Projects likely to disturb a streambed or banks and using motorized vehicular heavy equipment in the stream channel or anywhere below the top of banks require either a Protection of Waters Permit or an Excavation or Fill in Navigable Waters Permit.

5.9 Climate Change

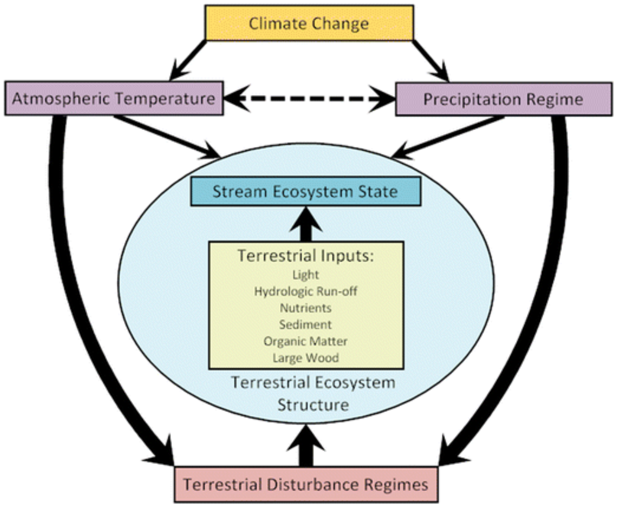
5.9.1 Climate-Driven Processes Related to Large Wood

In riverine ecosystems, a variety of ecological processes are influenced by climate. The climate can have direct temperature or precipitation impacts, as well as indirect impacts through effects on terrestrial inputs (e.g., large wood, nutrients, and sediment), structure and species composition, and disturbance regimes (see Figure 5-9). Different aspects of climate, such as climate averages, extremes, or variability, may be relevant to particular ecological processes.

Atmospheric temperature influences water temperature, which has direct effects on aquatic species. Temperature regulates metabolism, distribution, and abundance of individual aquatic species. Average temperatures influence habitat suitability for riverine species, and temperature extremes may limit species' ranges due to physical tolerances. Species distribution and abundance also affects biotic interactions, including predator-prey and competition; disruption of these interactions can alter the ecosystem function and services.

Flow regime in a river controls or influences many biological processes, such as reproduction and migration, as well as the physical environment (Wenger et al. 2011). Streamflow also influences water temperature, nutrient concentrations, and sediment. Streamflow quantity impacts the extent of available aquatic habitat, while variability in streamflow regulates species abundance and persistence.

Figure 5-9. Pathways by Which Climate Change May Alter Stream Ecosystem Structure and Function



Climate change will have direct effects on temperature and precipitation regimes, which will influence indirect effects of terrestrial disturbance that will alter terrestrial ecosystem structure. Changes in terrestrial ecosystem structure will in turn alter terrestrial inputs to streams. Source: Davis et al. (2013).

Precipitation is central to flow regime, directly through surface runoff and rainfall inputs, as well as through soil moisture and groundwater recharge in a watershed. Extreme high precipitation is directly related to flooding and high flow rates. Extreme low precipitation can also be a primary driver of drought, leading to extreme low flows in aquatic systems, stressing organisms. Extreme precipitation can be defined many ways, such as a total threshold amount in an event (i.e., 50 millimeters [2 inches]) or rate (i.e. 10 millimeters/hour [0.4 inches/hour]) or relative to historical averages (i.e., greater than 90% or less than 10% of all other events in the historical record).

Terrestrial disturbances in a watershed are connected to the processes in the aquatic environment and affect terrestrial inputs. Climate plays an important role in terrestrial disturbance, including wildfires, landslides, drought, and insect outbreaks. Extreme high temperatures and extreme low precipitation contribute to wildfire frequency and intensity, which leads to large wood inputs to riverine systems. Extreme precipitation events can trigger landslides, especially when following a wildfire (Cannon and DeGraff 2009). Change in average temperature and increases in minimum temperatures are known to control insect outbreaks, such as with bark beetles in boreal forests (Bentz et al. 2010), which also influence large wood inputs. Extreme winds are also known to contribute large wood to riverine systems (CCSP 2008b). Nutrients carried by runoff following average and extreme precipitation events impact riverine systems, and may lead to an oversupply of nutrients that leads to spread of harmful invasive species or decreased habitat quality. Sediment inputs from surface runoff and high-flow events also impact riverine systems, altering water quality.

The structure and species composition in the terrestrial environment is influenced by climate and is important to the potential for large wood inputs into riverine systems. Structure of watershed vegetation and species composition also affect the infiltration of water, soil moisture, groundwater recharge, and erosion patterns (Davis et al. 2013). Average temperature, average precipitation, seasonality and timing of seasons, and disturbance regimes can all influence the terrestrial structure and species composition in a watershed.

5.9.2 Recent and Future Climate Change

Climate change refers to any significant change in the measures of climate lasting for an extended period of time (usually decades or longer), including major changes in temperature, precipitation, or wind patterns, among other effects. Projected changes in such climatic variables will potentially impact ecological processes related to large wood. Changes may be related to long-term averages, variability, and extreme events. The characteristics of extreme events vary from place to place, but are generally defined as rare occurrences within a statistical reference distribution (e.g., rarer than the 10th or 90th percentile) at a particular place (IPCC 2007). While a single extreme event may not be directly attributed to climate change, the long-term trend of more frequent and severe weather events is projected under climate change for the United States (USGCRP 2009), and decisionmakers should consider this trend to adequately prepare for future risks to ecosystems and infrastructure from large wood in streams.

A variety of climate information may be relevant to decisions regarding large wood in restoration projects. This information spans a range of time scales and different geographies, and can include historical and current observations, and modeled projections of possible future conditions for variables such as temperature and precipitation. Projections of future climate over the next century are not precise forecasts; considering output from multiple models, over multiple scenarios and time periods provides insight into the range of possible future conditions (see Knutti et al. 2010).

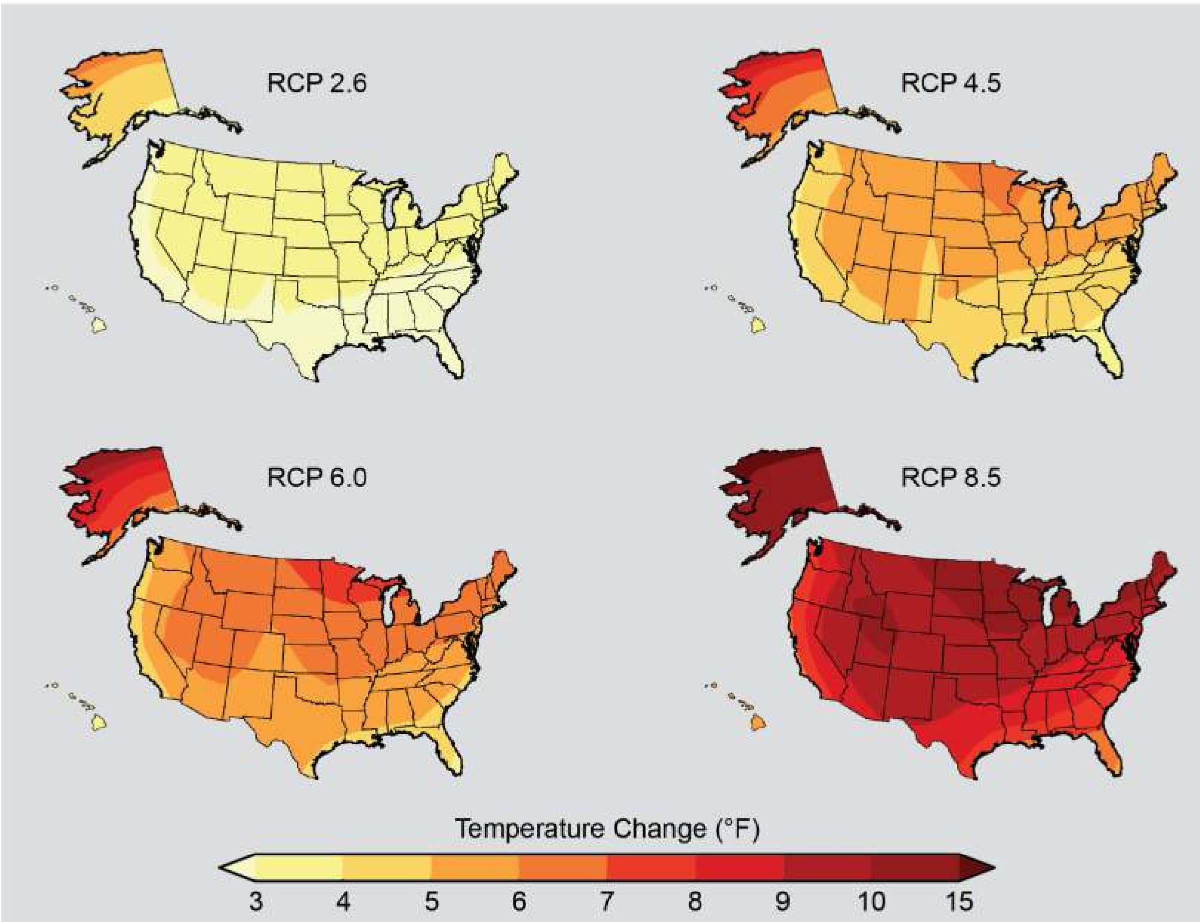
Data on possible future climate conditions are maintained and collected by numerous institutions including universities, federal and state climate agencies, and other organizations working on climate change. Building a formal or informal network that includes decision-makers and information providers can help improve the ability to plan for changes in climate and extreme events. While many different types of climate information exist, restoration planners and decision-makers should focus on the specific decision of interest to guide their use of this information. For example, in a remote area of low-value habitat where a rapid assessment is needed, knowing if the area is likely to become wetter or drier in the future may be sufficient to inform planning. In other cases, such as where there are species of concern and critical human infrastructure, more detailed information on precipitation, temperature, and extreme flow conditions and trends may be necessary. A two-way dialogue with information providers can help ensure that the best available information is applied (planners and decision-makers get information) and available (information providers collect and create useful results).

While many of the connections between ecosystems and climate are well understood, there is uncertainty in projecting future climate conditions and ecosystem response. Sources of uncertainty include climate model uncertainty, the future greenhouse gas concentration pathway, climate sensitivity, novel ecosystem conditions or thresholds, and biotic interactions and feedbacks. Each of these sources of uncertainty is an active area of research. Communication with information providers and other stakeholders can improve the understanding of these uncertainties and how to address them, if necessary. This dialogue can also help build capacity to update and adapt plans over time as conditions change or new information becomes available.

Recent changes in temperature have been observed in many parts of the United States, with water temperature increasing in some rivers (Kaushal et al. 2010). Average temperatures are expected to increase across the United States by the later part of the century (2071–2099) relative to historical (1970–1999) averages (see Figure 5-10). While temperature increases have been observed in all parts of the country, regional variations in the magnitude of warming are projected (Melillo et al. 2014).

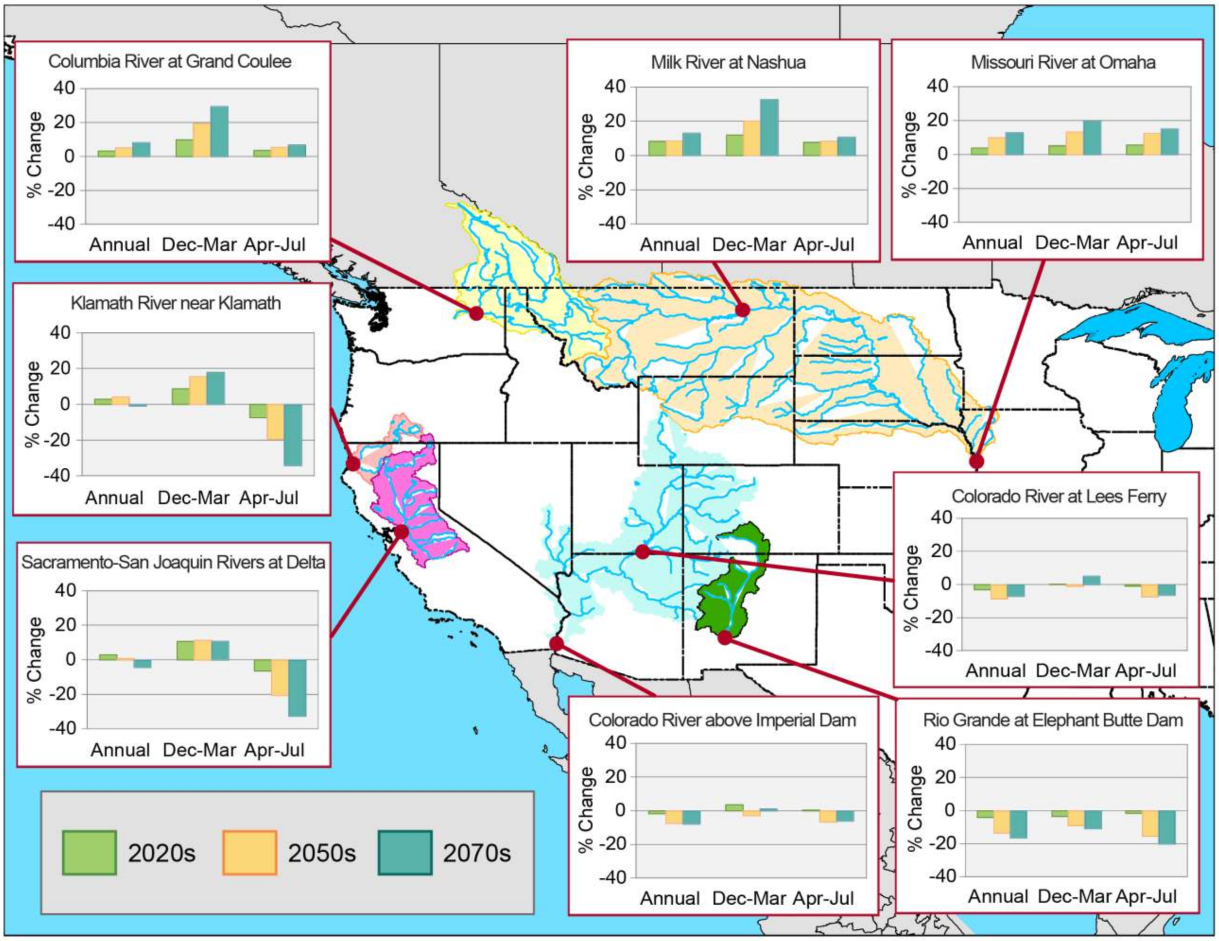
Changes in climate are already altering the water cycle in multiple ways over different geographic areas and time scales (Mellilo et al. 2014). By the middle of the century (2040–2070), changes in runoff and related river-flow are projected in many parts of the United States relative to the historical patterns (1971–2000). Spring runoff is projected to decline in the southwest and southern Rockies (e.g., the Rio Grande and Colorado River basins) and southeast (Figure 5-11; U.S. Department of Interior—Bureau of Reclamation 2011). In many cases, the projected changes in streamflow are outside the range of historical variability (Melillo et al. 2014). In the northwest to north-central United States, basins like the Columbia River and Missouri River are projected to see little change by the middle of this century, with some potential increase by the end of the century. Soil moisture is also projected to decrease across the southwest, which would impact flow regime.

Figure 5-10. Projected Temperature Change by 2071–2099



The largest uncertainty in projecting climate change beyond the next few decades is the level of heat-trapping gas emissions. Results are shown for four Representative Concentration Pathways (RCP): a low scenario that assumes rapid reductions in emissions (RCP 2.6); a high scenario that assumes continued increases in emissions (RCP 8.5) and the corresponding greater amount of warming; an intermediate scenario RCP 4.5; and RCP 6.0. Projections show change in average temperature in the later part of this century (2071–2099) relative to the late part of last century (1970–1999). Source: Melillo et al. (2014).

Figure 5-11. Streamflow Projections for River Basins in the Western United States



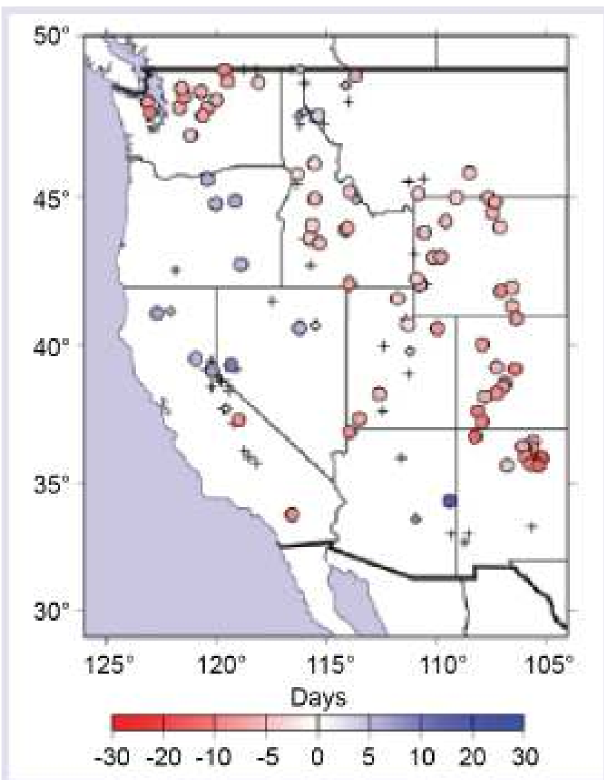
Annual and seasonal streamflow projections are based on possible climate scenarios for eight river basins in the western United States The panels show percent change in average runoff. Projections are for annual, cool, and warm seasons, for three future decades (2020s 2050s, and 2070s) relative to the 1990s. Source: Melillo et al. (2014) after U.S. Department of the Interior – Bureau of Reclamation (2011).

In mountain watersheds, warming under some scenarios is projected to directly affect flooding even in places that are not projected to have an overall increase in precipitation, due to more precipitation falling as rain rather than snow, or more rain falling on the snowpack (Knowles et al. 2006). Rainfall on snowpack can also affect the timing of peak runoff. In much of the western United States, earlier peak river levels have already been observed in snowmelt-fed rivers (see Figure 5-12), which are related to rain on snow, as well as other influences like dust and soot on snowpack and natural variability (Creamean et al. 2013). River flooding is not only driven by precipitation, as pre-existing soil moisture conditions, topography, and other factors, including human-caused changes, influence flooding in a basin-specific manner (e.g., Poff et al. 2006).

The extent of area burned in wildfires in the continental United States has significantly increased from 1987–2003 compared to the period from 1970–1986 (Westerling et al. 2006), due to multiple factors, including management practices that allowed fuel build-up and changes in temperature and precipitation in some regions (Melillo et al. 2014). Projections of future wildfires are difficult due to regional differences in seasonality of fire activity. There is a direct connection between land surface drying due to increases in temperature and increases in the size and intensity of wildfires (Westerling et al. 2003).

Increases in wildfire activity, particularly in the western United States, are correlated with earlier snowmelt, longer growing seasons, and higher summer temperatures (Westerling et al. 2006).

Figure 5-12. Changes in Timing of Streamflow from Snowmelt



Red dots indicate stream gauge locations where half of the annual flow is arriving from 5–20 days earlier (2001–2010 compared to 1951–2000 average). Blue dots indicate locations where annual flow is arriving later (2001–2010 compared to 1951–2000 average). Crosses are locations where observed changes are not significantly different from the past century baseline (90% confidence level); dots and diamonds indicate where timing is different (95% and 90% confidence level, respectively). Source: Melillo et al. (2014, page 768, Appendix 3).

Drought is expected to intensify in many parts of the United States due to longer periods of dry weather and more extreme heat (Melillo et al. 2014). More intense drought would lead to more moisture loss from plants, potentially affecting the risk of wildfire and large wood inputs to riverine systems. Long-term drought conditions (multi-season) are projected to increase in part of the southeast United States (Melillo et al. 2014).

5.9.3 Potential Climate Change Impacts on the Riverine Environment and Built Infrastructure

The water cycle is dynamic, and riverine ecosystems are able to maintain a healthy and self-sustaining condition in the face of large year-to-year variation in temperature conditions. However, in many places the range of projected changes in climate may lead to impacts that exceed the natural resilience of these ecosystems (CCSP 2008b). If the rate of climate change outpaces the ability of plant and animal species to adjust to temperature changes, population loss or extinction may result (Loarie et al. 2009).

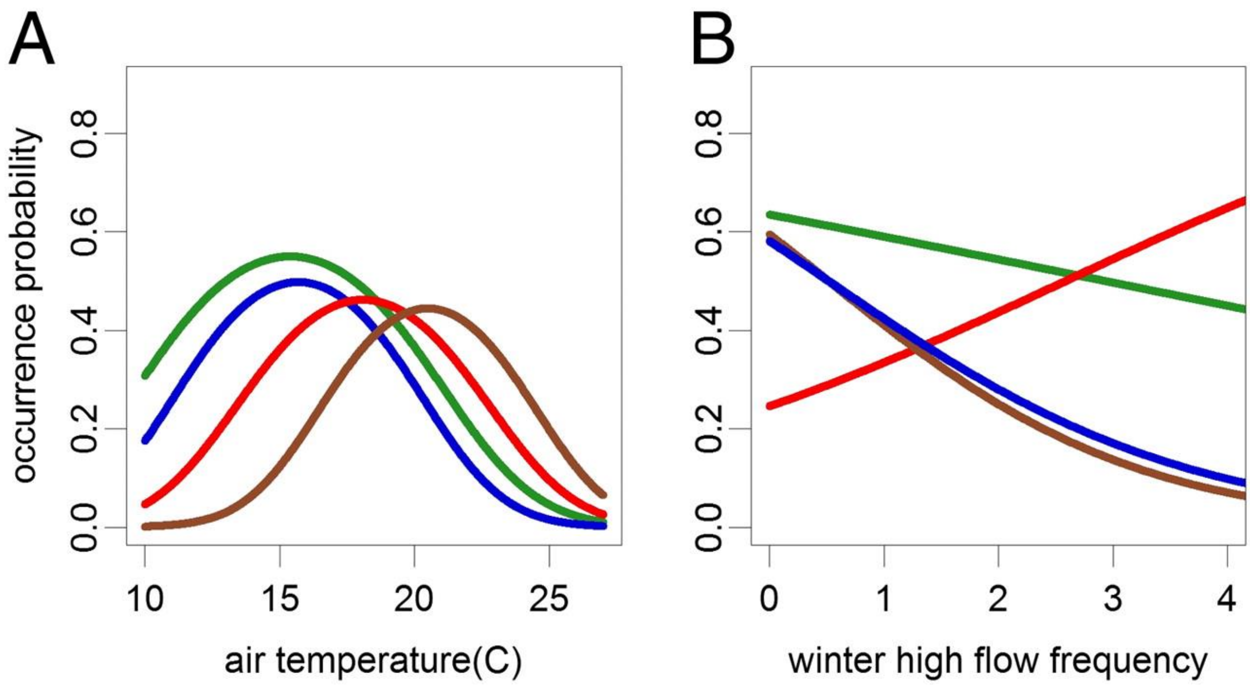
Habitat fragmentation, pollution, increased urbanization, and other stressors will interact with climate change, exacerbating the level of impact (CCSP 2008b). In the western United States, this includes increasing vulnerability due to projected increases in drought and water shortages (Falke et al. 2011). In southern states, projections are less certain but include potentially drier conditions, and the impacts may be greater due to interactions with projected increases in water withdrawals (Melillo et al. 2014). Irruptions of forest pests have increased tree mortality in many regions and may affect wood loading rates significantly.

The combined impacts of projected climate change and water withdrawals can lead to habitat loss and local extinctions of fish and aquatic species (Spooner et al. 2011). Climate impacts that result in changes to vegetation or stream hydrology will likely also affect instream wood, and the potential for small streams to form dynamic aquatic habitat (Hough-Snee et al. 2014). For example, trout habitat in the interior western United States is projected to decrease by 2080 under several different possible future climate scenarios (Wegner et al. 2011; see Figure 5-13). The projected impact on four trout species is driven not only by changes in water temperature beyond physiological optima, but also potential shifts in flow regime and biotic interactions, which are projected to change with climate (Wegner et al. 2011).

It is likely that temperature, flow regime, and biotic interactions will have a strong influence on changes in species distribution in response to climate change (Wenger et al. 2011). However, additional research is needed on the role of biotic interactions in changes in species distribution in response to changes in climate (Wenger et al. 2011).

The projected possible changes in timing of peak flows and runoff conditions can impact riverine ecosystems, as well as the operation, maintenance, and service of water management infrastructure. Water management plans and policies designed to provide adequate service and meet regulation for human use and environmental flows may not be adapted to possible future conditions (EPA 2013). In addition, ecosystems provide important services for improving water quality and regulating water flows, which are projected to be impacted by projected changes in climate (Melillo et al. 2014).

Figure 5-13. Occurrence Probability of Trout Species as a Function of Air Temperature and Winter High Flow Frequency



Projected loss of suitable habitat is driven by possible changes in climate that impact temperature and winter flooding (caused by warmer, rainier winters). Green indicates cutthroat trout; blue indicates brook trout; red indicates rainbow trout; and brown indicates brown trout. Source: Wegner et al. (2011).

Climate change, in combination with existing environmental stressors, is overwhelming the capacity of some ecosystems to recover from impacts from major disturbances, such as wildfires, floods, and storms (Melillo et al. 2014). Projected changes in climate may alter disturbance regimes, such as fire, landslides, and insect outbreaks (CCSP 2008b), which can alter the terrestrial inputs into riverine ecosystems. Reductions in forest cover or leaf area due to disturbances will likely alter the hydrology in a watershed (CCSP 2008b), which will impact riverine ecosystems.

Potential increases in flood magnitude or frequency could lead to impacts on terrestrial inputs to riverine systems. For example, more intense overbank flooding may change patterns of sediment erosion and deposition, resulting in transitions in riparian vegetation from large long-lived conifer trees to early-successional shrubs that do not contribute large wood to the riverine ecosystem (Hough-Snee et al. 2014). The flood regime also alters the stream power and channel geometry, and potential changes to the hydrologic regime would therefore affect wood mobility (Hough-Snee et al. 2014).

Possible changes in fire regime may lead to transition in forest vegetation toward early-seral species, altering the contribution of large wood to channels (Hough-Snee et al. 2014). Intense forest fires can also increase sediment production and water yield as much as 10 to 1,000 times (CCSP 2008b), impacting the riverine environment.

Changing climatic conditions, along with other drivers of change, can impact distribution and success of invasive species in a watershed (CCSP 2008b). The ability to outcompete in novel climate conditions will lead to altered forest stand composition. The species composition controls aspects of terrestrial inputs, including large wood, to riverine systems. Invasive species may also alter watershed erosion regimes due to shallow root systems, altering sediment inputs, as well.

Insect outbreaks, driven at least in part by changes in climate, are already having a significant impact on forests in the United States. In particular, bark beetles have damaged boreal conifer forests in the western United States, with higher temperatures allowing more beetles to survive the winter and to extend their range to higher elevations and more northern latitudes (Raffa et al. 2008), such as new areas in the Greater Yellowstone Ecosystem (Logan et al. 2010). The damage to forest areas can alter fire regimes and terrestrial inputs of large wood into riverine systems. Insect outbreaks can also increase base flows and advance the timing of peak runoff, resulting in impacts on riverine ecosystems (CCSP 2008b).

The increased intensity in individual precipitation events will likely affect transportation and stormwater infrastructure. Bridges, culverts, and other stormwater infrastructure will be vulnerable to the impacts of precipitation and flooding from higher water levels, increased flows, scour, sedimentation, etc. (CCSP 2008a). Runoff resulting from such events could lead to increased peak streamflow, which could affect the sizing requirement for bridges and culverts (CCSP 2008a). Historically, bridges and culverts have not been designed well enough to convey sediment and large wood, much less deal with increased flood peaks (see Figure 5-14). Both disaster planning and restoration efforts should consider replacing inadequately sized stream crossings and restoring riparian forests and stable instream large wood to attenuate flood peaks.

The accumulation of large wood and transportation of material downstream can pose risks to infrastructure. Large wood is a concern for highway engineering planning because it can accumulate at and obstruct the waterway entrance of culverts or bridges, adversely affecting the operation of the structure or causing failure of the structure.

Figure 5-14. Wood Inhibiting the Flow of Water through a Culvert under Highway 4 Following the Las Conchas, New Mexico Fire (2011)

Source: Jake Quintana, USFS.

5.9.4 Large Wood Contribution to Reducing Climate Vulnerabilities in Riverine Ecosystems and Built Infrastructure

Many of the important roles that large wood debris plays in riverine ecosystems also can reduce the vulnerability of riverine ecosystems to impacts from climate change. Large wood influences the physical condition of riverine ecosystems, including the temperature, hydrology, and sediment load. Potential increases in water temperatures with future climate change can be moderated by large wood placements. The effects of large wood in raising local water elevations, scouring bed, and creating low-velocity refugia can provide protection to aquatic species and habitat against the possible increase in duration and intensity of drought in some regions, like the southwestern United States Increases in floodplain connectivity due to the presence of large wood in rivers may also increase resilience of aquatic species to direct impacts of climate change on habitat quality within certain portions of a watershed. Increases in sediment load due to indirect effects of climate change can be modulated by large wood, which is known to effectively trap sediment. The increase in connectivity between rivers and groundwater (i.e., hyporheic exchange) due to large wood may provide a buffer to riverine habitats against nutrient loading and thermal impacts from climate change (Sawyer et al. 2011).

Large wood also influences the biological condition of riverine ecosystems, which can reduce the vulnerability to climate change. Large wood placements can improve biological structure and ecosystem productivity, improving resilience of these systems to indirect impacts from changes in terrestrial disturbance. Complex cover provided for aquatic organisms and improved water quality also can improve habitat quality, reducing some of the impact from climate change, such as higher temperatures and changes in species composition.

Restoring stream corridors with mature timber helps attenuate the effects of fires and debris flows by trapping sediment and debris before it reaches areas with infrastructure. Trees in riparian areas tend to be more resistant to fires because they have higher soil moisture; in many recent western fires, riparian corridors acted as critical fire breaks. Fires tend to burn tree canopies and leave most of the trunk, so if trees are mature they are more likely to provide stable wood to the channel.

Heavy precipitation events can increase the flow velocity and flow depth of a stream or river, which can affect local scour depth. During flood conditions, if the stream elevation reaches the low cord bridge elevation, the local scour depths could be increased by 200 to 300%. Using stable large wood placements will help to restore streams, increase flow resistance, partition shear stress, and slow flood peaks (Fischenich and Morrow 2000; Anderson 2006; Abbe and Brooks 2011), protecting downstream bridges.

Large wood in channels can be maintained by enlarging infrastructure (e.g., culverts and bridges) to allow large wood passage downstream and reduce risks to downstream infrastructure. Designing bridges and culverts to withstand more frequent and severe storm events (e.g., 500-year events rather than 50-year events) can allow for enhanced passage of large wood under and through this infrastructure. The American Association of State Highway and Transportation Officials Load and Resistance Factor Design specifications require that scour at bridge foundations be designed for the 100-year flood, while some bridges should be designed to withstand the 500-year flood (the "super flood") (Ghosn et al. n.d.).

In addition to changing the design of infrastructure, measures can also be taken to reduce the impact of large wood on bridges and culverts. Both structural and nonstructural measures can be used to mitigate the effects of large wood and protect infrastructure (see Table 5-2). Structural measures either prevent debris from entering or blocking passageways, or assist in the passage of debris through the passageways. Nonstructural measures include regular maintenance and clearing of debris during extreme events (FHWA 2005). Many of these measures are used to protect infrastructure from current conditions. These types of measures may be increasingly used as conditions change; therefore, decision-makers should consider climate change and extreme events in future applications of these measures.

5.10 Conclusion

Common themes in this chapter include uncertainty, change, variation within basins and between basins, variation within hydrophysiographic region and between regions, and other caveats and frustratingly unpredictable dynamics and interactions. Nonetheless, certain patterns and challenges emerge and become clear. Returning integrity and resilience to our aquatic and riparian ecosystems requires consideration of all regimes, including wood. Restoration must develop further expertise in assessing the efficacy of large scale, long term, passive processes and integrating them where necessary with more expensive and failure-prone engineered approaches. The limits of society's limited perspective, and the mixed performance of our decision-making and management institutions in protecting residents, infrastructure, economies, and ecosystems from the ravages of large floods are well recognized, but agencies, stakeholders, and the restoration community can and must do better in the contexts of increasingly developed river corridors, the various predicted effects of climate change, and increasing recognition of the ecosystem values and services of watersheds. Managers, restoration practitioners, and stakeholders must plan for future scenarios and not historical norms. This chapter offers some powerful initial principles, concepts, and tools to achieve these goals.

5.11 Uncertainties and Research Needs

1. The subjects addressed in this chapter, by their large scale and long term nature, all represent domains of uncertainty.
2. The transport dynamics of pulsed wood inputs from stochastic events are variable and largely unstudied.
3. The roles of thresholds and multiple or alternative stable states, in hydrologic, geomorphic, and ecological terms, remain largely unstudied.
4. Future peak flow hydrology as the driving variable for multiple processes and concerns, particularly in the context of climate change, is uncertain in terms of precise quantification but poses significant concerns.
5. Secondary effects of climate change, such as vegetative stress induced by base flow alteration as well as forest disease or insect issues, are largely unpredictable but have already induced dramatic impacts in some settings.

5.12 Key Points

1. The capacity of the watershed to produce a large wood supply of appropriate volume and size range and deliver it to the channel network is ultimately more significant and cost-effective than engineered wood features.
2. The trapping and transport roles played by the largest wood pieces (relative to channel geometry) are pivotal.
3. Similarly, the ability of the system to convey mobile wood elements is critical to mid-basin, lower basin, and terminus supply. This includes natural supply and recruitment as well as large wood management at dams and channel crossings that recognizes and addresses the importance of wood to downstream reaches.
4. The risks of flooding and structural damage at stream and river crossings are most effectively addressed by crossing retrofits and redesigns, offering long-term economic, public safety, and ecological benefits—particularly in view of peak flow increases predicted by climate change scientists.
5. Although pulsed wood inputs and jams created by stochastic floods must sometimes be managed through removal, this should not be the default response. Large wood offers important stability and habitat values. If removal is required, it should be retained for channel and floodplain restoration use elsewhere.
6. The patterns and trends of climate change remain unpredictable at quantifiable and local scales, along with associated hydrologic and ecological responses (e.g., disease and insect outbreaks, or the effects of altered base flows on vegetative stress), but significant impacts have been observed in multiple locations. The irruption of mountain pine bark beetle in many locations in the American west is one example.

5.13 References

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Agrawal, A., M. A. Khan, and Z. Yi. 2007. *Handbook of Scour Countermeasures and Design*. FHWA-NJ-2005-027. New Jersey Department of Transportation and Federal Highway Administration, Washington, DC.

Allan, J. D. 1995. *Stream Ecology: Structure and Function of Running Waters.* Boston, MA: Kluwer Academic Publishers.

Anderson, D. B. 2006. Quantifying the Interaction between Riparian Vegetation and Flooding: from Cross-Section to Catchment Scale. University of Melbourne.

Angradi, T. R., E. W. Schweiger, D. W. Bolgrien, P. Ismert, and T. Selle. 2004. Bank Stabilization, Riparian Land Use and the Distribution of Large Woody Debris in a Regulated Reach of the Upper Missouri River, North Dakota, USA. *River Research and Applications* 20:829–846.

Arnáez, J., V. Larrea, and L. Ortigosa. 2004. Surface Runoff and Soil Erosion on Unpaved Forest Roads from Rainfall Simulation Tests in Northeastern Spain. *Catena* 57:1–14.

Arneson, L. A., L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper. 2012. *Evaluating Scour at Bridges*. Hydraulic Engineering Circular 18, FHWA-HIF-12-003, National Highway Institute, Federal Highway Administration, Arlington, VA.

Beckman, N. D., and E. Wohl. 2014. Carbon Storage in Mountainous Headwater Streams: The Role of Old-Growth Forest and Logjams. *Water Resources Research* 50:2376–2393.

Beechie, T. J., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling Recovery Rates and Pathways for Woody Debris Recruitment in Northwestern Washington Streams. *North American Journal of Fisheries Management* 20:436–452.

Benda, L. E., and J. C. Sias. 2003. A Quantitative Framework for Evaluating the Mass Balance of In-Stream Organic Debris. *Forest Ecology and Management* 172:1–16.

Benda, L., Miller, D., Bigelow, P., Andras, K. 2003a. Effects of Post-Wildfire Erosion on Channel Environments, Boise River, Idaho. *Forest Ecology and Management* 178:105–119.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003b. Wood Recruitment Processes and Wood Budgeting. *American Fisheries Society Symposium* 37:49–73.

Benke, A. C. 2001. Importance of Flood Regime to Invertebrate Habitat in an Unregulated River-Floodplain Ecosystem. *Journal of the North American Benthological Society* 20:225–240.

Benke, A. C., and J. B. Wallace. 1990. Wood Dynamics in Coastal Plain Blackwater Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 47:92–99.

Bentz, B. J., J. Régnière, C. J. Fettig, M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negrón, and S. J. SeyboLd. 2010. Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience* 60:602–613.

Bertoldi, W., A. M. Gurnell, and M. Welber. 2013. Wood Recruitment and Retention: The Fate of Eroded Trees on a Braided River Explored Using a Combination of Field and Remotely-Sensed Data Sources. *Geomorphology* 180–181(0):146–155.

Bilby, R. E., and G. E. Likens. 1980. Importance of Debris Dams in the Structure and Function of Stream Ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E. and J. W. Ward. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48:2499–2508.

Bocchiola, D., M. C. Rulli, and R. Rosso. 2006. Transport of Large Woody Debris in the Presence of Obstacles. *Geomorphology* 76(1):166–178.

Bocchiola, D., M. C. Rulli, and R. Rosso. 2008. A Flume Experiment on the Formation of Wood Jams in Rivers. *Water Resources Research* 44: W02408, doi:10.1029/2006WR005846.

Bradley, J., D. Richards, and C. Bahner 2005. *Debris Control Structures – Evaluation and Countermeasures.* Hydraulic Engineering Circular No. 9. FHWA-IF-04-016. U.S. Department of Transportation, Federal Highway Administration., Salem, OR.

Bragg, D. C. 2000. Simulating Catastrophic and Individualistic Large Woody Debris Recruitment for a Small Riparian Ecosystem. *Ecology* 81:1383–1394.

Braudrick, C. A., and G. E. Grant. 2000. When Do Logs Move in Rivers? *Water Resources Research* 36(2):571–583.

Braudrick, C. A., and G. E. Grant. 2001. Transport and Deposition of Large Woody Debris in Streams: A Flume Experiment. *Geomorphology* 41:263–283.

Braudrick, C. A., G. E. Grant, Y. Ishikawa, and H. Ikeda. 1997. Dynamics of Wood Transport in Streams: A Flume Experiment. *Earth Surface Processes and Landforms* 22:669–683.

Brenkman, S., J. Duda, C. E> Torgersen, E. Welty, G. R. Pess, R. Peters, and M. L. McHenry. 2012. A Riverscape Perspective of Pacific Salmonids and Aquatic Habitats Prior to Large-Scale Dam Removal in the Elwha River, Washington, USA. *Fisheries Management and Ecology* 19:36–53.

Brooks, A. P., G. J. Brierly, and R. G. Millar. 2003. The Long-Term Control of Vegetation and Woody Debris on Channel and Flood-Plain Evolution: Insights from a Paired Catchment Study in Southeastern Australia. *Geomorphology* 51:7–30.

Brooks, A. P., T. Abbe, T. Cohen, N. Marsh, S. Mika, A. Boulton, T. Broderick, D. Borg, and I. Rutherfurd 2006b. *Design Guidelines for the Reintroduction of Wood into Australian Streams*. Land & Water Australia, Canberra, Australia.

Buckley B. M., and F. J. Triska 1978. Presence and Ecological Role of Nitrogen-Fixing Bacteria Associated with Wood Decay in Streams. *Internationale Vereinigung für Theoretische und Angewandte Limnologie Verhandlungen* 20:1333–1339.

Buffington, J. M., T. E. Lisle, R. D. Woodsmith, and S. Hilton. 2002. Controls on the Size and Occurrence of Pools in Coarse-Grained Forest Rivers. *River Research and Applications* 18:507–531.

Cannon, S. H., and J. DeGraff. 2009. The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change. Pages 177–190 in K. Sassa and P. Canuti (eds.), *Landslides—Disaster Risk Reduction*. Berlin Heidelberg: Springer-Verlag. Available: <http://landslides.usgs.gov/docs/cannon/Cannon_Degraff_2008_Springer.pdf>.

Carlson, J. Y., C. W. Andrus, and H. A. Froehlich. 1990. Woody Debris, Channel Features, and Macroinvertebrates of Streams with Logged and Undisturbed Riparian Timber in Northeastern Oregon, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 47:1103–1111.

Collins, B. D., and D. R. Montgomery. 2002. Forest Development, Wood Jams, and Restoration of Floodplain Rivers in the Puget Lowland, Washington. *Restoration Ecology* 10:237–247.

Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical Changes in the Distribution and Functions of Large Wood in Puget Lowland Rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59:66–76.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Comiti, F., A. Andreoli, M. A. Lenzi, and L. Mao. 2006. Spatial Density and Characteristics of Woody Debris in Five Mountain Rivers of the Dolomites (Italian Alps). *Geomorphology* 78:44–63.

Cook, W. J. 2014. *Bridge Failure Rates, Consequences, and Predictive Trends*. PhD Dissertation. Utah State University, Logan, UT.

Creamean, J. M., K. J. Suski, D. Rosenfeld, A. Cazorla, P. J. DeMott, R. C. Sullivan, A. B. White, F. M. Ralph, P. Minnis, J. M. Comstock, J. M. Tomlinson, and K. A. Prather. 2013. Dust and Biological Aerosols from the Sahara and Asia Influence Precipitation in the Western U.S. *Science* 339: 1572–1578, doi:10.1126/ science.1227279.

Curran, J. H., and E. E. Wohl 2003. Large Woody Debris and Flow Resistance in Step-Pool Channels, Cascade Range, Washington. *Geomorphology* 51:141–157.

Daniels, M. D., and B. L. Rhoads. 2004. Effect of Large Woody Debris Configuration on Three-Dimensional Flow Structure in Two Low-Energy Meander Bends at Varying Stages. *Water Resources Research* 40: W11302, doi:10.1029/2004WR003181.

Daniels, M. D., and B. Rhoads. 2007. Influence of Experimental Removal of Large Woody Debris on Spatial Patterns of Three-Dimensional Flow in a Meander Bend. *Earth Surface Processes and Landforms* 32:460–474.

Davis, J. M., C. V. Baxter, E. J. Rosi-Marshall, J. L. Pierce, and B. T. Crosby. 2013. Anticipating Stream Ecosystem Responses to Climate Change: Toward Predictions that Incorporate Effects via Land–Water Linkages. *Ecosystems* 16:909–922. DOI:10.1007/s10021-013-9653-4.

Dean, D. J., M. L. Scott, P. B. Shafroth, and J. C. Schmidt. 2011. Stratigraphic, Sedimentologic, and Dendrogeomorphic Analyses of Rapid Floodplain Formation Along the Rio Grande in Big Bend National Park, Texas. *Geological Society of America Bulletin* 123:1908–1925.

Diehl, T. H. 1997. *Potential Drift Accumulation at Bridges*. Publication FHWA-RD-97-028. U.S. Department of Transportation, McLean, VA.

Downs, P.W., and A. Simon. 2001. Fluvial Geomorphological Analysis of the Recruitment of Large Woody Debris in the Yalobusha River Network, Central Mississippi, USA. *Geomorphology* 37: 65-91.

Doyle, M. W., E. H. Stanley, J. M. Harbor, and G. S. Grant, G.S. 2003. Dam Removal in the United States: Emerging Needs for Science and Policy. *Eos, Transactions American Geophysical Union* 84:29.

Draut, A. E., J. B. Logan, and M. C. Mastin, M.C. 2011. Channel Evolution on the Dammed Elwha River, Washington, USA. *Geomorphology* 127:71–87.

Dunkerley, D. 2014. Nature and Hydro-Geomorphic Roles of Trees and Woody Debris in a Dryland Ephemeral Stream: Fowlers Creek, Arid Western New South Wales, Australia. *Journal of Arid Environments* 102:40-49.

Dwire, K. A., and J. B. Kauffman. 2003. Fire and Riparian Ecosystems in Landscapes of the Western USA. *Forest Ecology and Management* 178:61–74.

East, A. E., G. R. Pess, J. A. Bountry, C. S. Magirl, A. C. Ritchie, J. B. Logan, T. J. Randle, M. C. Mastin, J. T. Minear, J. J. Duda, M. C. Liermann, M. L. McHenry, T. J. Beechie, and P. B. Shafroth. 2014. Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change. *Geomorphology* 228:765–786.

Eaton, B. C., M. A. Hassan, and S. L. Davidson. 2012. Modeling Wood Dynamics, Jam Formation, and Sediment Storage in a Gravel-Bed Stream. *Journal of Geophysical Research* 117:F00A05, doi:10.1029/2012JF002385.

Falke, J. A., K. D. Fausch, R. Magelky, A. Aldred, D. S. Durnford, L. K. Riley, and R. Oad. 2011. The Role of Groundwater Pumping and Drought in Shaping Ecological Futures for Stream Fishes in a Dryland River Basin of the Western Great Plains, USA. *Ecohydrology* 4L682–697. doi:10.1002/eco.158. Available: http://onlinelibrary.wiley.com/doi/10.1002/eco.158/pdf.

Faustini, J. M., and J. A. Jones. 2003. Influence of Large Woody Debris on Channel Morphology and Dynamics in Steep, Boulder-Rich Mountain Streams, Western Cascades, Oregon. *Geomorphology* 51:187–205.

Federal Emergency Management Agency (FEMA). 1999. *Riverine Erosion Hazard Areas; Mapping Feasibility Study*. FEMA Technical Services Division, Hazard Study Branch.

Federal Highway Administration (FHWA) 1985b. *Hydraulic Design of Highway Culverts*. FHWA-IP-58-15. Available: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf.

Federal Highway Administration (FHWA). 2005. *Debris Control Structures Evaluation and Countermeasures*. Hydraulic Engineering Circular No. 9. Publication No. FHWA-IF-04-016. Available: <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/>.

FHWA 2012b. *Stream Stability at Highway Structures.* Hydraulic Engineering Circular No. 20. Publication No. FHWA-HIF-12-004. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Fischenich, C., and J.V. Morrow, Jr. 2000. *Streambank Habitat Enhancement with Large Woody Debris.* Publication No. ERDC TN-EMRRP-SR-13. U.S. Army Engineer Research and Development Center. Available: <http://el.erdc.usace.army.mil/elpubs/pdf/sr13.pdf>.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Fremier, A. K., J. I. Seo, and F. Nakamura. 2010. Watershed Controls on the Export of Large Wood from Stream Corridors. *Geomorphology* 117:33–43.

Friedman, J. M., G. T. Auble, P. B. Shafroth, M. L. Scott, M. F. Merigliano, M. D. Preehling, and E. K.Griffin. 2005. Dominance of Non-Native Riparian Trees in Western USA. *Biological Invasions* 7:747–751.

Furniss, M., T. Ledwith, M. Love, B. McFadin, and S. Flanagan 1998. *Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California*. USDA-Forest Service, Technology & Development Program, Corvallis OR.

Ghosn, M., F. Moses, and J. Wang. Undated. *Design of Highway Bridges for Extreme Events*.

Gillespie, N., A. Unthank, L. Campbell, P. Anderson, R. Gubernick, M. Weinhold, D. Cenderelli, B. Austin, D. McKinley, S. Wells, J. Rowan, C. Orvis, M. Hudy, A. Bowden, A. Singler, E. Fretz, J. Levine, and R. Kirn 2014. Flood Effects on Road-Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs. *Fisheries* 39(2):62–76.

Goode, J. R., C. H. Luce, and J. M. Buffington. 2012. Enhanced Sediment Delivery in a Changing Climate in Semi-Arid Mountain Basins: Implications for Water Resource Management and Aquatic Habitat in the Northern Rocky Mountains. *Geomorphology* 139-140:1–15.

Gosnell, H., and E. Kelly. 2010. Peace on the River? Social-Ecological Restoration and Large Dam Removal in the Klamath basin, USA. *Water Alternatives* 3:362–383.

Gowan, C., and K. D. Fausch. 1996. Long-Term Demographic Responses of Trout Populations to Habitat Manipulation in Six Colorado Streams. *Ecological Applications* 6(3):931–946.

Graf, W. L. 1999. Dam Nation: A Geographic Census of American Dams and Their Large-Scale Hydrologic Impacts. *Water Resources Research* 35:1305–1311.

Grant, G., J. Schmidt, J., and S. Lewis. 2003. A Geological Framework for Interpreting Downstream Effects of Dams on Rivers. Page 209–226 in *A Unique River, Water Science Application, Volume 7*. American Geophysical Union.

Gregory, K. J., R. J. Davis, and S. Tooth. 1993. Spatial Distribution of Coarse Woody Debris Dams in the Lymington Basin, Hampshire, UK. *Geomorphology* 6:207–224.

Gregory, S.V., M.A. Meleason, and D.J. Sobota. 2003b. Modeling the Dynamics of Wood in Streams and Rivers. *American Fisheries Society Symposium* 37:315–335.

Gurnell, A. M., H. Piegay, F. J. Swanson, and S. V. Gregory. 2002. Large Wood and Fluvial Processes. *Freshwater Biology* 47(4):601–619.

Gurnell, A. J., W. Bertoldi, and D. Corenblit. 2012. Changing River Channels: The Roles of Hydrological Processes, Plants and Pioneer Fluvial Landforms in Humid Temperate, Mixed Load, Gravel Bed Rivers. *Earth-Science Reviews* 111:129–141.

Guyette, R. P., D. C. Dey, and M. C. Stambaugh 2008. The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits. *Ecosystems* 11:643–653.

Haga, H., T. Kumagai, K. Otsuki, and S. Ogawa. 2002. Transport and Retention of Coarse Woody Debris in Mountain Streams: An In Situ Field Experiment of Log Transport and a Field Survey of Coarse Woody Debris Distribution. *Water Resources Research* 38:1126, doi:10.1029/2001WR001123.

Hamill, L. 1999. *Bridge Hydraulics.* New York, NY: Routledge.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

Hart, E. A. 2002. Effects of Woody Debris on Channel Morphology and Sediment Storage in Headwater Streams in the Great Smoky Mountains, Tennessee-North Carolina. *Physical Geography* 23:492–510.

Harwood, K., and A. G. Brown. 1993. Fluvial Processes in a Forested Anastomosing River: Flood Partitioning and Changing Flow Patterns. *Earth Surface Processes and Landforms* 18:741–748.

Hester, E. T., and M. W. Doyle. 2008. In-Stream Geomorphic Structures as Drivers of Hyporheic Change. *Water Resources Research* 44:W03427.

Homer, C. C., L. Huang, B. W. Yang, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* 70(7):829–840.

Hough-Snee, N., A. Kasprak, B. B. Roper, and C. S. Meredith. 2014. Direct and Indirect Drivers of Instream Wood in the Interior Pacific Northwest, USA: Decoupling Climate, Vegetation, Disturbance, and Geomorphic Setting. *Riparian Ecology and Conservation* 2:14–34.

Huryn, A. D., and J. B. Wallace. 1987. Local Geomorphology as a Determinant of Macrofaunal Production in a Mountain Stream. *Ecology* 68:1932–1942.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds.). Cambridge, UK, and New York, NY: Cambridge University Press.

Jeffries, R., S. E. Darby, and D. A. Sear. 2003. The Influence of Vegetation and Organic Debris on Flood-Plain Sediment Dynamics: Case Study of a Low-Order Stream in the New Forest, England. *Geomorphology* 51:61–80.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian Forest Disturbances by a Mountain Flood—The Influence of Floated Wood. *Hydrological Processes* 14:3031–3050.

Kasprak, A., F. J. Magilligan, K. H. Nislow, and N. P. Snyder, N.P. 2012. A Lidar-Derived Evaluation of Watershed-Scale Large Woody Debris Sources and Recruitment Mechanisms: Coastal Maine, USA. *River Research Applications* 28:1462–1476.

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010: Rising Stream and River Temperatures in the United States. *Frontiers in Ecology and the Environment* 8:461–466. doi:10.1890/090037.

Kloehn, K., T. Beechie, S. Morley, H. Coe, and J. Duda, J. 2008. Influence of Dams on River-Floodplain Dynamics in the Elwha River, Washington. *Northwest Science* 82:224–235.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in Snowfall versus Rainfall in the Western United States. *Journal of Climate* 19:4545–4559. doi:10.1175/JCLI3850.1. Available: http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3850.1.

Knutti, R., G. Abramowitz, M. Collins, V. Eyring, P. J. Gleckler, B. Hewitson, and L. Mearns. 2010. Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, and P.M. Midgley (eds.), *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Assessing and Combining Multi Model Climate Projections.* IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Kraft, C. E., and D. R. Warren. 2003. Development of Spatial Pattern in Large Woody Debris and Debris Dams in Streams. *Geomorphology* 51:127–139.

Kramer, N., and E. Wohl. 2014. Estimating Fluvial Wood Discharge using Time-Lapse Photography with Varying Sampling Intervals. *Earth Surface Processes and Landforms* 39:844–852.

Kreutzweiser, D.P., K. P. Good, and T. M. Sutton. 2005. Large Woody Debris Characteristics and Contributions to Pool Formation in Forest Streams of the Boreal Shield. *Canadian Journal of Forest Research* 35:1213–1223.

Kukulak, J., A. Pazdur, and T. Kuc. 2002. Radiocarbon Dated Wood Debris in Floodplain Deposits of the San River in the Bieszczady Mountains. *Geochronometria* 21:129–136.

Lagasse, P. F., P. Clopper, L. Zevenbergen, W. Spitz, and L. G. Girard.2010. *Effects of Debris on Bridge Pier Scour*. Federal Highway Administration. Washington, D.C.

Lagasse, P. F., L. W. Zevenbergen, W. J. Spitz, and L. A. Arneson 2012. *Stream Stability at Highway Structures, Fourth Edition. Hydraulic Engineering Circular No. 20*. Publication No. FHWA-HR-12-004. Office of Technology, Federal Highway Administration, Washington, DC.

Lassettre, N. S. and R. R. Harris 2001. The Geomorphic and Ecological Influence of Large Woody Debris in Streams and Rivers. University of California, Berkeley, CA.

Lassettre, N. S., and G. M. Kondolf. 2012. Large Woody Debris in Urban Stream Channels: Redefining the Problem. *River Research and Applications* 28(9):1477–1487.

Lassettre, N., and H. Piégay. 2008. Decadal Changes in Distribution and Frequency of Wood in a Free Meandering River, the Ain River, France. *Earth Surface Processes and Landforms* 1112:1098–1112.

Lautz, L. K., and R. M. Fanelli. 2008. Biogeochemical Hotspots in the Streambed around Restoration Structures. *Biogeochemistry* 91:85–104.

Lautz, L. K., D. I. Siegel, and R. L. Bauer. 2006. Impact of Debris Dams on Hyporheic Interaction along a Semi-Arid Stream. *Hydrological Processes* 20:183–196.

Lisle, T. E., Y. Cui, G. Parker, J. E. Pizzuto, and A. M. Dodd. 2001. The Dominance of Dispersion in the Evolution of Bed Material Waves in Gravel-Bed Rivers. *Earth Surface Processes and Landforms* 26:1409–1420.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The Velocity of Climate Change. *Nature* 462:1052–1055. doi:10.1038/nature08649.

Logan, J. A., W. W. Macfarlane, and L. Willcox. 2010. White-Bark Pine Vulnerability to Climate Change Induced Mountain Pine Beetle Disturbance in the Greater Yellowstone Ecosystem. *Ecological Application* 20:895–902. doi:10.1890/09- 0655.1. Available: http://www.esajournals.org/doi/pdf/10.1890/09-0655.1.

MacFarlane, W. A., and E. Wohl. 2003. Influence of Step Composition on Step Geometry and Flow Resistance in Step-Pool Streams of the Washington Cascades. *Water Resources Research* 39:1037. doi:10.1029/2001WR001238.

MacVicar, B., and H. Piégay. 2012. Implementation and Validation of Video Monitoring for Wood Budgeting in a Wandering Piedmont River, the Ain River (France). *Earth Surface Processes and Landforms* 37:1272–1289.

Magilligan, F. J., and K. H. Nislow. 2005. Changes in Hydrologic Regime by Dams. *Geomorphology* 71:61–78.

Magilligan, F. J., K. H. Nislov, G. B. Fisher, J. Wright, G. Mackey, and M. Laser 2007. The Geomorphic Function and Characteristics of Large Woody Debris in Low Gradient Rivers, Coastal Maine, USA. *Geomorphology* 97:467–482.

Major, J., J. O'Connor, C. Podolak, M. K. Keith, G. E. Grant, K. Spicer, S. Pittman, H. M. Bragg, J. R. Wallick, D. Q. Tanner, A. Rhode, and P. Wilcock. 2012. *Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam.* U.S. Geological Survey Professional Paper 1792.

Manga, M., and J. W. Kirchner. 2000. Stress Partitioning in Streams by Large Woody Debris. *Water Resources Research* 36:2373–2379.

Manners, R. W., M. W. Doyle, and M. J. Small. 2007. Structure and Hydraulics of Natural Woody Debris Jams. *Water Resources Research* 43, doi:10.1029/2006WR004910.

Manners, R. B., J. C. Schmidt, and M. L. Scott, M.L. 2014. Mechanisms of Vegetation-Induced Channel Narrowing on an Unregulated Canyon Bound River: Results from a Natural Field-Scale Experiment. *Geomorphology* 211:100–115.

Mao, L., and F. Comiti. 2010. The Effects of Large Wood Elements During an Extreme Flood in a Small Tropical Basin of Costa Rica. *WIT Transactions on Engineering Sciences* 67:225–236.

Marcus, W. A., R. A. Marston, C. R. Colvard, and R. D. Gray. 2002. Mapping the Spatial and Temporal Distributions of Woody Debris in Streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology* 44:323–335.

Marcus, W. A., J. Rasmussen, and M. A. Fonstad. 2011. Response of the Fluvial Wood System to Fire and Floods in Northern Yellowstone. *Annals of the Association of American Geographers* 101:21–44.

Martin, D. J., and L. E. Benda. 2001. Patterns of Instream Wood Recruitment and Transport at the Watershed Scale. *Transactions of the American Fisheries Society* 130:940–958.

Massachusetts Department of Transportation (MassDOT). 2010. *Design of Bridges and Culverts for Wildlife Passage at Freshwater Streams.* Highway Division, Environmental, Bridge, Construction, and Hydraulics Sections, Boston, MA.

Matheussen, B., R. L. Kirschbaum, I. A. Goodman, G. M. O'Donnell, and D. P. Lettenmaier. 2000. Effects of Land Cover Change on Streamflow in the Interior Columbia River Basin (USA and Canada). *Hydrological Processes* 14:867–885.

May, C. L., and R. E. Gresswell. 2003a. Large Wood Recruitment and Redistribution in Headwater Streams in the Southern Oregon Coast Range, USA. *Canadian Journal of Forest Research* 33:1353–1362.

May, C. L., and R. E. Gresswell. 2003b. Processes and Rates of Sediment and Wood Accumulation in Headwater Streams of the Oregon Coast Range, USA. *Earth Surface Processes and Landforms* 28:409–424.

May, C. L., E. B. Welch, R. R. Horner, J. R. Karr, and B. W. Mar, B.W. 1997. *Quality Indices for Urbanization Effects on Puget Sound Lowland Streams.* Water Resource Series Tech Report 154. Seattle, Washington.

Meleason, M. A., R. J. Davies-Colley, and G. M. J. Hall. 2007. Characterizing the Variability of Wood in Streams: Simulation Modelling Compared with Multiple-Reach Surveys. *Earth Surface Processes and Landforms* 32:1164–1173.

Melillo, J. M., T. C. Richmond, and G. W. Yohe (eds.). 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment.* U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Meredith, C., B. Roper, and E. Archer. 2014. Reductions in Instream Wood in Streams near Roads in the Interior Columbia River Basin. *North American Journal of Fisheries Management* 34(3):493–506.

Merritt, D. M., N. L. R. Poff. 2010. Shifting Dominance of Riparian Populus and Tamarix Along Gradients of Flow Alteration in Western North American Rivers. *Ecological Applications* 20:135–152.

Merten, E., J. Finlay, L. Johnson, R. Newman, R., H. Stefan, and B. Vondracek. 2010. Factors Influencing Wood Mobilization in Stream. *Water Resources Research* 46:W10514.

Merten, E. C., P. G. Vaz, J. A. Decker-Fritz, J. C. Finlay, and H. G. Stefan. 2013. Relative Importance of Breakage and Decay as Processes Depleting Large Wood from Streams. *Geomorphology* 190:40–47.

Mikuś, P., B. Wyżga, R. J. Kaczka, E. Walusiak, and J. Zawiejska. 2013. Islands in a European Mountain River: Linkages with Large Wood Deposition, Flood Flow and Plant Diversity. *Geomorphology* 202:115–127.

Montgomery, D. R. 1999. Process Domains and the River Continuum. *Journal of the American Water Resources Association* 35:397–410.

Montgomery, D. R., and T. B. Abbe. 2006. Influence of Logjam-Formed Hard Points on the Formation of Valley-Bottom Landforms in an Old-Growth Forest Valley, Queets River, Washington, USA. *Quaternary Research* 65:147–155.

Montgomery, D. R. and H. Piégay 2003. Wood in Rivers: Interactions with Channel Morphology and Processes. *Geomorphology* 51:1–5.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1995a. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Morris, A. E. L., P. C. Goebel, and B. J. Palik. 2010. Spatial Distribution of Large Wood Jams in Streams Related to Stream-Valley Geomorphology and Forest Age in Northern Michigan. *River Research and Applications* 26:835–847.

Moulin, B., E. R. Schenk, and C. R. Hupp. 2011. Distribution and Characterization of In-Channel Large Wood in Relation to Geomorphic Patterns on a Low-Gradient River. *Earth Surface Processes and Landforms* 36:1137–1151.

Munn, N. L., and J. L. Meyer. 1990. Habitat-Specific Solute Retention in Two Small Streams: An Intersite Comparison. *Ecology* 71:2069–2082.

Mutz, M. 2003. Hydraulic Effects of Wood in Streams. *American Fisheries Society Symposium* 37:93–107.

Nagayama, S., F. Nakamura, Y. Kawaguchi, and D. Nakano. 2012. Effects of Configuration of Instream Wood on Autumn and Winter Habitat Use by Fish in a Large Remeandering Reach. *Hydrobiologia* 680:159–170.

Naiman, R. J., R. E. Bilby, and P. Bisson. 2000. Riparian Ecology and Management in the Pacific Coastal Rain Forest. *Bioscience* 50:996–1011.

Naiman, R. J., J. S. Becthold, T. J. Beechie, J. J. Laterell, and R. Van Pelt. 2010. A Process-Based View of Floodplain Forest Patterns in Coastal River Valleys of the Pacific Northwest. *Ecosystems* 13:1–31.

Nakamura, F., and F. J. Swanson. 1993. Effects of Coarse Woody Debris on Morphology and Sediment Storage of a Mountain Stream System in Western Oregon. *Earth Surface Processes and Landforms* 18:43–61.

National Resources Conservation Service (NRCS) 2007e. Use of Large Woody Material for Habitat and Bank Protection - Technical Supplement 14j of Part 654. *The National Engineering Handbook*. 210–VI–NEH, August 2007. U.S. Department of Agriculture, Washington, DC.

New York State Department of Environmental Conservation (NYSDEC). 2014. Removal of Woody Debris and Trash from Rivers and Streams. In *Post-Flood Stream Reconstruction: Guidelines and Best Practices*. Albany, NY.

Nilsson, C., and K. Berggren. 2000. Alterations of Riparian Ecosystems Caused by River Regulation. *Bioscience* 50:783–792.

Oswald, E. B., and E. Wohl. 2008. Wood-Mediated Geomorphic Effects of a Jökuhlaup in the Wind River Mountains, Wyoming. *Geomorphology* 100:549–562.

Pealer, S. 2012. *Lessons from Irene – Building Resiliency as We Rebuild.* Vermont Agency of Natural Resources Climate Change Team, Montpelier, VT. Available: http://www.anr.state.vt.us/anr/climatechange/Pubs/Irene_Facts.pdf.

Pettit, N. E., and R. J. Naiman. 2006. Flood-Deposited Wood Creates Regeneration Niches for Riparian Vegetation on a Semi-Arid South African River. *Journal of Vegetation Science* 17:615–624.

Pettit, N. E., R. J. Naiman, K. H. Rogers, and J. E. Little. 2005. Post-Flooding Distribution and Characteristics of Large Woody Debris Piles Along the Semi-Arid Sabie River, South Africa. *River Research and Applications* 21:27–38.

Phillips, J. D. 2012. Log-Jams and Avulsions in the San Antonio River Delta, Texas. *Earth Surface Processes and Landforms* 37:936–950.

Piégay, H. 1993. Nature, Mass and Preferential Sites of Coarse Woody Debris Deposits in the Lower Ain Valley (Mollon Reach), France. *Regulated Rivers: Research and Management* 8:359–372.

Poff, N. L., and H. K. H. Zimmerman. 2010. Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshwater Biology* 55:194–205.

Poff, N. L., B. P. Bledsoe, and C. O. Cuhaciyan. 2006. Hydrologic Variation with Land Use across the Contiguous United States: Geomorphic and Ecological Consequences for Stream Ecosystems. *Geomorphology* 79:264–285. doi:10.1016/ j.geomorph.2006.06.032.

Pohl, M. M. 2002. Bringing Down Our Dams: Trends in American Dam Removal Rationales. *Journal of the American Water Resources Association* 38:1511–1519.

Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-Scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *Bio-Science* 58:501–517. doi:10.1641/b580607. Available: http://www.jstor.org/stable/pdfplus/10.1641/B580607. pdf.

Raikow, D. F., S. A. Grubbs, and K. W. Cummins. 1995. Debris Dam Dynamics and Coarse Particulate Organic Matter Retention in an Appalachian Mountain Stream. *Journal of the North American Benthological Society* 14:535–546.

Ravazzolo, D., L. Mao, L. Picco, and M. A. Lenzi 2015. Tracking Log Displacement During Floods in the Tagliamento River Using RFID and GPS Tracker Devices. *Geomorphology* 228:226-233.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and Function of Large Woody Debris in Subalpine Rocky Mountain Streams in Northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Rigon, E., F. Comiti, and M. A. Lenzi. 2012. Large Wood Storage in Streams of the Eastern Italian Alps and the Relevance of Hillslope Processes. *Water Resources Resea*rch 48:W01518, doi:10.1029/2010WR009854 18 p.

Robison, E. G., and R. L. Beschta. 1990. Identifying Trees in Riparian Areas that can Provide Coarse Woody Debris to Streams. *Forest Science* 36:790–801.

Rood, S. B., and J. M. Mahoney. 1990. Collapse of Riparian Poplar Forests Downstream from Dams in Western Prairies: Probable Causes and Prospects for Mitigation. *Environmental Management* 14:451–464.

Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppettone, S. Swanson, and P. L. Wagner. 2003. Flows for Floodplain Forests: A Successful Riparian Restoration. *Bioscience* 53:647–656.

Rosgen, D., and H. L. Silvey 1996. *Applied River Morphology.* Pagosa Springs, CO: Wildland Hydrology.

Ryan, S. E., E. L. Bishop, and J. M. Daniels. 2014. Influence of Large Wood on Channel Morphology and Sediment Storage in Headwater Mountain Streams, Fraser Experimental Forest, Colorado. *Geomorphology* 217:73–88.

Sawyer, A. H., M. B. Cardenas, and J. Buttles. 2011. Hyporheic Exchange due to Channel-Spanning Logs. *Water Resources Research* 47(8):W08502.

Schenk, E. R., J. W. McCargo, B. Moulin, C. R. Hupp, and J. M. Richter. 2014a. The Influence of Logjams on Largemouth Bass (*Micropterus salmoides*) Concentrations on the lower Roanoke River, a Large Sand-Bed River. *River Research and Applications* 2014(DOI: 10.1002/rra.2779).

Schenk, E. R., B. Moulin, C. R. Hupp, and J. M. Richter. 2014b. Large Wood Budget and Transport Dynamics on a Large River Using Radio Telemetry. *Earth Surface Processes and Landforms* 39:487–498.

Schiff, R., J. S. Clark, G. Alexander, and M. Kline 2008a. *The Vermont Agency of Natural Resources Reach Habitat Assessment (RHA).* Prepared by Milone & MacBroom, Inc. with the Vermont Agency of Natural Resources, Departments of Environmental Conservation and Fish and Wildlife, Waterbury, VT.

Schiff, R., J. S. Clark, and S. Jaquith 2008b. *The Vermont Culvert Geomorphic Compatibility Screening Tool.* Prepared by Milone & MacBroom, Inc. with the VT DEC River Management Program, Waterbury, VT.

Schiff, R., E. Fitzgerald, J. MacBroom, M. Kline, and S. Jaquith 2014. The Vermont Standard River Management Principles and Practices (Vermont SRMPP): Guidance for Managing Vermont's Rivers Based on Channel and Floodplain Function. Prepared by Milone & MacBroom and Fitzgerald Environmental Associates for and in collaboration with the Vermont Rivers Program, Montplelier, VT.

Schmidt, J. C., and P. R. Wilcock. 2008. Metrics for Assessing the Downstream Effects of Dams. *Water Resources Research* 44:W04404. doi:10.1029/2006WR005092.

Scott, M. L., J. M. Friedman, G. T. Auble. 1996. Fluvial Process and the Establishment of Bottomland Trees. *Geomorphology* 14:327–339.

Sear, D. A., C. E. Millington, D. R. Kitts, and R. Jeffries. 2010. Logjam Controls on Channel:Floodplain Interactions in Wooded Catchments and their Role in the Formation of Multi-Channel Patterns. *Geomorphology* 116:305–319.

Senter, A. E., and G. B. Pasternack. 2010. Large Wood Aids Spawning Chinook Salmon (*Oncorhynchus Tshawytscha*) in Marginal Habitat on a Regulated River in California. *River Research and Applications* 27:550–565.]

Shields, F. D., and R. H. Smith. 1992. Effects of Large Woody Debris Removal on Physical Characteristics of a Sand-Bed River. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:145–163.

Sklar, L. S., J. Fadde, J. G. Venditti, P. Nelson, M. A. Wydzga, Y. Cui, and W. E. Dietrich. 2009. Translation and Dispersion of Sediment Pulses in Flume Experiments Simulating Gravel Augmentation Below Dams. *Water Resources Research* 45:W08439, doi:10.1029/2008WR007346.

Sleeter, B., T. Wilson, W. Acevedo, W. 2012. *Status and Trends of Land Change in the Western United States—1973–2000.* U.S. Geological Survey Professional Paper 1794-A.

Smith, M. P., R. Schiff, A. Olivero, and J. G. MacBroom 2008. The *Active River Area: A Conservation Framework to Protect Rivers and Streams.* Boston, MA: The Nature Conservancy.

Smith, R. D., R. C. Sidle, and P. E. Porter. 1993. Effects on Bedload Transport of Experimental Removal of Woody Debris from a Forest Gravel-Bed Stream. *Earth Surface Processes and Landforms* 18:455–468.

Spanhoff, B., and E. I. Meyer. 2004. Breakdown Rates of Wood in Streams. *Journal of the North American Benthological Society* 23(2):189–197.

Spooner, D. E., M. A. Xenopoulos, C. Schneider, and D. A. Woolnough. 2011. Coextirpation of Host-Affiliate Relationships in Rivers: The role of Climate Change, Water Withdrawal, and Host-Specificity. *Global Change Biology* 17:1720–1732. doi:10.1111/j.1365-2486.2010.02372.x.

Thompson, D. M. 1995. The Effects of Large Organic Debris on Sediment Processes and Stream Morphology in Vermont. *Geomorphology* 11(3):235–244.

Tyler, R. N. 2011. *River Debris: Causes, Impacts, and Mitigation Techniques*. Prepared for Ocean Renewable Power Company by the Alaska Center for Energy and Power, Fairbanks, Alaska.

Umazano, A.M., R.N. Melchor, E. Bedatou, E.S. Bellosi, and J.M. Krause. 2014. Fluvial Response to Sudden Input of Pyroclastic Sediments During the 2008–2009 Eruption of the Chaitén Volcano (Chile): The Role of Logjams. *Journal of South American Earth Sciences* 54:140–157.

U.S. Environmental Protection Agency, Office of Water. 2013. *Climate Change Adaptation Implementation Plan*. Available: http://epa.gov/climatechange/Downloads/impacts-adaptation/office-of-water-plan.pdf.

U.S. Climate Change Science Program (CCSP). 2008a. *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (S. H. Julius and J.M. West [eds.], J. S. Baron, B. Griffith, L. A. Joyce, P. Kareiva, B. D. Keller, M. A. Palmer, C. H. Peterson, and J. M. Scott [Authors]). U.S. Environmental Protection Agency. Washington, D.C. 873 pp.

U.S. Climate Change Science Program (CCSP). 2008b. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. G. Ryan, S. R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W.

Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, B. Peterson, and R. Shaw). U.S. Department of Agriculture. Washington, D.C. 362 pp.

U.S. Climate Change Science Program (CCSP). 2008c. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (M. J. Savonis, V. R. Burkett, and J. R. Potter [eds.]). U.S. Department of Transportation. Washington, D.C.

U.S. Department of the Interior – Bureau of Reclamation. 2011. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*. Technical Memorandum No. 86-68210–2011-01

U.S. Environmental Protection Agency, Office of Water. 2013. *Climate Change Adaptation Implementation Plan*. Available: http://epa.gov/climatechange/Downloads/impacts-adaptation/office-of-water-plan.pdf.

U.S. Forest Service (USFS). 2008. *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*. Forest Service Stream-Simulation Working Group. San Dimas, CA. May. Available: http://www.stream.fs.fed.us/fishxing/publications/PDFs/AOP_PDFs/08771801.pdf. Accessed: February 27, 2015.

U.S. Global Change Research Program (USGCRP). 2009. *Global Climate Change Impacts in the United States*. Edited by T. R. Karl, J. M. Melillo, and T. C. Peterson. Cambridge, MA: Cambridge University Press.

University of New Hampshire (UNH). 2009. *New Hampshire Stream Crossing Guidelines.* University of New Hampshire, Durham, NH.

Vermont Agency of Natural Resources (VTANR). 2014. V*ermont Stream Alteration General Permit.* Department of Environmental Conservation, Montpelier, VT.

Vermont Agency of Transportation (Vtrans). 2001. *Hydraulics Manual*. Montpelier, VT.

Walsh, C., and A. Roy. 2005. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. *Journal of the North American Benthological Society* 24:706–723.

Walter, R.C. and D.J. Merritts. 2008. Natural Streams and the Legacy of Water-Powered Mills. *Science* 319(5861):299-304.

Warren, D. R. and C.E. Kraft. 2008. Dynamics of large wood in an eastern U.S. mountain stream. Forest Ecology and Management 256(4):808-814.

Warren, D. R., C. E. Kraft, W. S. Keeton, J. S. Nunery, and G. E. Likens. 2009. Dynamics of Wood Recruitment in Streams of the Northeastern US. *Forest Ecology and Management* 258:804–813.

Watts, R. J., B. D. Richter, J. J. Opperman, and K. H. Bowmer. 2011. Dam Reoperation in an Era of Climate Change. *Marine and Freshwater Research* 62:321–327.

Webb, A. A., and W. D. Erskine. 2003. Distribution, Recruitment, and Geomorphic Significance of Large Woody Debris in an Alluvial Forest Stream: Tonghi Creek, Southeastern Australia. *Geomorphology* 51:109–126.

Welber, M., W. Bertoldi, and M. Tubino. 2013. Wood Dispersal in Braided Streams: Results from Physical Modeling. *Water Resources Research* 49:7388–7400.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002. Riparian Aquatic Interaction Simulator (RAIS): A Model of Riparian Forest Dynamics for the Generation of Large Woody Debris and Shade. *Forest Ecology and Management* 162:299–318.

Wemple, B. C., and J. A. Jones 2003. Runoff Production on Forest Roads in a Steep, Mountain Catchment. *Water Resources Research* 39(8). doi:10.1029/2002WR001744

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young, M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams. 2011. Flow Regime, Temperature, and Biotic Interactions Drive Differential Declines of Trout Species under Climate Change. *Proceedings of the National Academy of Sciences* 108:14175–14180. doi:10.1073/pnas.1103097108. Available: http://www.pnas.org/content/108/34/14175.full.pdf+html.

Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger. 2003. Climate and Wildfire in the Western United States. *Bulletin of the American Meteorological Society* 84:595–604. doi:10.1175/BAMS-84-5-595. Available: http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-84-5-595.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science* 313: 940–943. doi:10.1126/science.1128834.

White, P. S., and S. T. A. Pickett. 1985. Natural Disturbance and Patch Dynamics: An Introduction. Pages 3–9 in S. T. A. Pickett and P. S. White (eds.), *The Ecology of Natural Disturbance and Patch Dynamics*. San Diego, CA:Academic Press.

Whiting, P. J. 2002. Streamflow Necessary for Environmental Maintenance. *Annual Review of Earth and Planetary Sciences*. 30:181–206.

Williams, G. P. 1986. River Meanders and Channel Size. *Journal of Hydrology* 88(1-2):147–164.

Williams, G.P., and M. G. Wolman. 1984. *Downstream Effects of Dams on Alluvial Rivers*. USG S Professional Paper 1286.

Wipf, T. J., B. M. Phares, and J. Dahlberg 2012. *Debris Mitigation Methods for Bridge Piers*. Iowa State University, Ames, IA.

Wohl, E. 2011a. Seeing the Forest and the Trees: Wood in Stream Restoration in the Colorado Front Range, United States. Pages 399–418 in A. Simon, S. J. Bennett, and J. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Washington, D.C.: American Geophysical Union Press.

Wohl, E. 2011b. What Should these Rivers Look Like? Historical Range of Variability and Human Impacts in the Colorado Front Range, USA. *Earth Surface Processes and Landforms* 36:1378–1390.

Wohl, E. 2011c. Threshold-Induced Complex Behavior of Wood in Mountain Streams. *Geology* 39:587–590.

Wohl, E. 2013a. Redistribution of Forest Carbon Caused by Patch Blowdowns in Subalpine Forests of the Southern Rocky Mountains, USA. *Global Biogeochemical Cycles* 27:1205-1213.

Wohl, E. 2014. A Legacy of Absence: Wood Removal in US Rivers. *Progress in Physical Geography* 38:637–663.

Wohl, E., and N. Beckman. 2014a. Controls on the Longitudinal Distribution of Channel-Spanning Logjams in the Colorado Front Range, USA. *River Research and Applications* 30:112–131.

Wohl, E., and N. D. Beckman. 2014b. Leaky rivers: Implications for the loss of longitudinal fluvial disconnectivity in headwater streams. *Geomorphology* 205:27–35.

Wohl, E., and D. Cadol. 2011. Neighborhood Matters: Patterns and Controls on Wood Distribution in Old-Growth Forest Streams of the Colorado Front Range, USA. *Geomorphology* 125:132–146.

Wohl, E., and J. R. Goode. 2008. Wood Dynamics in Headwater Streams of the Colorado Rocky Mountains. *Water Resources Research* 44:W09429.

Wohl, E., and K. Jaeger. 2009. A Conceptual Model for the Longitudinal Distribution of Wood in Mountain Streams. *Earth Surface Processes and Landforms* 34:329–344.

Wohl, E. and D. M. Merritt. 2008. Reach-Scale Channel Geometry of Mountain Streams. *Geomorphology* 93(3-4):168–185.

Wohl, E., and F. L. Ogden. 2013. Organic Carbon Export in the Form of Wood During an Extreme Tropical Storm, Upper Rio Chagres, Panama. *Earth Surface Processes and Landforms* 38:1407–1416.

Wohl, E., F. L. Ogden, and J. Goode. 2009. Episodic Wood Loading in a Mountainous Neotropical Watershed. *Geomorphology* 111:149–159.

Wohl, E., L. E. Polvi, and D. Cadol. 2011. Wood Distribution Along Streams Draining Old-Growth Forests in Congaree National Park, South Carolina, USA. *Geomorphology* 126:108–120.

Wohl, E., S. Bolton, D. Cado, F. Comiti, J. R. Goode, and L. Mao. 2012. A Two End-Member Model of Wood Dynamics in Headwater Neotropical Rivers. *Journal of Hydrology* 462-463:67–76.

Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards. 2009. Changes in Hyporheic Flow Following Experimental Removal of a Small, Low-Gradient Stream. *Water Resources Research* 45:W05406, 13 pp.

Wyżga, B., and J. Zawiejska. 2005. Wood Storage in a Wide Mountain River: Case Study of the Czarny Dunajec, Polish Carpathians. *Earth Surface Processes and Landforms* 30:1475–1494.

Young, M. K., E. A. Mace, E. T. Ziegler, and E. K. Sutherland. 2006. Characterizing and Contrasting Instream and Riparian Coarse Wood in Western Montana Basins. *Forest Ecology and Management* 226:26–40.

Chapter 6

ENGINEERING CONSIDERATIONS

Complex timber revetment designed to protect bank by partitioning shear stress while also creating cover and hydraulic refugia for salmonids, South Fork Nooksack River, Northwest Washington (Tim Abbe 2012)

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6.1 Overview

This chapter provides an introduction to the engineering design of large wood placements in streams. There are many factors to consider in any stream engineering endeavor and many assumptions to be made to assess a design quantitatively. Project documentation should include a basis of design describing the methodology and assumptions used to develop the design, no matter how simple or intricate the project. As with other aspects of large wood placement projects, the effort devoted to engineering should be commensurate with project risk and scale (Figure 6-1). Higher risk projects should receive more intensive engineering (e.g., higher resolution pre-project surveys, multidimensional computer models, collection of calibration data, establishment of ecological baselines) to reduce uncertainty surrounding technical issues. Even so, much uncertainty will remain after state-of-the art engineering is employed.

CROSS-REFERENCE

Chapter 7, *Risk Considerations*, provides detailed guidance on overall project risk assessment and management.

As described previously, fluvial systems are directly influenced by biological (e.g., plants), physical (e.g., hydrologic and geomorphic), and social (e.g., recreation and flood control) factors, all of which interact and change over time. This underlies the need for interdisciplinary design. The design team's responsibility is to develop a conceptual design that achieves the project objectives within the site constraints. The role of professional geologists is to ensure the design achieves the desired geomorphic conditions and can be constructed given surface and subsurface conditions, and to predict how the design will perform through time. The role of professional engineers is to take this design to reality by developing a set of bid documents (plans and specifications) that can be constructed within the allocated budget. Preparation of and format of plans, specifications, and estimates typically follows standards established by local, state, or federal agencies, which are familiar to contractors. Because stream restoration typically involves unique circumstances and structures, special provisions are often required, which underscores the need for experience and expertise working in fluvial systems.

The information and guidelines presented here provide an introduction to the use of wood in restoring fluvial systems. Designs should always be led and reviewed by professionals with expertise and experience in fluvial systems and restoration. This chapter assumes that objectives for a given project have been set prior to the design process using information from within this manual. Typically, these objectives will involve either habitat rehabilitation, channel stabilization, or both. Clear, written objectives are needed to drive and justify design decisions.

6.2 Introduction

Naturally occurring large wood influences or governs hyporheic exchange, habitat complexity, hydraulics, sediment storage and transport, and reach-scale geomorphology.

CROSS-REFERENCE

Chapter 1, *Large Wood Introduction*, Chapter 3, *Ecological and Biological Considerations*, and Chapter 4, *Geomorphology and Hydrology Considerations*, provide much more information about the functional role of large wood in riverine ecosystems.

Much evidence attests to the fact that North American rivers had much higher rates of large wood loading (both on the floodplain and instream) prior to European settlement.

Figure 6-1. Impact of Spatial Scale and Relative Risk on Engineering Aspects of a Large Wood Project

Spatial Scale				Relative Risk		
	Channel Width (meters)	Watershed Size (km^2)	Bankfull Discharge (m^3/s)	Low	Medium	High
Small	1	10	1			
Medium	↓	↓	↓			
Large	10^3	10^6	10^5			

km^2 = square kilometers; m^3/s = cubic meters per second.

Appropriate commitment of project resources to design, breadth of stakeholder engagement, and multidisciplinary involvement in the design process should reflect both spatial scale and relative risk. For example, low-risk, small scale projects might be designed using qualitative impressions from visual reconnaissance, professional judgment and manual computations. Intermediate level projects would rely on aerial photos, survey data, gage records, and spreadsheet analysis. Higher risk projects, particularly those in larger streams, require high-resolution hydrologic, sediment, and topographic and bathymetric data to construct, calibrate, and verify numerical (computer) models. Some small scale projects are high risk due to land use context, geomorphology, or hydrology; and some large scale projects are low risk due to similar factors.

Currently, large wood density and stability have been drastically compromised by the combined influence of large wood removal, beaver decline, riparian and watershed deforestation, "splash damming" to transport logs to mill, channelization, dam construction, and channel enlargement due to incision. Accordingly, stream restoration efforts often include replacement of stable large wood by constructing instream large wood structures, supplying loose large wood to the channel (replenishment of supply), or trapping mobile wood.

Large wood and structures comprising large wood have been used for river training and stabilization for centuries (Figure 6-2). In the latter half of the twentieth century timber was largely replaced by rock, concrete, and steel in channel stabilization. Wooden structures intended to improve fish habitat have been described in literature from the nineteenth and twentieth centuries (Thompson and Stull 2002). Entering the twenty-first century there has been an increase in timber use driven by environmental concerns.

Figure 6-2. Examples of Wood Placements Used to Stabilize River Banks

Photo a. Bundles of small wood have been used for several thousand years in China to stabilize banks and levees (Glenn Wilson).

Photo b. Placement of cedar brush mattress along toe of Puyallup River North Levee, May 24, 1916 (photo courtesy of Pierce County, Washington).

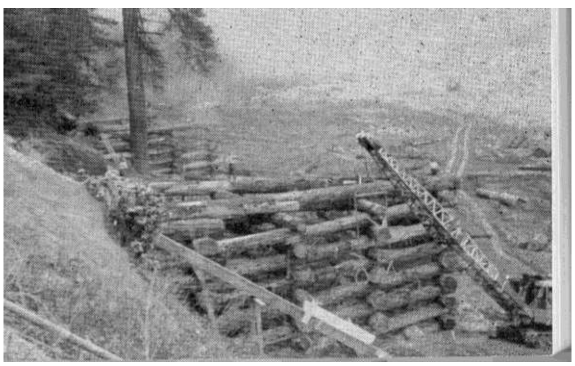

Photo c. Large timber cribs constructed in 1930s to deflect flows on the Eel River, Northern California, circa 1960).

Photo d. Complex timber revetment with internal rock collar ballast, 2010 (Tim Abbe).

Photo e. Series of ELJ flow deflectors constructed in 1999, Cispus River, Washington (Tim Abbe).

Photo f. Detail of engineered logjam, Cispus River, Washington, 2004 (Tim Abbe).

Photo g. Wood structure placed to accelerate flows and flush fine sediment deposited on gravel bed of Fawn River, Ohio, following rapid drawdown of an upstream impoundment. (Photo courtesy of Fawn River Restoration and Conservation Charitable Trust.)

Photo h. Large wood with complex fine branches placed along outside of bend to trigger sediment deposition along steep, eroding bank of a Georgia stream.

Photo i. Headwater or small perennial stream construction can use wood scaled appropriately to provide overhead cover and bank stability that can last 100 years or more(Photo by Inter-Fluve).

Photo j. The wood is not visible in the post-project photo, taken 10 years later, but will continue to provide habitat value in this stream for many decades (Photo by Inter-Fluve).

The new generation of timber structures builds upon basic principles of earlier structures such as crib walls and deflectors, but they represent a major change to more physical complexity that better emulates natural conditions (Abbe et al. 1997, 2003b, 2003c; Abbe and Brooks 2011).

Many of the earliest river training structures built on large rivers in the United States included willow mattresses, brush mattresses, or wooden pilings driven into the bed (Vanoni 1975; Keown et al. 1977). During the 1990s, increasing appreciation of the importance of large wood in natural riverine ecosystems triggered efforts to design structures that emulated the form and function of naturally occurring, stable accumulations of wood, particularly in rivers of the Pacific Northwest (Abbe et al. 1997; Hilderbrand et al. 1998). Additional research and successful installations have been carried out in Australia since about 2000 (Brooks 2006; Brooks et al. 2006; Simon et al. 2012).

Although success rates for Australian projects have been relatively high, the results of large wood installations for ecological restoration in the United States have varied widely (Roni et al. 2008). A 1986 evaluation of 137 log habitat structures in the Northwest revealed high rates of damage and failure (Frissell and Nawa 1992). Of 72 large wood structures placed within a short reach of a small stream in the Southeast, 51 were damaged or destroyed within 3 years (Shields et al. 2008). Nevertheless, careful planning and design can reduce the risk associated with large wood projects (*see Chapter 7, Risk Considerations*).

The planning process should include establishment of measurable objectives. Biological objectives should be based on assessment of current and desired habitat quality and quantity.

CROSS-REFERENCE

More quantitative analyses include assessment of limiting factors for populations of target species according to principles found in Chapter 3, *Ecological and Biological Considerations*.

The outcome of such analyses provides a rationale for selecting the numbers and types of large wood structures to be added to the project reach.

This chapter focuses on the design of large wood structures, which is a bit paradoxical. On the one hand, large wood reintroduction is a step toward a more natural fluvial system in which large wood is both plentiful and mobile. Conversely, in almost all large wood structure projects, the designer's intention is for the large wood to be stationary for years if not decades. In many cases placed large wood structures will accumulate additional large wood that is naturally transported from upstream. Natural large wood residence times vary widely from hours to centuries. However, unless a piece of large wood is much longer than the channel width and has a large enough wood volume relative to the channel cross-section to act as a key member or is deeply buried in the bed or floodplain, it eventually moves downstream. On the other hand, most large wood structures are designed to resist movement up to a specified discharge.

CAVEAT

Designing for Dynamic Process not Static Structure

When engineers design structures for the river environment, normally great care is taken to ensure that the structures will retain a constant position in space despite fluctuating flow and sediment load. Although stream beds may fill scour and forces imposed by flow vary widely and hydrographs rise and fall, we expect well-designed revetments, training structures, bridges, dams, or gates to stay in place so that they will fulfill their intended function. However, designing large wood additions is often a different proposition. Instead of static structure, we are striving for more or less static function. If a large wood structure is intended to create and maintain pool habitat or cover, it may do this even if the individual wood members in the structure shift, rotate, or are replaced by fluvially transported wood. Wood structures shrink and subside as wood decays and grow as floating wood is racked up, sediments deposit, and, in some cases, as trees colonize the structures and associated sediment bars. If a wood project is intended to shift the channel morphology of a reach, say from a braided condition to an anastomosed channel or from a channel evolution model type IV to type V or VI, the original placed wood may be buried or otherwise "lost" as the channel shifts to the desired state.

Therefore, temporally dynamic wood structures do not represent failure. Wood can provide habitat benefits or temporary channel stabilization benefits even if large wood structures lose their integrity when placed wood is completely washed away and is not replaced by other wood, when undesirable scour or deposition occurs, or when the expected habitat benefits are not realized, project outcomes are not deemed successful.

As discussed in Chapter 3, *Ecological and Biological Considerations,* riparian revegetation is a key component of large wood addition. Vegetation growing on sediments deposited in or adjacent to large wood can anchor and restrain the wood, serve many of the same functions as nonliving wood, and, over the longer term, supply additional large wood to the fluvial system as in lightly degraded stream corridors. Large wood is not added to be a permanent feature of the river system, but to assist the natural fluvial system in recovering a cycle that involves wood addition, riparian zone regeneration, natural vegetative succession, and more wood addition.

CROSS-REFERENCE

The content of this chapter presupposes completion of a geomorphic assessment (Chapter 4, *Geomorphology and Hydrology Considerations*) and biological evaluation (Chapter 3, *Ecological and Biological Considerations*) of the project site.

The geomorphic assessment should include a description of the regions upstream and downstream as well as the project reach. At a minimum, the assessment should include these features.

- Characterization of geometry (thalweg profile, bed slope, cross section characteristics).
- Historic changes in geometry.
- Sediments (size, cohesion).
- Banks (erosion rates, locations, and processes).
- Riparian vegetation.
- Wood loading.
- Hydrology (frequency of overflow, magnitude of floods, and duration of droughts).
- A disturbance history (dams, dam removals, channelization, instream mining, fires, floods, logging, farming, etc.).
- Major sediment fluxes associated with these disturbances.
- Assessment of dynamic equilibrium/disequilbrium.

With these data, the project team should be able to ascertain the trajectory of ongoing channel evolution (e.g., incision, aggradation, widening, narrowing, braiding, avulsion.). Large wood structures may not be successful if applied in an effort to force a fluvial system to reverse the overall course of geomorphic evolution acting at the watershed scale (Shields et al. 2008), although reach-scale transformations have been initiated by some projects in the Pacific Northwest. Clearly, natural large wood accumulations have exerted major landscape impacts (Montgomery et al. 1995a, 1995b; Abbe 2000; Abbe and Montgomery 2003; Montgomery et al. 2003; Montgomery and Abbe 2006; Collins et al. 2012; Wohl 2013). The most ecologically beneficial large wood projects have floodplain-scale effects. There are still many rural areas where this scale is possible, and the projects can deliver important benefits to downstream human communities by trapping mobile debris and attenuating flood peaks. But most sites constrain project scale due to floodplain development. While there are natural circumstances such as confined bedrock canyons where natural large wood frequencies and densities are quite low, wood can be effectively applied in a wide range of site conditions, including urban streams. Ecological evaluation is needed to determine if existing large wood loading and stability is lower than a reference or other desirable state, or if positive biotic response is likely to follow stable large wood reintroduction. In cases where there is a desire to reintroduce mobile large wood, such as mitigating the impacts of dams, careful analysis should be done regarding the downstream fate of the large wood. If the large wood simply flushes through the system it will not provide desired benefits. Therefore if it is assumed the wood will be retained to enhance habitat, the project proponents should describe where and how large wood will be trapped and the function it will provide, and ensure stakeholders it will not be a threat to infrastructure, which might entail improving infrastructure or creating stable structures to trap large wood in desirable locations.

CROSS-REFERENCE

Effects of dams, wood sources, floodplain interactions and other topics relating to large spatial scales are discussed in Chapter 5, *Watershed-Scale and Long-Term Considerations*.

6.3 Area of Applicability

The site context of large wood structure projects is an essential aspect of success or failure. First, candidate sites should display low large wood loading relative to reference states or sites, but large wood should be a natural component of the geomorphic landscape. Reach context plays an important role in large wood risk profile and overall feasibility. If local land use and infrastructure permits significant channel change and increased flooding, great ecological benefit may be derived from large wood projects. Large wood projects can be extensive enough to raise flood stages, increase floodplain connection, develop or accentuate side channels, trigger migration or channel avulsions that create habitat, and reinitiate the cycle of tree growth and large wood supply from the floodplain (Collins et al. 2012). Because much of the local habitat value associated with large wood is due to scour and deposition, streams with nonerodible boundaries that transport little sediment are poor candidates to improve local habitat. Deeply incised channels[1] or channels with very narrow or absent floodplains present difficulties due to the relatively frequent deep submergence of the large wood, with attendant higher shear stresses and buoyant forces. In such channels, larger, more robust designs may be required that present difficulties in terms of flow conveyance or cost. Because channel incision is typically a progressive condition with negative implications for both habitat and infrastructure, robust large wood placement may be a priority for checking or reversing incision and attendant lateral instability (widening and narrowing). In general, large wood structures applied to channels that are not actively incising and have cobble or finer bed material may be designed with lower safety factors because they incur less risk (Table 6-1).

Because most tree species produce wood that decays within a few years unless it is continuously submerged, large wood structures are generally not suited for long-term stabilization unless the wood is preserved by continuous submersion. Section 6.4, *Design Life of Places Wood*, discusses decay rates and design life considerations. Large wood projects are best viewed as measures that will require periodic maintenance or as bridges toward a target state that facilitates riparian forest regrowth, large wood recruitment, and ongoing geomorphic evolution (Abbe and Brooks 2011). The latter approach necessarily involves regeneration of forested riparian zones and floodplains that serve as large wood sources (Erskine et al. 2012). The target state for the fluvial system features higher levels of naturally recruited stable large wood, channel stability, or habitat quality (Kail et al. 2007). Large wood loadings featuring extremely large trees produce resilient fluvial systems characterized by high levels of biogeomorphic complexity (Collins et al. 2012). So, in most cases, placed large wood will not persist in its constructed form. Wood will decay, be re-arranged by river flows, or accumulate and trap drifting wood. Sustainable benefits of wood placement are usually not due to the immobility or permanence of the placed members but due to rejuvenation of constructed large wood features with colonizing woody vegetation or recruited large wood material and sediment.

[1] Defined here as channels with average depths more than three times the average depth of nonincised reaches or channels with flow capacity greater than the 10-year return interval discharge.

Table 6-1. Limitations on the Applicability of Large Wood Structures

Variable	Considerations
Habitat requirements	Provides physical diversity, cover, velocity shelter, substrate sorting, pool development, undercut banks, and sites for terrestrial plant colonization using natural materials.
Existing large wood density	Absent or depressed relative to similar nearby reaches that are lightly degraded.
Sediment load	Generally best for gravel bed systems, but have been applied to sand and cobble systems. Resultant habitat value diminished when placed in streams with very low sediment loads. Large wood structures may be rapidly buried in high sediment load reaches, diminishing their aquatic habitat value, but accelerating recovery of terrestrial riparian habitats.
Bed material	Anchoring will be difficult in hard beds such as cobble, boulder, or bedrock. Structures placed in cobble bed rivers are often held in place with bed material used as ballast.
Bed stability	Not suitable for rapidly avulsing, degrading or incising channels unless riparian infrastructure and land use can tolerate large-scale channel movement. The best situations include areas of general or local sediment deposition along reaches that are stable or gradually aggrading. Deposition induced by large wood structures may be stabilized by planted or volunteer woody vegetation, fully rehabilitating a naturally stable bank by the time the placed woody materials decay. Unlike some of the other structure types, rootwads often create scour zones, not deposition.
Bank material	Large wood structures placed adjacent to erodible banks are subject to flanking, with special care needed for structures on sandy banks.
Bank erosion processes	Not recommended where the mechanism of failure is mass failure, subsurface entrainment, or channel avulsion. Best when toe erosion is the primary process.
Flow velocity or shear stress	Well-anchored structures have been successfully applied to situations with estimated velocities ~2.5 meters/second (D'Aoust and Millar 2000). Rootwad installations have withstood velocities of 2.7 to 3.7 meters/second (Allen and Leech 1997). ELJ-type structures withstood 1.2 meters/second in a sand-bed stream (Shields et al. 2004) and flows that produced estimated mean boundary shear stresses of 50 to 170 N/m^2 1.0 to 3.5 lbs/sq ft (Abbe and Brooks 2011).
Site access	Heavy equipment access to bring in and place large trees with rootwads is needed for all but the smallest project.
Conveyance	Large wood structures can increase flow resistance if they occupy significant parts of the channel prism (Shields and Gippel 1995).
Navigation and recreation	Design should minimize potential hazards to commercial or recreational navigation. Potential hazards are greatest for structures that span the channel.
Raw materials	Suitable sources of adequately sized logs needed within economically feasible haul distance.
Risk	Situations where failure would endanger human life or critical infrastructure call for rigorous risk analysis and higher safety factors.

Source: Fischenich and Morrow 2000.

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Regional Considerations in Large Wood Design

The basic physics of water, sediment, and wood are universal. However, wood decay rates are only one of the important regional differences facing large wood project planners and designers. Workers in other regions should be alert to differences between their project context and constraints and those found in the Northwest. Among these are hydrology, geomorphology, tree size, riparian land use and land ownership, aquatic ecology, endangered species, and patterns of recreational and navigational use of waterways. As noted by Shields et al. (2004):

> *Design of large wood structures…has been described for gravel-bed rivers … in the Pacific Northwest. Placing structures in incised, sand-bed channels of smaller streams typical of the Midwestern and southeastern U.S. presents a different set of challenges. In addition to basic differences in ecology, available wood tends to be smaller, material coarser than fine gravel for ballast is unavailable, and channel erosion rates (relative to channel width) are higher. Channel width–depth ratios are an order of magnitude smaller ~typically, 10), so storm flows tend to be deep, and structures are more frequently submerged. Bed slopes and current velocities are typically lower in sand-bed systems.*

Additional concerns attend the presence of ice loading and ice flows in northern states and the much wider difference between base flows and high flows for much of the rest of the country than those found in the Northwest. Regional differences exist in the likelihood of major wood loading associated with hurricanes, tornadoes, or avalanches.

Because much of the research on and implementation of large wood projects to date have been in the Pacific Northwest, there is a strong regional bias in the literature. Sources of regional design information include the following:

- Pacific Northwest: Knutson and Fealko (2014)
- Lower reaches of the Sacramento and San Joaquin Rivers and their tributaries: ICF International (2010)
- Southeastern Coastal Plain: Shields et al. (2004 and 2008)
- Appalachians: Hilderbrand et al. (1998)
- Australia: Brooks (2006)

6.4 Design Life of Placed Wood

Large wood naturally decays and breaks into smaller pieces. Large logs that are subjected to wetting and drying cycles may last only a couple of years in hot, humid climates but decades or even longer in cooler regions like the Pacific Northwest. Accordingly, large wood placement should be viewed as a "transitional rehabilitation technique" (Lester and Boulton 2008), and should not be attempted if reach- and watershed-scale geomorphology are not conducive to sediment retention, woody plant colonization, and stabilization of sediments retained by wood structures (Shields et al. 2008). A long-term goal of a large wood project is to replace the natural wood source—the riparian forest—and associated processes that will naturally replenish instream large wood and on the floodplain (Abbe and Brooks 2011).

Decay rates for logs that are periodically wetted and dried vary radically with tree species (Table 6-2) and with the wetting frequency, ambient temperatures, and humidity due to the requirements of the fungi responsible for aerobic decomposition of wood (Harmon et al. 1986). These decay rates are accelerated with increasing temperature and precipitation. Scheffer (1971) developed the following index for comparing potential decay rates of above-ground wood structures in different climatic regions of the United States.

Equation 6-1:

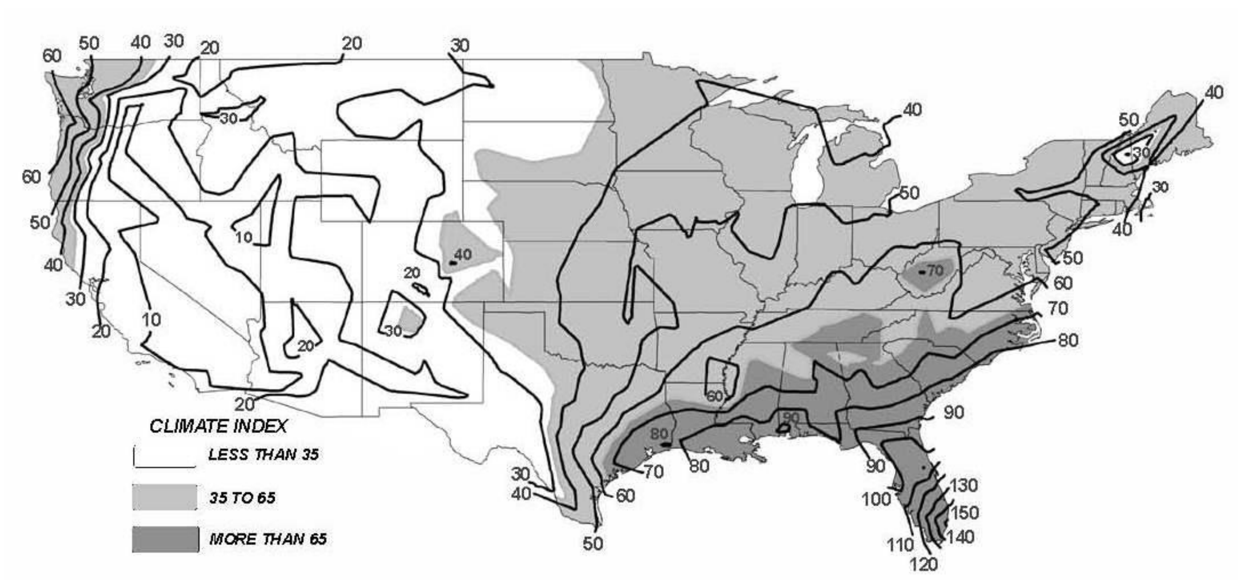
$$\text{Climate index} = \frac{\sum_{Jan}^{Dec}\left[(T-35)(D_p-3)\right]}{30}$$

where T is the mean monthly temperature (°F), D_p is the mean number of days in the month with 0.03 centimeter (0.01 inch) or more of precipitation, and the summation represents the sum of products for all of the months of the year. The sum is divided by 30 to make the index fall between 0 and 100 for most of the United States.

For example, Scheffer (1971) computed values of 82.5, 44.8, and 22.0 for Atlanta, Georgia, Des Moines, Iowa, and Casper, Wyoming, respectively (Figure 6-3). This implies a wood structure would last about four times longer in a climate typical of Wyoming than one typical of Georgia, all other factors being equal.

Hardwood species decay very slowly if continuously wet (Bilby et al. 1999) while decay is accelerated by periodic wetting and drying. Shields et al. (2008) reported breakup and decay of large wood structures comprising primarily deciduous species in a flashy, sand-bed Mississippi stream within 3 years. Cederholm et al. (1997a, 1997b, 1997c) reported significant degradation of partially submerged red alder logs in a western Washington stream after 3 years, but little degradation of conifer logs in an adjacent reach of the same stream.

Figure 6-3. Climate Index for Wood Decay Hazard



Source: Forest Products Laboratory 2010

Table 6-2. Comparison of Desirability of Various Tree Species for Stream Structures

Species	Durability (assuming wetting and drying)	Source[1]
Cottonwood (*Populus* spp.)	Poor	Johnson and Stypula (1993)
Alder (*Alnus* spp.)	Poor	Johnson and Stypula (1993) Cederholm et al. (1997a, 1997b, 1997c)
Maple (*Acer* spp.)	Fair (will survive 5 to 10 years)	Johnson and Stypula (1993)
Hemlock (*Tsuga* spp.)	Least of conifers	Johnson and Stypula (1993)
Sitka spruce (*Picea sitchensis*)	Excellent	Johnson and Stypula (1993)
Douglas-fir (*Pseudotsuga* spp.)	Excellent, will survive 25–50 years 32–56	Johnson and Stypula (1993) Harmon et al. (1986)
Western red cedar (*Thuja plicata*)	Most desirable, will survive 50 to 100 years	Johnson and Stypula (1993)
Yellow-poplar (*Liriodendron tulipifera*)	0.4 year	Harmon et al. (1986)
Aspen (*P. tremuloides*)	5 years	Harmon et al. (1986)
White fir (*A. concolor*)	4 years	Harmon et al. (1986)
Norway spruce (*Picea abies*)	~30 years	Kruys et al. (2002)
Conifers (*P. sitchensis, T. heterophylla, P. menziesii, T. plicata*)	Half-life of ~20 years	Hyatt and Naiman (2001)
Black locust (*Robinia pseudoacacia*), red mulberry (*Morus rubra*), Osage orange (*Maclura pomifera*), Pacific yew (*Taxus brevifolia*)	Exceptionally high heartwood decay resistance	Simpson and TenWolde (1999)
Old growth bald cypress (*Taxodium distichum*), catalpa (*Catalpa* spp.), cedars (*Cedrus*), black cherry (*Prunus serotine*), chestnut (*Castanea* spp.), Arizona cypress (*Cupressus arizonica*), junipers (*Juniperus* spp.), honey locust (*Gleditsia triacanthos*), mesquite (*Prosopis glandulosa*), old growth redwood (*Sequoia sempervirens*), sassafras (*Sassafras albidum*), black walnut(*Juglans nigra*)	Resistant or very resistant to heartwood decay	Simpson and TenWolde (1999)
Young growth bald cypress (*Taxodium distichum*), western larch (*Larix occidentalis*), longleaf old growth pine (*Pinus palustris*), old growth slash pine (*Pinus elliottii*), young growth redwood (*Sequoia sempervirens*), tamarack (*Larix laricina*), old growth eastern white pine (*Pinus strobus*)	Moderately resistant to heartwood decay	Simpson and TenWolde (1999)

Species	Durability (assuming wetting and drying)	Source[1]
Red alder (*Alnus rubra*), ashes (*Fraxinus* spp.), aspens (*Populus tremuloides*), beech (*Fagus* spp.), birches (*Betula* spp.), buckeye (*Aesculus glabra*), butternut (*Juglans cinerea*), cottonwood (*Populus* spp.), elms (*Ulmus* spp.), basswood (*Tilia Americana*), true firs (*Abies* spp.), hackberry (*Celtis occidentalis*), hemlocks (*Tsuga* spp.), hickories (*Carya* spp.), magnolia (*Magnolia grandiflora*), maples (*Acer* spp.), pines (*Pinus* spp.), spruces (*Picea* spp.), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), tanoak (*Notholithocarpus densiflorus*), willows (*Salix* spp.), yellow-poplar (*Liriodendron tulipifera*)	Slightly or nonresistant to heartwood decay	Simpson and TenWolde (1999)

[1] Information from Johnson and Stypula (1993) is qualitative and unsubstantiated. Evidently these comments pertain to the region of King County, Washington. Harmon et al. (1986) provide a review of scientific literature dealing with decomposition rates of snags and logs in forest ecosystems. The times from Harmon et al. (1986) represent the time required for 20% decomposition (mineralization) of a log based on exponential decay constants obtained from the literature. Fragmentation of logs in streams due to mechanical abrasion would accelerate the decay process, as would more frequent wetting and drying. Kruys et al. (2002) provide data on decay of fallen and standing dead trees in a forest in mid-northern Sweden. Hyatt and Naiman (2001) provide data on residence time of large wood in Queets River, Washington. Simpson and TenWolde (1999) provide data for evaluating wood products, not whole trees. Additional data on lumber (not large wood) are available from Forest Products Laboratory (2010).

Effects of the red alder logs on habitat were projected to disappear within 5 years of placement, but the conifer structures had a design life of 25 years. Hertzberg (1954) reported that fence-type wooden revetments made of wood impregnated with preservative (creosote) had a design life of 20 years along the Lower Mississippi River, while structures made of cylindrical bundles of fresh willow brush exhibited "rapid deterioration."

In sharp contrast to the above, certain natural log accumulations have been shown to be stable for centuries in the Pacific Northwest and in Australia (Abbe and Montgomery 1996; Nanson et al. 1995). Conifers in the Pacific Northwest and eucalypt species in Australia are decay-resistant relative to other species. In general, decay rates are lowest for species with high-density wood. Writing about decay-resistant wood placed in Australian rivers, Brooks (2006) suggests that a "well designed structure in the right conditions" may be expected to have an effective design life of "50 years or more." Wohl (2013) reviewed available literature and found that the decay rates of logs on a forest floor are as follows:

Climate	Time for Full Decay (years)
Cold Boreal/Subarctic	>100
Dry	50–100
Humid-Temperate	10–100
Tropical	<10

Wohl (2013) further noted that although the rates of decay for waterlogged instream wood may be slower due to anaerobic conditions, the relative rates of decay between regions based on forest-floor decay rates likely hold for instream wood.

Clearly, large wood species, climate, local hydraulics, and reach hydrology all play a role in the stability of natural wood and large wood structures. It is very important to note that decaying wood loses mass and volume at an exponential rate (Harmon et al. 1986):

Equation 6-2:

$$Y_t = Y_0 e^{-kt}$$

where

Y_0 = initial quantity (density, mass, or volume) of wood

Y_t = amount left at time t (year), and

k is a decay-rate constant (year^{-1})

Harmon et al. (1986) reported species-specific values of k for logs lying on a forest floor range from 0.004 to 0.52 year^{-1}, which implies that logs of these species will lose 1–63% of their density within only 2 years. A more recent study of six species in Sweden documented k values ranging from 0.039 to 0.102 year^{-1} (Freschet et al. 2012).Therefore, using appropriate k values, Equation 6-2 may be used to predict the relative density or mass of large wood after a given period of time (Abbe 2000; Abbe et al. 2003b; Abbe and Brooks 2011).

In some cases, the design life of components other than wood should be considered when estimating the design life of a large wood installation. For example, fiber rope may decay faster than wood, or metal hardware may corrode and weaken.

Living plant materials such as willow cuttings may be used in a large wood project to promptly establish vegetation on sediment deposits induced by large wood structures or to revegetate riparian areas disturbed during construction or pre-project erosion. Guidance such as that of the Natural Resources Conservation Service (NRCS) (2007a) can be quite helpful regarding use of such measures.

6.5 Level of Design Effort

Fluvial systems and their interactions with riparian vegetation and large wood are exceedingly complex. The engineer must devote sufficient effort to planning and design of large wood structure projects to achieve an acceptable standard of care and rate of success without wasting resources on excessively elaborate analyses. As described in Table 6-3, the levels of design effort used for instream large wood structures are used to determine the context and expertise needed to complete an analysis. In some cases it may be wise to confine feasibility studies to Levels I and II, with Level III used in preliminary and final designs. Pencil and paper analyses are rapid and relatively cheap while spreadsheets are dynamic and allow for sensitivity analyses in the computation of applied and resisting forces or costs when key parameter values are uncertain and only a range may be specified. Only numerical simulation allows the engineer to approach understanding the impacts of structures on flows and sediment movements at the reach scale. Accordingly, modeling allows the designer to view the impacts (e.g., on conveyance) of changing the numbers, locations, or sizes of structures placed in the study reach. Additional modeling may allow quantification of habitat benefits, although biotic responses may not follow habitat improvements.

6.6 Design Decisions and Data Requirements

Large wood structure design may be viewed as a series of data gathering and analysis exercises, each of which leads to a decision point. Feedback is required as certain design decisions affect previous design decisions. Key design issues are outlined in Table 6-4.

Table 6-3. Levels of Design Effort for Instream Large Wood Structures

Level	Description and Example	Context	Relative Risk Level
I	Pencil and paper	Small stream, experienced designer, overall risk to infrastructure or human life small, small equipment or hand tools, construction done under arrangement (i.e., hourly hire) that freely allows adjustment of design in the field.	Low
II	Spreadsheet, Bank Stability and Toe Erosion Model (BSTEM)	Small to medium stream, overall risk to infrastructure or human life small, heavy equipment, construction done under contract that requires development of plans and specifications.	Medium
III	1D and 2D numerical simulation including geomorphic response streambank stability and other types of geotechnical engineering	Medium to large stream, design by team of specialists across range of disciplines, significant risk, construction under contract that requires development of plans and specifications. See below for additional discussion on numerical model selection.	High

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Minimum Data Requirements for Successful Designs (Brooks 2006)

1. Cross-section surveys including representative sections spaced at no more than one channel width, ideally at each structure location, with a minimum of 10 per reach to try to capture more than one complete riffle-pool sequence (if they exist).
2. Thalweg profile survey (at least three riffle-pool sequences or 15 to 20 channel widths long). This information will help determine the reach bed slope (i.e., as a regression line passing through crossing or riffle crests).
3. One bed material sample from the center of each cross section.
4. Streamflow data or regional regression relations for flow frequency.
5. Desired wood loading.
6. Wood dry density and approximate sizes of available wood.

Table 6-4. Key Engineering Issues for Instream Large Wood Structure Placement

Category	Decisions
Hydrology	What is the design event? How will the structures affect/interact with smaller and larger flows? Should ice be considered in the design?
Reach layout	How many structures will be placed and where?
Materials	What types and sizes of logs and other materials will be used? Sources?
Structure dimensions and details	What type/shape of structures will be employed? What will their dimensions be?
Hydraulics	How will the project affect habitat quality and high flow stages?
Sediment	What effect will the project have on local scour and deposition, bank erosion, reach scale morphology, channel response, habitat value, and terrestrial plant colonization?
Vegetation	How much effort should be devoted to planting vegetation? Should effects of vegetation on structural stability (surcharge, sediment cohesion), erosion, and bank stability be included in analysis, and, if so, how?
Anchoring	What is the magnitude of forces that the structures must be designed to resist? Will anchoring involve passive or active restraints? What factors of safety will be used?
Construction	What construction methods will be utilized? Will channel be de-watered or large wood placed in the "wet"? What adverse impacts will be created by construction, and how can they be controlled? What time windows (seasons) will be used for construction?
Economics	Can the project be delivered within budget? How can value be increased?

6.6.1 Hydrology

6.6.1.1 Determination of Design Discharge

Features within stream corridors are normally designed to withstand loadings imposed by discharges with a certain frequency or return interval such as the 100-year, 10-year, or 2-year event. Computation of hydraulic loadings imposed by a design event requires knowledge of the discharge associated with the design event frequency. Design discharges may be determined by statistical analyses of data from nearby gages or using other techniques described below.

The design event return interval may be based on the design life of the structure (Knutson and Fealko 2014); the tacit assumption here is that larger events will impose larger shear forces (drag, lift, buoyancy) on the structures. However, peak velocities may be associated with more frequent (e.g., bankfull) events. In some systems, the design condition may correspond to prolonged high flows, while in other cases driving forces will be greatest during a sudden rise in stage after a long drought that desiccated the wood (Abbe and Brooks 2011). In such a case, the buoyant forces and wave drag would reach maxima when the structure is initially overtopped (Shields and Alonso 2012). Design discharge selection should be consistent with the risk analysis and be completed prior to design (*see Chapter 7, Risk Considerations*). The expected frequency of the design event should be compatible with the design life of the structures and the planned intensity of maintenance.

The ratio of more frequent to less frequent discharges may be considered. For example, in some systems the difference between the Q_2 (2-year return interval discharge) and Q_{25} is small, while in others it is an order of magnitude or more. So in some cases the difference between designing for the smaller and the larger event is small. In some cases, large wood design for Q_{100} may not be economically or technically feasible. In the Pacific Northwest it is not unusual for designs to be required by regulators to be stable at or above the 100-year flood level. Streams with large variability usually feature flashy hydrology, and large wood structures are repeatedly wet and dried, accelerating decay and deterioration and shortening design life.

Hydrologic Data from Gaged Sites

Ideally, a gaging station is located near the project site with an established gaging record of mean daily flow (typically an average of all the 15-minute interval flows reported in a day). The U.S. Geological Survey (USGS) is the primary source of mean daily flow data in the United States, with gaging location information and data available online (http://water.usgs.gov/osw/). Data from gages operated by the state, local municipalities, water districts, and hydropower companies may also be available.

Collecting Data from Ungaged Sites

Depending on the scale of the project and time available to collect new data, it may be practical to collect data at least for a few high-frequency events. The basic approach to developing a new stream gaging record is to correlate observations of flow stage with discharge measurements made at the same time to develop a stage-discharge relationship. Multiple flow measurements are required to create enough data points spanning low to high flows through which a stage-discharge curve could be drawn. Stream gaging is described in textbooks and other restoration handbooks and will not be described further here. Sauer and Turnipseed (2010) provide details on stage and discharge measurement at gaging stations.

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StreamStats

The StreamStats software is a web-based GIS tool (http://water.usgs.gov/osw/streamstats/) that can be used to obtain streamflow statistics, basin characteristics, and other information for user-selected sites on streams to aid in regional regression analysis. Specific capabilities of the National Streamflow Statistics Program include:

- Estimate rural and urban flood-frequency discharges for ungaged streams by use of regression equations, or for six states, by region-of-influence analysis.
- Estimate a wide range of low-flow duration and frequency discharges for ungaged streams.
- Estimate discharges for natural streams. The program does not account for the effects of water diversions, dams, flood-detention structures, and other human-made works.
- Statistically weight estimated peak discharges for ungaged sites with drainage basins that span multiple hydrologic regions using the percentage of drainage area in each region within a given state.
- Statistically weight estimated and observed peak discharges for stream gaging stations using the equivalent years of record of the regression estimate and the number of years of observed record as the weighting factors.
- Statistically weight estimated peak discharges for ungaged sites obtained from regression equations and from the flow per unit area for an upstream or downstream gaging station.
- Plot hydrographs of flood and low flows.
- Generate frequency graphs for both high- and low-flow frequency analyses.

Flow Frequency Analysis

Once a design discharge frequency is selected, standard analyses may be used to derive the discharge magnitude using gage data. The designer should check on the adequacy of available data. A minimum of 10 years of peak discharge data is required under Bulletin 17B guidelines (IACWD 1982), and 30 or more years of data are preferred. Estimating flood frequencies for recurrence intervals more than twice the annual series record length is cautioned against. Longer periods of record reduce the need for extrapolation to determine infrequent return period discharges, and thus increase the certainty in the estimate. However, the designer should evaluate long periods of record for time-homogeneity (i.e., stationary) to establish that the causative hydrological processes remain consistent over the annual series and that two events of the same magnitude in the annual series are likely to occur at any time in the series (Subramanya 2008). Altered hydrology arising from changed land use conditions and actions such as dam construction, changes in reservoir operations, or water diversions could systematically change peak flow values, which must be accounted for in the frequency analysis by only including the most recent continuous homogeneous portion of the annual series. Likewise, long-term changes to peak flows due to climate change and extreme events that could occur must be considered in the implementation and interpretation of the flood frequency analysis.

Procedures for frequency analysis of discharge data are outlined in textbooks (e.g., Subramanya 2008; Eslamian 2014) and other river restoration handbooks (e.g., NRCS 2007f) and will not be described further here.

If gaging data are unavailable or the period of record is insufficient, then alternative techniques are required. If a stream gage is located upstream or downstream of the project reach with 10 or more years of record, it may be possible to transfer information from the gaged site. If drainage areas for the two gages have similar terrain and land cover, discharges from the gaged site may be transferred to the ungaged site using a ratio of drainage areas or more sophisticated approaches as described by NRCS (2007f) and Saur (1974).

Also for ungaged sites, discharges of a given frequency may be estimated using region-specific regression formulas that use watershed characteristics as dependent variables (National Streamflow Statistics Program[2]). Many of these formulas are included in StreamStats.[3] In addition to application of the USGS tools, regional regression equations applicable to the project may have been developed by others. The designer is cautioned that the empirical regression equations are based on statistical models, and must be applied within the limits of the data used to develop the equations with the acknowledgement of associated scatter in the data (Gotvald et al. 2012). StreamStats provides confidence limits for peak discharge estimates. For example, standard error values from the Sierra Nevada hydrologic region were reported by the USGS as ranging from 51.5% for a 4% exceedance probability to 74.4% for a 50% exceedance probability (Gotvald et al. 2012). Discharge values from regression formulas may be checked against uniform flow computations (e.g., Manning formula) based on survey data and appropriate resistance coefficients.

Rainfall-Runoff-Routing Modeling

Rainfall-runoff-routing models can be used where gaging data is not available or reliance on historical data or regional regression equations alone is not sufficient. Results from hydrologic models can be compared with separate flood frequency estimates, and offer the benefit of evaluating hydrologic conditions for future conditions where climate and land use may vary appreciably from the historic conditions of the gaging record. Numerous rainfall-runoff-routing models are available,

[2] Available at http://water.usgs.gov/software/NSS/
[3] Available at http://streamstats.usgs.gov/.

including the relatively easy to use Soil Conservation Service's curve number based WinTR-55 (for areas <65 square kilometers [25 square miles]) and without snowmelt capability), USACE's Hydrologic Modeling System, and the U.S. Environmental Protection Agency's (EPA's)/USGS' Hydrological Simulation Program-Fortran model. These models require information on watershed land use, topography, soil characteristics and infiltration, storage, and other variables to transform design precipitation events into runoff hydrographs that are routed through channel networks. The designer must use intensity-duration-frequency data to determine the precipitation hyetograph of a specified design storm frequency and duration and use the rainfall-runoff-routing model to calculate volume, stage, and peak flow.

The frequency of the design storm event is commonly assumed to be approximately equal to the frequency of the design flood event. However, this is not always true due to watershed complexities and variations in storm intensity and duration. Instead of calculating peak flows from all different types of 100-year storms, it is common practice that for smaller watersheds the storm duration is set to equal the time of concentration, whereas in larger watersheds with times of concentration over 1 hour it is common to only evaluate the 6-hour and 24-hour storm (Viessman and Lewis 2003).

6.6.1.2 Hydrologic Design for Habitat

Base Flow

Base flow is typically the minimum flow in the stream supplied by groundwater and release of water stored in the channel's banks. In regulated systems base flow conditions can be altered by controlled reservoir flow releases or water diversions or inputs. Various techniques are available for determining base flow conditions from hydrographs (Subramanya 2008). In many perennial stream hydrographs, base flow is readily observed as the slowly decreasing flow on the receding portion of the hydrograph that reaches a minimum prior to the addition of direct runoff from the next rainfall or snowmelt event. The designer should evaluate how base flow conditions may change between wet and dry water year types to ensure that elevations of the structure intended to be continually submerged will in fact be submerged.

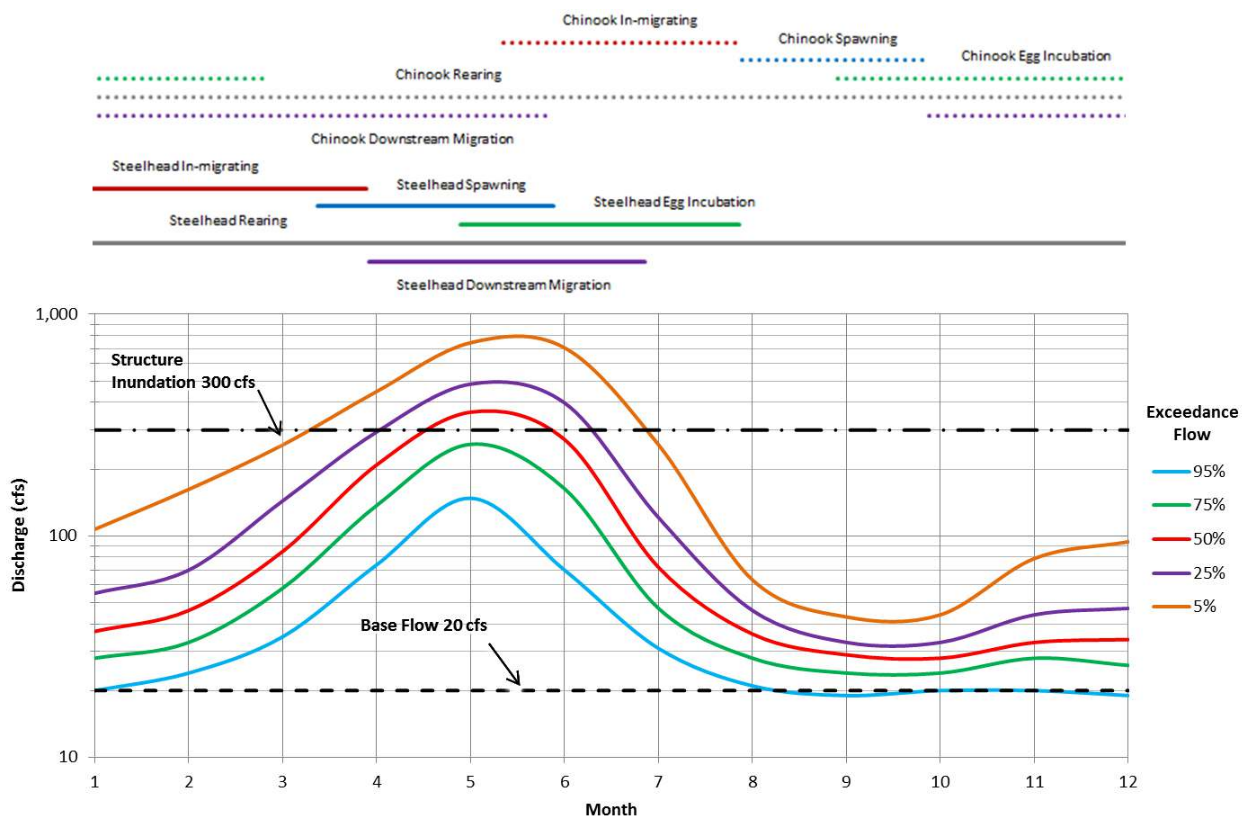
Exceedance or Flow Duration Curve Analysis

Exceedance analysis is performed to determine the probability that a flow of a particular magnitude is equaled or exceeded based on statistical analysis of the flow record. A plot of discharge versus the percentage of time the discharge is equaled or exceeded at a given site is called a *flow duration curve*. The analysis is typically performed on the mean daily flow record available from a stream gage or determined from a rainfall-runoff simulation model or other method. For flashy streams exhibiting rapid changes in flow magnitude over the course of several hours as opposed to days, the 15-minute flow record can be used in the analysis instead of daily flows.

Procedures for developing flow duration curves are presented in standard texts (e.g., Subramanya 2008) and handbooks (e.g., NRCS 2007f) and will not be described here. The entire measured or simulated flow record can be used in the analysis; however, the same data considerations discussed above for peak flow analysis also apply, namely analysis of the data to establish that the causative hydrological processes remain consistent and time-homogeneity is achieved. Factors that have affected the long-term flow record, such as flow regulation, land use change, or climate change, should be accounted for in the period of record selected for the analysis. Furthermore, the designer should evaluate the length of the flow record and determine if it contains a representative sample of wet and dry water years, and consider performing separate analyses for different water year types to better understand flow variability between water years. For cases where a gaging record has incomplete data for a particular water year, it is common to exclude all of the data for the year to prevent skewing of the probability analysis. Separate exceedance analyses can be performed on different periods of time in the flow record (e.g., 10- to 20-year increments) to test for departures from the data trend indicative of a non-stationary flow record.

Performing an exceedance analysis of the flow record on a monthly (or other desired time-step) basis is helpful for assessing the habitat value of a wood structure during various seasons. Ecological events or seasons tied to life cycles for species of interest may be displayed on an annual hydrograph showing various flow exceedance levels and key project attributes to assess habitat performance (Figure 6-4).

Figure 6-4. Graphical Output of Mean Daily Flow Monthly Exceedance Analysis and Project-Specific Salmonid Life Stages



6.6.2 Reach Layout

Reach layout refers to the arrangement of large wood within the channel. Approximate locations of proposed large wood placements should be recorded on hard copy or digital maps of the project reach. Because the number of structures will directly influence project costs, it is important to strategically size and place wood structures. Initial plans may be based on study of *target reaches*. A target reach is defined here as a lightly impacted reach with similar width, depth, slope and grain size to the project site. There are no true target reaches due to the ubiquity of human influences, although our understanding of pre-European settlement conditions indicates that rivers of North America had levels of wood loading much greater than even contemporary heavily loaded systems (*see Chapter 1, Large Wood Introduction, and Chapter 4, Geomorphology and Hydrology Considerations*). A target reach must be selected with reference to the project goals (e.g., habitat rehabilitation, erosion control). Target reach levels and types of wood loading may be used as design analogs for the amount and distribution of wood in the design reach.

Reach layout should tie in heavily with project geomorphic objectives: are wood structures intended to facilitate or mitigate channel avulsion and braiding; engage side channel development; and control bank erosion, store sediments, or trap wood? How much aggradation or incision is currently occurring, and how will the large wood interact with that process? As for naturally occurring large wood, structures may be placed at the head of a bar or an island, in mid channel (to foster development of a bar or island), along the bank on the outside of a bend, at the upstream entrance to a side channel, fully spanning the channel, or secured on floodplain surfaces (to reduce potential for channel avulsions by increasing flow resistance or to serve as instream wood after future channel shifting occurs) (Cramer 2012).

Although the specific types of large wood structures should be selected in the next design step, a general determination must be made for reach layout. Large wood placement usually has a primary goal of improving habitat quality by adding woody substrate, cover, scour pools, and physical heterogeneity. Large wood structures may be intended to address either vertical (bed) or horizontal (bank) erosion processes. Cramer (2012) noted the variation of large wood configuration with stream size and the associated function and risk (Table 6-5).

Table 6-5. Recommendations for Placement of Large Wood in Streams for Aquatic Habitat Benefits

Stream Size	Width (meters)	Large Wood Structure Functions and Risks	Natural Large Wood Configurations
Small	<10	Single or multiple pieces of wood can be effectively used to create habitat, stabilize the channel, dissipate energy, and store sediment. Logs in small streams may be used to create step pools (i.e., plunge pools). Because small streams generally have less energy to move large wood, a greater variety of large wood locations and orientations can be employed without excess risk.	Logs most often lie perpendicular or are angled downstream to flow, but any orientation is feasible. They may span the channel or intrude partway into the channel.
Medium	10–20	Channel-spanning wood structures may be applicable, but the results are less predictable than for small streams and their vulnerability to flood damage is relatively high.	Wood tends to accumulate in jams, but single pieces and small complexes also occur. The outside of bends and the head of natural gravel bars tend to be relatively stable locations for wood jams.

Stream Size	Width (meters)	Large Wood Structure Functions and Risks	Natural Large Wood Configurations
Large	>20	Stabilizing woody debris becomes a significant concern on larger streams. Wood placement in the main stem of the channel is only recommended in the form of anchored structures (i.e., log jams, large wood complexes, and wood trapping structures), unless transport can be tolerated. Key pieces and log complexes can be effectively used in side channels and floodplain habitats.	Lateral jams, as opposed to full-spanning jams, are a common feature. As with medium-sized streams, locations at the outside of bends and the head of natural gravel bars tend to be relatively stable.

Source: Saldi-Caromile et al. (2004); Cramer (2012).

6.6.2.1 Bed Control

Bed control structures (Figure 6-5) should be spaced so that backwater from one structure reaches the next structure upstream during channel-forming flows (about Q_2 for many channels). Bank erosion control structures may be continuous blankets or intermittent, spur-type structures (Figure 6-6). Spacing for intermittent structures is normally expressed as a multiple of the length of the structure from bank to riverward tip, measured perpendicular to the approach flow (this distance is called the projected crest length or effective length or structure protrusion width) (Table 6-6).

Figure 6-5. Large Wood Bed-Control Structures

Photo a. Natural channel-spanning large wood, Trail Creek in the Snowy Range of the Medicine Bow Mountains, Wyoming (Claire Ruffing).

Photo b. Constructed bed control large wood structure in Australia (Andrew Brooks).

Figure 6-6. Continuous and Intermittent, Spur-Type Large Wood Structures

Photo a. Continuous blanket type structure. Cabled spruce trees and brush layering immediately after installation, Ciechanski Recreation Site, Kenai River. Alaska Department of Fish and Game.

Photo b. Intermittent large wood structures; Little Topashaw Creek, Mississippi, showing sediment deposition at toe of eroding bank induced by structures.

Table 6-6. Criteria for Spacing Intermittent Large Wood Structures along the Outside of Meander Bends[a]

Channel Planform	Large Wood Structure Spacing	Source
Rc/W > 3	3 to 5 x projected crest length	Sylte and Fischenich (2000)
Rc/W < 2.5	Spacing goes to zero—use continuous type structure	
Tight bends	3 x projected crest length	Drury et al. (1999), Brooks (2006)
Straight reaches	5 x projected crest length	
All	1.5 to 2.0 x crest length	Petersen (1986) in Shields et al. (2004)
All	2/3 to 2.5 times the length of the upstream structure	Pokrefke (2013)

Rc/W = bend radius of curvature divided by channel top width

[a] These design criteria are extracted from works guiding placement of river training and bank protection structures designed to produce channel stability. If higher levels of dynamism are desired or tolerable, spacing should be increased. Erosion between widely spaced structures may lead to flanking (river avulsion around the land side of structure).

6.6.2.2 Bank Protection

For erosion control objectives, reach layouts may be designed using guidelines for traditional spur dikes and groins (Ahmad 1951; Copeland 1983; Klingeman et al. 1984; Design Guideline 2 in Lagasse et al. 2009). Although large wood may be effectively employed to control bank erosion and protect infrastructure (Figures 6-7 and 6-8) (Abbe et al. 1997, 2003c; Shields et al. 2004), well-designed placements also offer aquatic habitat benefits (Shields et al. 2006).

Figure 6-7. ELJ Spacing to Protect Road and Enhance Habitat Along the Cispus River

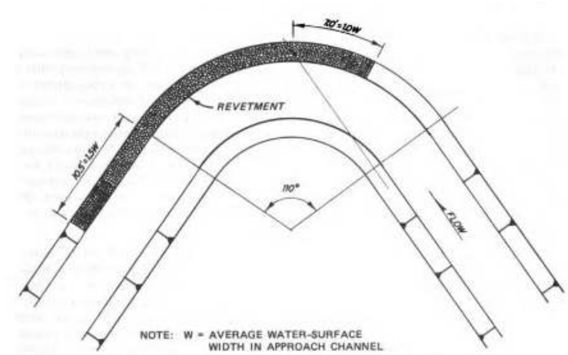
Gifford Pinchot National Forest, Washington—project was constructed in 1999 and had been subjected to a 25-year and two 10-year flood events by 2014. Structures successfully established a forest buffer between highway and river.

Figure 6-8. Example of the Use of Two Sets of ELJs in Bank Protection Along Hoh River

The Hoh River is a large gravel bedded river draining the Olympic Mountains of Northwest Washington—the first set is laid out upstream of eroding bank to deflect flow into chute channels across point bar. The second is placed along outer bend similar to series of spur dikes.

Continuous or intermittent structures should cover the entire zone of potential erosion. Many streambank projects fail because protection was not extended far enough upstream, downstream, or into the bed. Protection should be extended well past the anticipated zone of current attack during design events. Figure 6-9 may be used for an initial estimate of the required downstream extent of bank protection. The initial extent of bank protection determined from Figure 6-9 should be adjusted according to field observations of active scour, channel surveys at low flow, and aerial photography and field investigations at high flow. Investigators of field installations of bank protection have found that protection commonly extends farther upstream than necessary and not far enough downstream.

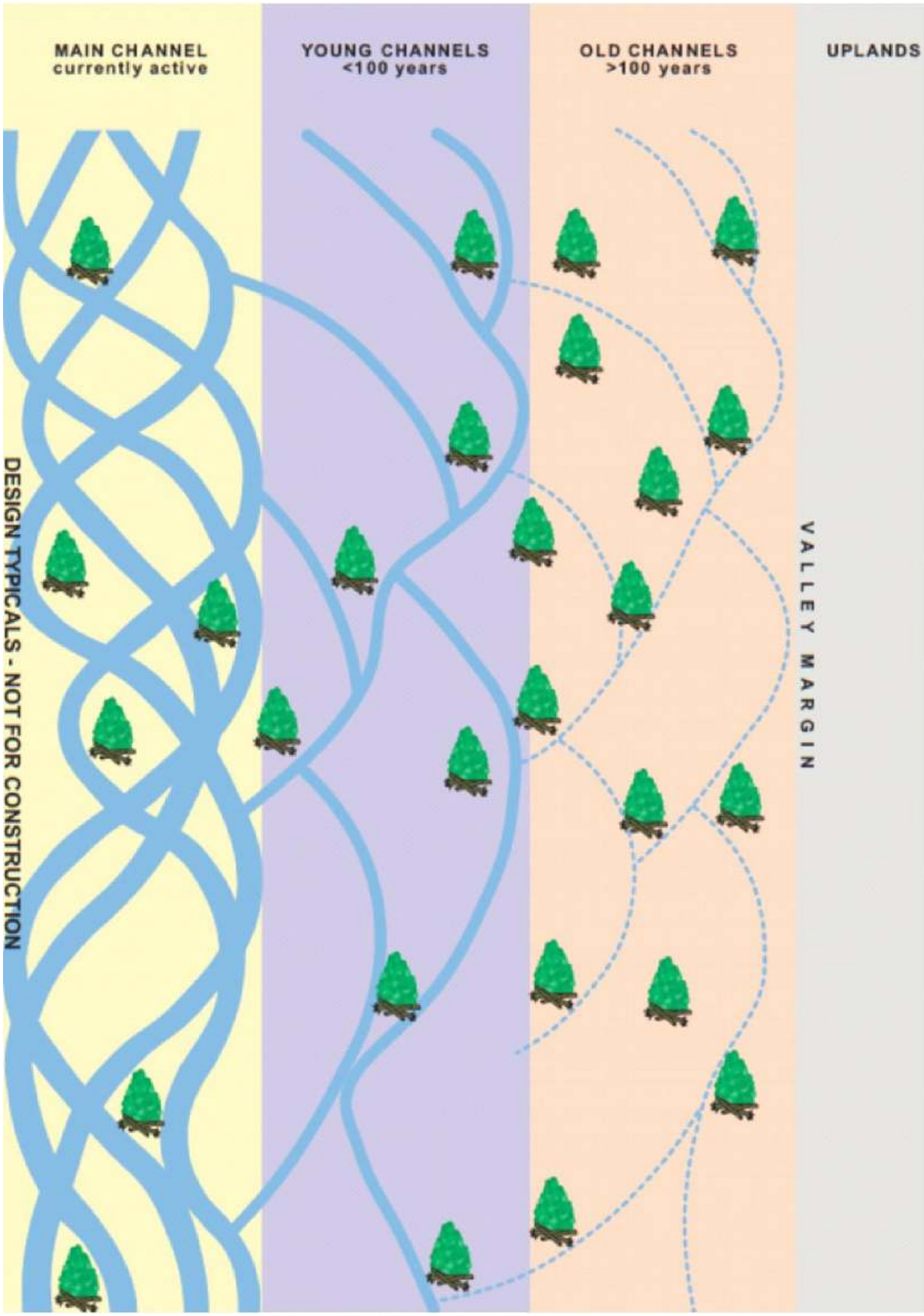
Figure 6-9. Recommended Extent of Riprap Revetment for 110° Bend



Source: USACE (1981) in Lagasse et al. (2009).

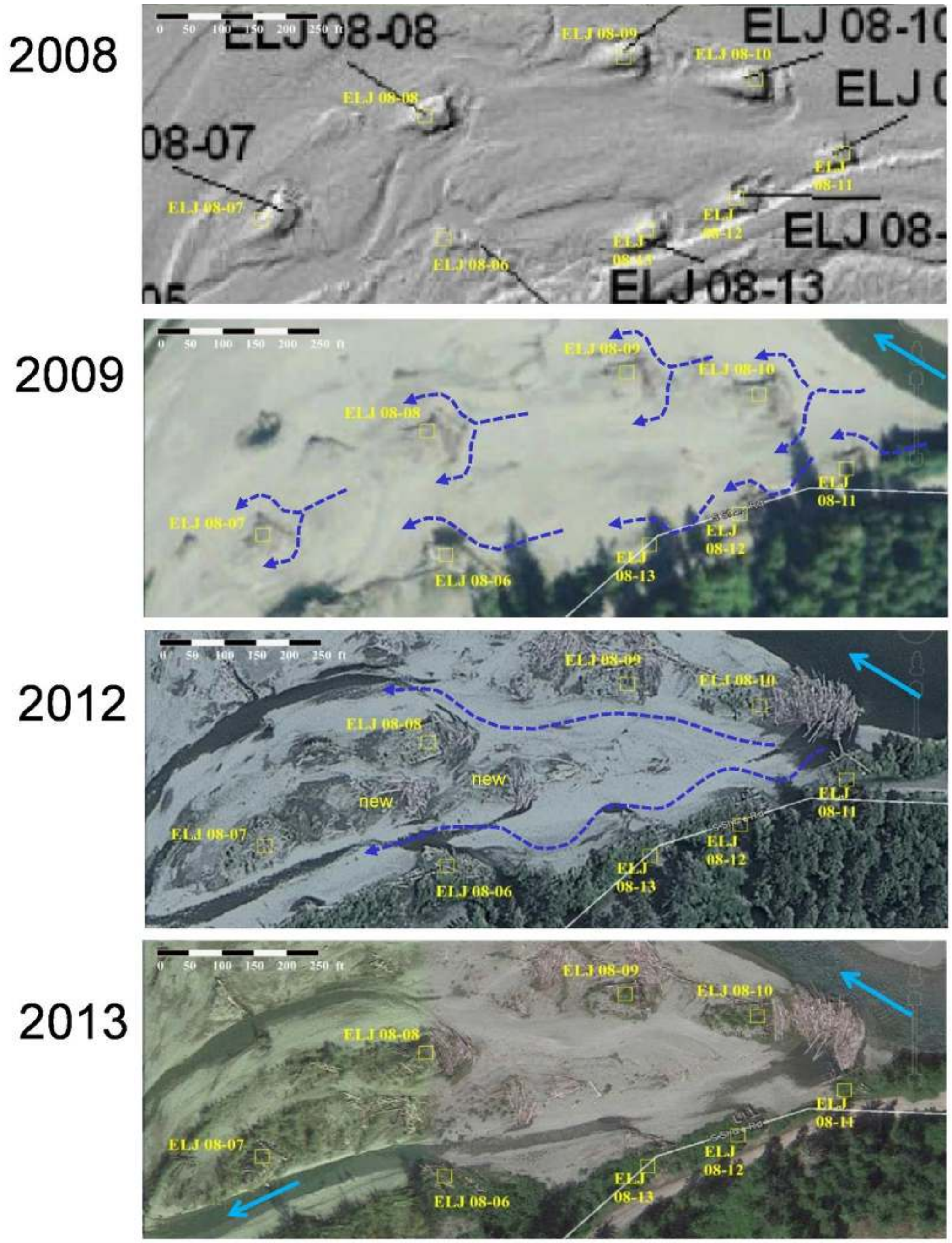
More aggressive designs have used large wood structures to split a main channel into smaller channels prior to reaching the eroding bank where additional large wood structures are positioned (Figure 6-8). For rivers that have a sufficient floodplain corridor this approach is a sustainable means of balancing restoration and flood protection. An array of ELJs that increases in density with distance from large migrating rivers will split the channel into smaller anabranches and diminish erosive energy to effectively limit the extent of channel migration, restore floodplain forests, and protect areas that might otherwise be at risk of eroding (Figure 6-10) (QIN 2008). This strategy diminishes the stream power reaching the site of concern in a way that restores the channel and floodplain complexity the river once had (Figures 6-10 and 6-11) (QIN 2008).

Figure 6-10. Valley Scale Restoration Approach to Limiting Bank Erosion Along Valley Margins



Density of roughness elements (i.e., ELJs) increases toward the margin of the valley. This type of layout breaks up the channel into smaller and smaller channels or anabranches with distance from the main channel (from QIN 2008)

Figure 6-11. Upper Quinault River Valley Floodplain and Side Channel Restoration



Array of ELJs constructed on large point bar in 2008 (depicted in LiDAR DEM at top). Main channel is in upper right and flowing to right to left (west) By 2012 the river migrated into ELJ 08-10, forming a new pool, added more than 100 feet of racked wood, initiated new side channels, and two new logjams formed. By 2013 the side channels are more pronounced and ELJs are forming forested islands.

6.6.3 Select Types of Structures

Reach layout and selection of large wood structure type are closely related, and some cycling back and forth between these two decision steps is usually required. More than one type of structure should be used in a reach, and structure type should be matched to the local morphology and desired functions.

Structures that protrude into the flow like logjams, weirs, or spurs tend to create greater habitat diversity than those that parallel banks like revetments. When selecting structures that fully, span the channel, avoid using single-log weirs, they are subject to undercutting and have no redundancy should the log fail. The more logs used, the stronger the structure and greater the factor of safety. Whether using a step-pool or reinforced riffle design, it is important to minimize the magnitude of individual drops and thus create broad-crested structures (Table 6-7; Figure 6-8). This typically increases the cost, but greatly increases structure stability and enhances fish passage. In steep step-pool or cascade channels this may entail placing wood throughout the length of the stream. Considerable research has been recently completed on step-pool streams (e.g., Comiti and Mao 2012).

Two schools of thought exist on large wood structure design and typology: one relies on emulation of natural large wood formations (jams) observed in the Pacific Northwest (Abbe et al. 2003b), while the other is loosely based on more traditional river training structures (Shields and Wood 2007). A combination of these two schemes is presented in Table 6-7. Uniform spacing and structure configuration should be avoided in favor of variation in the frequency, size, and type of structure applied (Erskine et al. 2012).

GUIDANCE

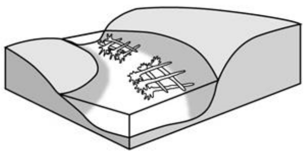
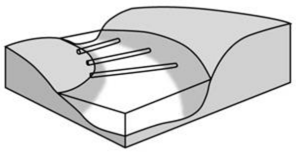
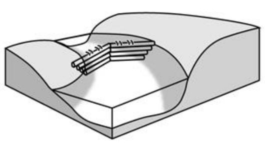
Key Considerations for Selecting the Types of Large Wood Structures for a Given Reach

- The configuration should address the dominant fluvial (erosion, deposition, etc.) processes operating on the site.
- Key habitat deficiencies (e.g., lack of pools, lack of cover, lack of woody substrate) should be addressed. *These should have been established in accordance with principles described in Chapters 3 and 4 of this manual*.
- The project should be in harmony with the anticipated future geomorphic and riparian response of the reach.
- Economic, political, institutional, social, and construction access issues should be considered.
- Suitable materials must be available at a reasonable cost. "Key" logs of adequate size to be naturally stable without anchoring may not be available, and designs must be modified accordingly.
- Safety issues for recreational use of the completed project reach should be addressed, if appropriate (*Chapter 7, Risk Considerations*).
- The most desirable types of structure emulate naturally occurring large wood formations. Permanently fixed structures placed at regular intervals for erosion control are often necessary but do not replicate features typical of natural settings. When possible (i.e., when dynamic, mobile boundaries and wood are acceptable), structures should look and behave like stable wood jams.

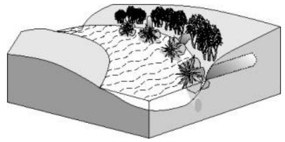
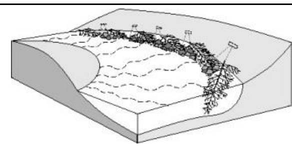
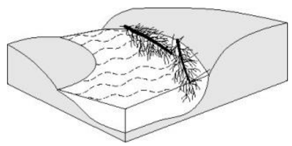
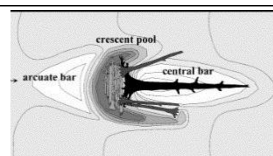
CROSS-REFERENCE

See Chapter 1, *Large Wood Introduction,* and Chapter 4, *Geomorphology and Hydrology Considerations*, for images and descriptions of natural large wood formations.

Table 6-7. Classification of Large Wood Instream Structures Based on Architecture[4]

Configuration	Sketch	Description	Functional Role and Strengths and Weaknesses	References
ELJs or flow deflection jams		Intermittent structures built into eroding banks by stacking whole trees and logs with rootwads in crisscross arrangements. Often filled with gravel or cobble as ballast. Large quantities of smaller wood (*racked debris*) may be added to upstream face.	Emulates natural formations if dimensions and spacing vary. Creates diverse physical conditions, traps additional debris. Suitable for banks subject to mass failure.	Abbe et al. 1997; Drury et al. 1999; Drury 1999; Shields et al. 2004; Brooks 2006; Brooks et al. 2006
Log vanes/step jams		Single logs or small bundles of logs secured to bed. Also called log bendway weirs (if partially spanning channel and angling upstream) or log steps (if fully spanning channel, and usually placed perpendicular to channel). Ends of logs held in place by burying in sediment or in bank, or secured against trees, boulders, or bedrock.	Low-cost, minimally intrusive. Generally limited to channels with low banks not subject to mass failure. May be used to retard bed erosion (fully spanning logs) or divert flow away from concave bank (log bendway weirs). High failure rates due to undermining by downstream scour hole.	Derrick 1997; ODFW 2010 provides nine configurations.
Log weirs/valley jams		Weir-like accumulations built around one or more large logs (key members).	Creates pool habitat. Prone to failure by flanking or undermining.	D'Aoust and Millar 2000

[4] Many variations on these basic configurations have been used. Note that "strengths and weaknesses" are subject to the project goals and objectives. In some settings, erosion control and channel stabilization are desirable while other projects are intended to increase fluvial dynamism.

Configuration	Sketch	Description	Functional Role and Strengths and Weaknesses	References
Rootwads or meander jams		Logs buried in bank with rootwads protruding into channel. Usually placed on outside of bends.	Protects low banks by reducing shear stress acting on bank toe, provides scour pools with woody cover Accumulates fluvially transported wood. Does not emulate natural features.	Wood and Jarrett 2004
Tree revetments or roughness logs or bench jams		Whole trees placed along bank parallel to current. Trees are overlapped (shingled) and securely anchored or lodged into bedrock outcrops, boulders, or other obstructions.	Deflects high flows and shear from outer banks; may induce sediment deposition and halt erosion. Provides complex cover until smaller branches decay or break away.	Cramer et al. 2002
Toe logs		One or two rows of logs or whole trees running parallel to current and secured to bank toe. Gravel fill may be placed immediately behind logs.	Temporary toe protection. Generally only for low banks because banks above toe remain unprotected and therefore allow toe logs to be flanked if banks are high and erodible.	Cramer et al. 2002; Brooks 2006
Bar apex jam		Wood structure composed of 10–30 logs placed in the middle of the channel to initiate bar formation or placed on the upstream end of an existing bar or island.	Readily accumulates fluvially transported wood. Designed to emulate a commonly occurring natural large wood formation.	Abbe and Montgomery 1996; Cramer 2012; Brooks 2006

6.6.4 Determine Dimensions

The next step is to determine the constructed dimensions of the structures. Following construction, dimensions will increase slightly as additional large wood is trapped by (or "racked up on") the structures, and some lowering will occur due to settlement and decay. However, as-built dimensions are useful for estimating required wood quantities and for hydraulic analyses.

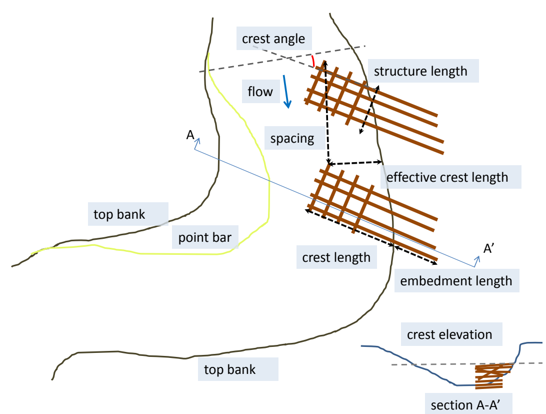
The geometry of intermittent structures (ELJs or flow-deflection jams) may be specified by six parameters: crest angle, crest length, embedment length, crest elevation, structure length, and spacing (Figure 6-12). Guidelines for selecting these parameters for wood structures, as for stone river training structures, are primarily based on long-running experience (e.g., Design Guideline 2 in Lagasse et al. 2009; Pokrefke 2013). However, a few systematic investigations have been conducted using physical models in flumes (e.g., Kuhnle et al. 1999, 2002; Thompson 2005; Svoboda and Russell 2011), which focus on effects of structure design on local scour. Additionally, a few workers have conducted investigations using numerical models (e.g., Jia et al. 2009). For high-risk projects, it may be helpful to construct site-specific numerical or physical models and analyze effects of design parameters (Table 6-3). Below we encapsulate guidance that may be used to generate trial dimensional characteristics that should be further refined and modified through iterative hydraulic analysis or modeling to fully complete design.

6.6.4.1 Crest Angle

The *crest angle* is defined as the angle between a line normal to the approach flow vector and the weir crest. A crest angle of 90° has the effect of forcing the main flow current and channel thalweg farther from the concave bank than upstream or downstream orientations. Stone spurs oriented in an upstream direction cause greater scour than if oriented normal to the bank, and spurs oriented in a downstream direction cause less scour. Wood members embedded in the bank so that their butts or rootwads are pointing upstream may gain stability as drag forces tend to push them into the bank.

For structures that will not overtop at flows less than bankfull stage, an orientation perpendicular to flow is generally considered to be the most effective (e.g., Klingeman et al. 1984). Rapidly changing, dynamic sites should be evaluated for likely changes in the effect of channel migration on orientation angle with incident flow.

Figure 6-12. Definition Sketch for Large Wood Geometric Variables



Structures such as bendway weirs, which are designed to overtop at relatively low flows, are oriented upstream to set up a hydraulic gradient directed away from the bank. Accordingly, the crest angle for structures that are overtopped frequently may be set at 15° upstream from a line drawn perpendicular to flow to promote deflection of overtopping flow away from eroding banks. However, for sites with heavy drift wood loading, it is best to assume the structure will end up with an upstream face oriented perpendicular to the flow, or possibly with a downstream orientation. As wood accumulates upstream of a structure the pile of racked material tends to taper, giving a structure a blunt arrowhead form pointed upstream.

6.6.4.2 Crest Length

The *crest length* for structures that do not span the channel may be based on a projected value for the equilibrium width of the channel. Crest length will then be the difference between the existing channel width and the equilibrium width times the cosine of the crest angle. Alternatively, crest length may be based on a target flow conveyance for the design cross-section. In any event, crest length should be small enough that blockage is less than one-third the channel width (Johnson et al. 2001). Flume experiments by Thompson (2002) showed that high (overtopped by the 0.27-year event) deflectors that projected only 25% of the way across the flume produced more scour during high flows than lower ones (overtopped at 9% bankfull discharge) that projected 75% of the way across the channel.

6.6.4.3 Embedment Length

Embedment length is critical for structural stability. The approach outlined below under "Geotechnical Forces" may be used to compute embedment length, but a rule of thumb is to embed at least two-thirds of the log or structure length (Oregon Department of Transportation 2011).

6.6.4.4 Crest Elevation

Abbe et al. (1997) and Castro and Sampson (2001) suggest *crest elevation* be set equal to that of the channel-forming flow stage. Still other practitioners suggest that to achieve effective flow deflection the general rule of thumb is that the height of the structure (distance from channel bed to crest) should be 0.5 times the "channel-forming flow" depth (Klingeman et al. 1984; Drury 1999). All other factors being equal, local scour depths tend to be greater for higher structures. In incised channels crest elevations for ELJ-type structures must be high enough so that the sediment berms that form over the structures stabilize the existing near-vertical banks. Stable bank heights and angles may be based on geotechnical analyses (e.g., the Bank Stability and Toe Erosion Model [BSTEM]) (Simon et al. 2000, 2014, USDA 2013) or empirical criteria based on regional data sets.

6.6.4.5 Structure Streamwise Length

Structure length is dependent upon the upper limit length of available logs for simple structures and often is 1 to 3 times the crest length. Length may be adjusted to achieve specific geomorphic or ecological objectives.

6.6.4.6 Spacing

Spacing is set as a preliminary or trial value in initial reach layout (see Section 6.6.2, *Reach Layout*), but refined as dimensions of individual structures are selected. Spacing between intermittent wood structures is measured crest to crest. Spacing should be great enough to provide segments of unprotected bankline between structures to reduce cost and to create physical habitat diversity (Shields et al. 1995), but prevent flanking and structural failure. See Table 6-6 above for standard guidelines. Similar guidance is provided by Shields et al. (2004) and by Lagasse et al. (2009). A rule of thumb is that the maximum downstream influence of a structure will be less than 7 times the effective crest length when Rc/W <3; spacing should always be less than this (Drury et al. 1999). Lagasse et al. (2009:2.12–2.15) provide a procedure for locating and spacing structures in a given meander bend. Considerable research has been conducted on step-pool channels (e.g., Comiti and Mao 2012).

6.6.5 Select Wood Materials

Minimum dimensions, species, and sources for woody materials should be specified during design. Cramer et al. (2002) suggest the following guidelines for roughness trees.

Dimension	Minimum Size
Rootwad Diameter	Bankfull discharge depth
Trunk Diameter	0.5 x bankfull discharge depth
Tree Length	0.25 x bankfull discharge width

Clearly, wood materials this large are not always available on site (some scientists have suggested that the near universal mobility of large wood in present-day rivers [e.g., Curran 2010] is due to the scarcity or absence of extremely large trees that were present prior to European settlement). Although using onsite wood is preferred given the extreme cost of bringing in large materials, importation may be necessary to obtain large enough logs and avoid detrimental environmental impacts. Benefits to the habitat and stream ecosystem must be weighed against the impacts of clearing and grubbing on existing riparian and floodplain habitat.

Complex woody material structures that feature numerous branches and thus high stem density locally depress velocity, inducing sediment deposition. Accordingly, materials should be selected that have numerous branches, and breakage and removal of branches should be avoided during construction. Clearing within the stream corridor should be avoided, but bar scalping to provide temporary relief of outer bank erosion in a sharp bend may be advisable in certain cases, and resulting woody materials (e.g., willow rootwads and stems) may be used in structures to trigger rapid revegetation.

Species that are decay resistant are preferred, such as eastern red cedar (*Juniperus virginiana*), western red cedar (*Thuja plicata*), coastal redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga* spp.), or bald cypress (*Taxodium distichum*). Rapidly decaying species such as cottonwood (*Populus* spp.), pines native to the Southeast (e.g., *Pinus echinata* and *Pinus taeda*), and alder (*Alnus* spp.) should be avoided. However, as noted above, use of freshly cut or grubbed willow or cottonwood trees may be desirable for quick revegetation in structures that are partially buried. Additional information about desirability of various species is found in Table 6-2 above.

In some cases, material other than wood may be more desirable for process restoration. If another material can be used that provides the same function and better meets stability and longevity requirements at a lower cost, it is certainly worthwhile, especially if it helps to retain natural wood moving through the system. For example, large concrete jacks (dolosse), together with large quantities of native wood, have offered an economical and long-term alternative to simulate the function of logjams in restoring habitat and protecting roads in the Pacific Northwest (Abbe and Brooks 2011). Synthetic large wood material for stream work is available commercially (Bolton et al. 1998). Synthetic wood products are engineered to compare favorably with natural materials in terms of durability or habitat value. However, they may be less effective in terms of habitat creation or more costly than natural materials. Cost comparisons should consider full project life cycles.

6.6.6 Hydraulic Analysis

Well-designed large wood projects have reportedly withstood flows in channels with average bed shear stresses of 50–170 Pa and estimated velocities of 3 to 4 m s^{-1} (Allen and Leech 1997, Plate 13, and Table 1 in Abbe and Brooks 2011). However, design of large wood for a specific site should not be based on the average shear stress or velocity but on a detailed force balance because turbulent flows in the immediate vicinity of the boundary are quite complex and loading on a given structure is poorly represented by cross-sectional mean velocities or stresses.

Except for extremely simple projects, a hydraulic analysis is strongly recommended. Such an analysis should include assessment of the flow conveyance, sediment transport capacity, and velocity and shear stress at design discharge for the existing channel and for the channel after large wood structure construction (Cramer 2012: Appendix E). Rough analysis may be based on pencil and paper or worksheet computations using uniform flow formulas (Gippel et al. 1996) and simple sediment transport relations, but a collection of cross-section and thalweg profile surveys allows 1D modeling with tools such as the Hydrologic Engineering Centers River Analysis System (HEC-RAS). Large wood structures may be simulated by modifying cross sections, adding blocked obstructions, or increasing roughness (Manning) coefficients (Valverde 2013). HEC-RAS has limited sediment transport capability and can simulate unsteady flows but will not simulate dynamic boundaries (i.e., bed or bank scour) during a given hydrologic event. Therefore, HEC-RAS will likely over-predict peak flood stages, particularly for channels with sand or fine-gravel beds that readily scour during the rising limb of hydrographs (Brooks 2006). Flow depths and velocities may be used as input to scour analysis, as described below.

Higher risk projects may call for two-dimensional simulations, which are far superior to 1D models in examining large wood effects. These tools allow more detailed analysis of the local impacts of structures on flow stages, velocities, shear stresses, bed scour, and habitat characteristics as well as reach-scale effects. Such efforts are more resource intensive, but these models do allow some estimation of the morphologic response to a given large wood design (placement of structures and their dimensions). Examples are provided by Abbe in Brooks (2006), He et al. (2009), and Smith et al. (2011). Calibration and validation of hydraulic analyses and hydrodynamic models for projects not yet constructed are problematic. In years to come, numerical modeling capabilities should allow detailed models of water and sediment movement in reaches with a range of large wood structure sizes and frequencies.

6.6.7 Scour Analysis

Channel bed scour or degradation is often a primary causal factor in large wood structural failures (Shields et al. 2004, 2006; Herrera Environmental Consultants 2006). Scour pools provide important aquatic habitat, but scour that undercuts an instream structure can pose a significant threat to the structural integrity. Undercutting occurs when the depth of bed scour exceeds the depth of the structure. Scour estimates are needed to design the portion of the structure that will be placed below bed level. A first order approximation of scour depths in gravel bed channels may be obtained using a regression line fitted to the thalweg profile. The difference between the maximum positive residual and the maximum negative residual (riffle/pool amplitude) provides an estimate of the scour potential within the reach (Brooks 2006).

More detailed analyses include estimates of different types of scour. Total scour estimates are the sum of general scour, contraction scour, and local scour. Local scour for large wood structures placed on or beside banks may be estimated using approaches used for bridge abutments, while local scour at mid-channel structures (e.g., bar apex jams) may be estimated using bridge pier scour equations. Local scour associated with large wood may be quite dynamic in sand-bed channels with considerable scour and fill occurring during flow events (Borg et al. 2007).

Detailed guidance for scour analysis is not provided here; designers must consult the references below. A range of empirical formulas is available to generate scour estimates, as described by Cramer (2012: Appendix E), Arneson et al. (2012), and Shields (2007); and examples of scour analyses applied to large wood structure projects are provided by Brooks (2006) and Abbe and Brooks (2011). Drury (1999) provides example scour computations for engineered log jams placed in the North Fork Stillaguamish River, Washington.

Scour depths are sensitive to structure dimensions. Structures may become smaller due to decay or loss of members, but they may become much larger if they trap and retain floating wood. If significant amounts of large wood are being transported into the project reach and wood trapping is likely, approaches described by Lagasse et al. (2010) or by Elliot et al. (2012) for estimating the amount of large wood trapped on bridge piers and the associated scour, modified by the user for large wood structures, may be useful. Knutson and Fealko (2014) offer guidance for estimating wood trapping on large wood structures in the Pacific Northwest.

6.6.8 Bank Erosion

Bank erosion analyses are less straightforward than bed scour analyses and subject to more site-specific factors. Large wood placement may deflect flows toward banks and locally accelerate bank erosion; this may not be undesirable as it may scour zones that provide pool habitat or cover at base flow. Approaches for assessing bank erosion potential include a general assessment of erosion rates through the project reach using historical aerial photos, surveys, landowner interviews, and geomorphic assessments. Assessments specific to structure locations may be based on professional judgment or computation of peak shear stresses on banks using numerical (2D) models and comparing those values with critical values for the sediments on the boundary. Additional analysis may be performed using BSTEM (Simon et al. 2000, 2014; USDA 2013), which is a model implemented in Microsoft Excel to estimate bank stability, failure modes, methods, and distances. BSTEM can be used to test the effects of hydraulic scour, water table height, vegetation, and stage on stability; used iteratively with knowledge of the flow regime to predict widening rates; and used to test various mitigation strategies to control undercutting and mass failure (Simon et al. 2014). BSTEM requires significant amounts of site-specific input data.

6.6.9 Force and Moment Analysis

Forces that should be considered for large wood design include net buoyancy, friction between the wood structure and the bed, fluid drag and lift, and geotechnical forces on buried members. For very large, critical projects with asymmetric structures, a moment analysis of each large wood structure is recommended, and a separate factor of safety with respect to moments should be computed as shown by Shields and Wood (2007) and Knutson and Fealko (2014). Below is an example of a simpler approach similar to the one developed by Drury (1999) that considers vertical and horizontal forces separately. The large wood structure is treated as a unit; in other words, it is assumed that large wood members (logs) are secured to one another by hardware (chain or cable[5]) or by interlocking construction and ballast. A free body diagram is useful in ensuring inclusion of all forces in the analysis (Figure 6-13). If the structure cannot be assumed to act as an integrated unit, a more complex force and moment analysis for each structural component is required.

[5] As used herein, the term “cable” refers to cable larger than about 10 millimeters in diameter. Such cable is often called “wire rope” because it consists of several strands of metal wire laid (or “twisted”) into a helix. Steel is the main material used for wire ropes.

6.6.9.1 Vertical Forces

Buoyant Force and Gravity

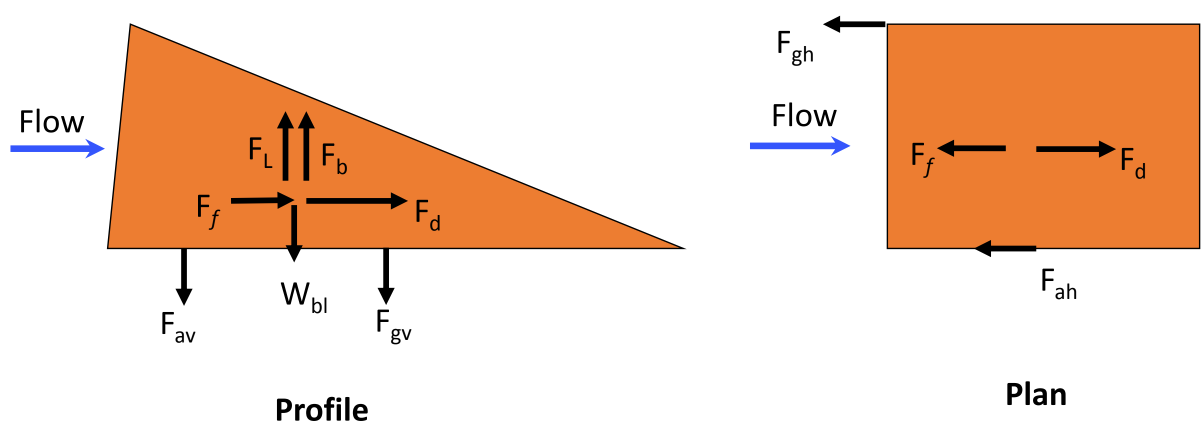
Vertical forces often result in lower factors of safety than horizontal forces and thus control design (Drury 1999; Shields et al. 2004). The buoyant force is equal to the weight of the displaced water volume. The net buoyant force, $\vec{F}_b$, is the only vertical component of the driving force and is equal to the difference between the weight of the structure and the weight of displaced water:

Equation 6-3:

$$\vec{F}_b = [\gamma_d V_d - \gamma_w V_w]$$

where γ represents specific weight, and V represents volume with subscripts d and w referring to wood and water, respectively. It is important to note that V_w represents displaced water volume. If the design water surface elevation is high enough to inundate the structure, then V_w = V_d. If the structure is not fully submerged, V_w is only the displaced water volume, and is equal to the volume of submerged wood, not the total wood volume for the entire structure.

Figure 6-13. Typical Free Body Diagram for a Large Wood Structure



Forces may be determined as follows. F_{av} = restraining force due to anchors or other restraints in vertical direction, W_{bl} = weight of ballast, F_{gv} = geotechnical forces in vertical direction, F_f = force of friction between LW and stream boundary, F_d = drag force, F_L = lift force, F_b = buoyant force, F_{gh} = geotechnical force in horizontal direction, F_{ah} = force due to anchors or other restraints in horizontal direction. Points of application for force vectors shown are arbitrary.

Wood structures may have complex geometries, which makes determination of volume difficult, particularly for partially submerged structures. Shields et al. (2004: Appendix) provide an example computation of V_{water} as a function of flow depth. Computations may be simplified by assuming that logs are cylinders or cones, adopting advantageous coordinate systems, and treating rootwads and boles as separate elements (Braudrick and Grant 2000; Shields et al. 2004; Abbe and Brooks 2011). For example, for a structure with n logs, we may approximate the boles as cylinders and the rootwads as cones:

Equation 6-4:

$$V_{wood} = \pi \sum_{k=0}^{n} l_k r_k^2 + \frac{t_k w_k^2}{3}$$

where l_k and r_k represent the length (exclusive of rootwad) and DBH radius of the *k*th log, respectively, and t_k and w_k represent the thickness (measured in direction parallel to trunk) and radius of the kth rootwad. Brooks (2006) suggests that t_k and w_k may be approximated by $4r_k$ and $2.5r_k$, respectively.

The specific weight of wood, γ_d, should be assumed to represent worst-case or driest and partially decayed conditions. Unless more specific data are available (Shields 2004; Brooks 2006; Shields and Wood 2007; Ruiz-Villanueva et al. 2014; Miles and Smith 2009; Forest Products Laboratory 2010), a value of 3,900 N/m^3 (corresponding to a specific gravity of 0.40) should be used. If rootwads are approximated by a cone (as in the above equation), the resulting volume should be multiplied by an appropriate void ratio to allow for the empty spaces between roots after soil is removed.

Lift

Fluid lift is generated by flow acceleration above and below a solid object. Drag on a large wood structure may be computed using the following equation.

Equation 6-5:

$$\vec{F}_L = \frac{C_L A \gamma_w U_o^2}{2g}$$

where $\vec{F}_L$ = lift force, CL = drag coefficient, A = area of structure projected in the plane perpendicular to flow, and U_o = approach flow velocity in the absence of the structure. Many designers neglect lift when analyzing forces on large wood structures (Shields 2004; Abbe and Brooks 2011), as lift forces are usually small relative to buoyant forces (Merten et al. 2010; Knutson and Fealko 2014). Measurements of lift forces on simple logs with few branches showed lift can be quite large in cases where significant flow occurs above and below trunks and branches (Shields and Alonso 2012). However, lift coefficients ranged from 0.8 to 1.7 for large wood with less interstitial space (a rootwad) that was suspended above the channel bed. In the absence of better information, C_L may be assumed = 1.0 for complex large wood structures that are submerged. Lift may be assumed = 0 for large wood in contact with the bed that is not fully submerged. For purposes of computing A, a large wood structure may be treated as a single body, rather than as individual cylinders if the upstream face of the structure is only slightly porous due to ballast, racked debris, or trash (Gippel et al. 1996). For structures located on the outside of bends, the approach flow velocity may be assumed equal to 1.5 times the cross-sectional mean velocity (U.S. Army Corps of Engineers 1994).

Ballast

If ballast is provided by gravel or cobble fill, the maximum ballast volume is the volume computed using external structure dimensions less the volume of wood. If the structure is approximated by a rectangular prism, then the weight of the ballast, W_{bl}, is computed using the following equation.

Equation 6-6:

$$\vec{W}_{bl} = \gamma_{bl}(W_s H_s L_s - V_d)$$

where γ_{bl} = specific weight of ballast (typically 14,000 N/m^3 < γ_{bl} < 19,000 N/m^3 for gravel or cobble), and W_s, H_s, and L_s are the width, height, and length of the large wood structure, respectively. If boulders are used for ballast, their volume may be approximated by that of an equal number of spheres, and

Equation 6-7:

$$\vec{W}_{bl} = n\gamma_{bl}\left(\frac{\pi d_b^6}{2}\right)$$

where n is the number of boulders, γ_{bl} is the specific weight of the boulder (not bulk weight), usually 25,000–27,000 N/m^3, and d_b is the diameter of a sphere with volume equal to that of a representative boulder. Alternatively, a more conservative approach would be to apply Equation 6-6 above using the bulk density of boulders for γ_{bl}.

Conservative designers may wish to reduce $\vec{W}_{bl}$ in subsequent computations to allow for loss of ballast due to erosion at structure margins. If velocities within the structure exceed critical velocities for erosion of the ballast particles, rapid loss of ballast may occur, destroying the structure (Shields et al. 2004).

6.6.9.2 Horizontal Forces

The free body diagram (Figure 6-13) is also useful in considering and analyzing forces in the horizontal plane.

Friction

The movement of large wood structures by sliding along the bed will be resisted by a frictional force $\vec{F}_f$ with magnitude equal to the normal force times the coefficient of friction between the woody material and the bed. If $\vec{F}_n$ > 0,

Equation 6-8:

$$\vec{F}_f = \mu_{bed} F_n$$

In the absence of measured data, it may be assumed that μ_{bed} = tan ϕ, where ϕ is the friction angle for the bed sediments (Braudrick and Grant 2000; D'Aoust and Millar 2000; Castro and Sampson 2001). If vertical restraint is provided by ballast, the normal force will be equal to the weight of the wood and ballast above the waterline plus the submerged weight of the wood and ballast below the waterline. If the structure is fully submerged, then the submerged weight of the ballast, $W_{bl(sub)}$, will be equal to the difference between the weight of the submerged ballast and the weight of the displaced water:

Equation 6-9:

$$\vec{W}_{bl(sub)} = (\gamma_{bl} - \gamma_{water})(W_s H_s L_s - V_d)$$

and

Equation 6-10:

$$\vec{F}_n = W_{bl(sub)} - \vec{F}_b - \vec{F}_L$$

Drag

Fluid drag is a driving force in the horizontal direction. Drag on a large wood structure may be computed using the equation

Equation 6-11:

$$\vec{F}_d = \frac{C_D A \gamma_w U_o^2}{2g}$$

where $\vec{F}_d$ = drag force, C_D = drag coefficient, A = area of structure projected in the plane perpendicular to flow, and U_o = approach flow velocity in the absence of the structure. Drag coefficients vary greatly from one large wood formation to another due to differences in the way the members engage the flow. However, C_D tends to decline to values typical of cylinders (0.5–1.0) when large wood becomes so complex that interstitial flow is nil. C_D values reach their maximum (~1.5) when large wood structures are just barely overtopped due to the additional drag incurred due to formation of standing waves (Shields and Alonso 2012). In the absence of better information, C_D may be assumed = 0.9 for fully submerged conditions and = 1.5 for conditions where the water surface is within one (typical) log diameter of the top of the structure (Shields and Gippel 1995; Brooks 2006; Shields and Alonso 2012). Drag forces rapidly diminish with time during the first few high flow events as patterns of scour and deposition reshape the local topography (Wallerstein et al. 2001). As for lift computations, when computing A, a large wood structure may be treated as a single body, rather than as individual cylinders if the upstream face of the structure is only slightly porous due to ballast, racked debris, or trash (Gippel et al. 1996). For structures located on the outside of bends, the approach flow velocity may be assumed equal to 1.5 times the cross-sectional mean velocity (U.S. Army Corps of Engineers 1994).

6.6.9.3 Determining How Structural Elements Will Be Restrained

Large wood added to a stream may be unrestrained, ballasted, or anchored. Many natural large wood accumulations are stable for decades or centuries, particularly when the length of the large wood is large relative to channel width. Natural large wood stability is improved by the presence of rootwads, shallow flow depth, partial burial, high length relative to channel width, and bracing against trees, rocks, banks, etc. (Merten et al. 2010). In some cases (such as undeveloped watersheds), transport of wood downstream may not be objectionable. However, in most cases, large wood structures are intended to remain in place over their design life in order to generate the intended benefits and to avoid hazards to downstream bridges and other infrastructure, so large wood installation design must include passive or active restraint.

Passive anchoring restraint refers to a design approach in which the shape, weight, ballast and placement of large wood structures are adequate to resist movement in events up to the design flow. Passive anchoring along smaller streams includes entanglement of logs within boles of trees adjacent to the stream (Figure 6-14). Logs within a passively anchored structure may be attached to one another, but not to external anchors. Passive anchoring is not recommended for high hazard situations, for sites with vulnerable infrastructure downstream, or for sites where structures will be frequently overtopped.

Figure 6-14. Entanglement of Logs in Riparian Stumps and Boles for Passive Restraint, Hylebos Creek, Milton, Washington

(Photo by Mike Hrachovec)

Active restraining approaches include placing ballast (soil, cobbles, boulders) on or within the structure; embedding part or all of the large wood in the bank or in a stone structure such as a revetment or spur dike; and using cable, rope, or chain to secure the structure to boulders, mechanical anchors placed in soil, rock or concrete, stumps, trees, deadmen, or pilings (Fischenich and Morrow 2000; Shields and Wood 2007; Knutson and Fealko 2014).

CROSS-REFERENCE
Additional information on options for large wood restraints is provided in Table 8-3 of Chapter 8, *Regulatory Compliance, Public Involvement, and Implementation.*

A wide range of mechanical anchors for soil and rock are available; vendors can supply information about each type. Detailed guidance for large wood structure active restraint suitable for smaller structures is provided by the Natural Resources Conservation Service (2007b) and by Cramer (2012: Appendix G).

When boulders are used for ballast, the buoyant, drag, and lift forces on the ballast rock must be considered in the force balance (D'Aoust and Millar 2000). Logs in complex structures may be attached to one another or to boulders by drilling holes through them and pinning them together with rebar. Alternatively, logs may be fastened with chains, which are less likely to fail from repeated bending stress. Epoxy adhesive has been used for attaching chains, cables, or metal rods to holes drilled in boulders or bedrock. More details about the methods to epoxy cable into rocks can be found in published documents such as the *California Salmonid Stream Habitat Restoration Manual* (Flosi et al. 1998). Cable (wire rope) should be galvanized or stainless steel and sized to withstand loads greater than those computed. Hardware used to affix cable to itself or to other components should be carefully specified. See Cramer (2012: Appendix G) for recommendations.

6.6.9.4 Safety Factors for Designing Restraints

Safety factors are ratios of resisting to driving forces. Restraint systems should be designed to achieve safety factors that are scaled to the risk profile of each large wood placement (*see Chapter 7, Risk Considerations*). Resisting forces include the weight of the structure plus ballast, friction with the bed, and forces due to anchors. Driving forces include buoyancy and fluid lift and drag. Additional driving forces may arise due to waves, ice action, or collisions from floating debris,[6] but computation of these forces is beyond the scope of this guide. Put simply, restraining systems should be designed to meet:

Equation 6-12:

$$F_{sv} = \frac{\overrightarrow{W}_{bl} + \vec{F}_{gv} + \vec{F}_{av}}{\vec{F}_b + \vec{F}_L}$$

and

[6] Knutson and Fealko (2014) present suggestions on consideration of ice and debris loading in large wood structure design.

Equation 6-13:

$$F_{sh} = \frac{\vec{F}_f + \vec{F}_{gh} + \vec{F}_{ah}}{\vec{F}_d}$$

where F_{sv} and F_{sh} are safety factors with respect to vertical (floating) and horizontal (sliding) movement, $\vec{F}_{gv}$ and $\vec{F}_{gh}$ are vertical and horizontal restraint forces, respectively, provided by geotechnical processes (embedded logs or piles), and $\vec{F}_{av}$ and $\vec{F}_{ah}$ are vertical and horizontal restraint forces, respectively, provided by anchors. $\overrightarrow{W}_{bl}$ is the vertical force due to ballast as defined by Equation 6-6.

6.6.9.5 Geotechnical Forces

Horizontal Large Wood Embedded in Bank

Members of a large wood structure may provide significant restraining forces if they are embedded in banks by excavating trenches and burying them ("keying in"). However, because of the disturbance required, this approach may not be practical for extremely high, steep banks or banks providing sensitive habitats. The embedment length or bank key-in distance for structures that are partially buried in the bank should vary with bank height, soil type, and stream size. As a rule of thumb, a log will be stable if two-thirds of the log is buried in the bank (Oregon Department of Transportation 2011). The key-in should be sufficient to maintain the position of the rest of the structure throughout its design life, and should be greater for frequently overtopped and highly erodible banks (Sylte and Fischenich 2000). Site-specific computations are suggested (D'Aoust and Millar 2000). A simplified analysis is presented below; a more detailed treatment that includes sloping banks and a nonhorizontal water table is presented by Wood and Jarrett (2004). Because these geotechnical analyses involve considerable professional judgment, an experienced geotechnical engineer should perform or review this part of the design.

RISKS

Safety Factors

Safety factors are ratios of resisting to driving forces. Engineers often compensate for uncertainty in design computations by modifying designs in order to increase the safety factor. Safety factors recommended for design of concrete gravity structures like dams, pumping stations, and floodwalls range from 1.1 to 3.0 based on the anticipated loading and the quality of site information (U.S. Army Corps of Engineers 2005). Factors for bearing capacity of soils range from 2 to 4 (U.S. Army Corps of Engineers 1992). Knutson and Fealko (2014) recommend different safety factors for large wood structures based on risk profile and failure mode as shown below.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10=year	1.25	1.5	1.25

Designers often deal with uncertainty by making conservative assumptions when computing the components that constitute the right-hand sides of Equations 6-12 and 6-13. These assumptions can result in "implicit" factors of safety that should be considered when assessing the overall factor of safety for the design. If the large wood placement is intended to survive several years, increased factors of safety may be needed to allow for the possibility that:

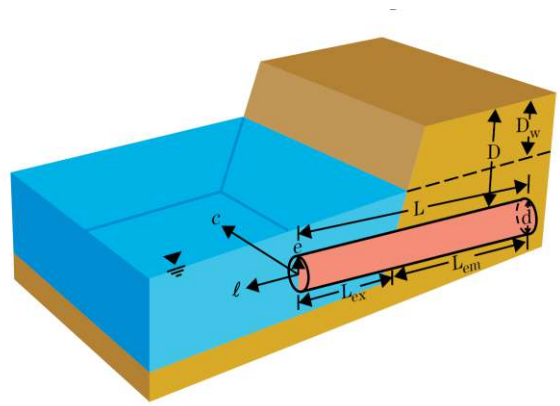
1. Wood is partially decayed and thus less dense,
2. The current angle of attack has shifted, with flow impinging directly on the structure,
3. Branches and twigs have been removed, simplifying the wood and increasing drag coefficients, or
4. Ballast has been eroded or moved.

For example, if a designer decides to use 300 N/m^3 for the specific weight of wood rather than a more realistic value of 500 N/m^3 in order to be conservative, there is an implicit $\boldsymbol{F_{sv}}$ = 1.66 (assuming the lift force $\vec{\boldsymbol{F}}_{\boldsymbol{L}}$ is negligible). In other cases, elevated safety factors are used to compensate for uncertainties in the underlying data and assumptions used in the design analysis.

Embedment depths must be increased if bank erosion is likely so that depths are adequate even after erosion has occurred.

The resistive forces due to passive soil pressure acting on buried portions of logs are direct reactions to fluid forces. The following equations assume that the log is embedded horizontally in the streambank; the top of the bank is horizontal; the bank is composed of homogeneous, isotropic soil with bulk specific weight γ_s, effective friction angle ϕ', and effective cohesion c'; and the groundwater table elevation in the bank is approximately equal to the stream surface elevation, which is high enough to fully submerge the log (Figure 6-15), and is a distance D_w below top bank elevation. In addition, the bank slope is assumed to be near vertical, and the log is assumed to be frictionless. The log has a length L, a diameter d, and is buried a distance D below the top bank and a horizontal depth L_{em} (embedment length). The soil passive resistance distribution is assumed to be triangular with its maximum value at the bank face and decreasing linearly to zero at the embedded tip of the log. This implies that the resultant passive resistance force acts on the log a distance of two-thirds L_{em} from the embedded tip. The active earth pressure force is assumed to be small relative to the passive force.

Figure 6-15. Definition Sketch for Derivation of Geotechnical Forces on a Horizontally Embedded Log



Source: Shields and Wood (2007)

The vertical loading on the log due to the weight of the soil above it will be given by

Equation 6-14:

$$\vec{F}_{soil} = \sigma_v' L_{em} d$$

$$\sigma_v' = (D - D_w)(\gamma_s - \gamma_w) + D_w \gamma_s$$

where γ_s is the bulk (or moist) unit weight of the soil above the log. Alternatively, $\vec{F}_{soil}$ may be computed using equations developed to compute soil loading on conduits buried in ditches. When the ditch width is no greater than three times the log diameter

Equation 6-15:

$$F_{soil} = \frac{C_w \sigma_v' B_d^2 L}{D}$$

where B_d is the width of the ditch and C_w is a coefficient that captures the interaction between the ditch walls and the fill. C_w is given by

Equation 6-16:

$$C_w = \frac{\left[1 - e^{-0.38D/B_d}\right]}{0.38}$$

for $\frac{D}{B_d} < 2$ and

$$C_w = \frac{D}{B_d}$$

for $\frac{D}{B_d} \geq 2$. Here, e is the base of natural logs. The two approaches for computing F_{soil} converge for ditches with widths just slightly greater than the log diameter. Clearly, greater restraint can be provided at shallower depth with denser soil or by using gravel or rock instead of soil due to higher γ_{soil} in Equation 6-14.

Assuming friction between the soil and log is negligible, the passive soil pressure force, $\vec{F}_p$, is given by

Equation 6-17:

$$\vec{F}_p = 0.5 \sigma_p L_{em} d$$

where σ_p, the passive soil pressure, is given by

Equation 6-18:

$$\sigma_p = \sigma_v' K_p + 2c' \sqrt{K_p}$$

where K_p, the Rankine coefficient of passive earth pressure, is given by

Equation 6-19:

$$K_p = tan^2\left(45 + \frac{\emptyset'}{2}\right)$$

where $\emptyset'$ is the effective angle of internal friction and c' is the effective soil cohesion. If unknown, effective soil cohesion may conservatively be assumed to equal 0.

6.6.9.6 Moments, Horizontal Large Wood Embedded in Bank

The driving moment about the buried tip of the embedded log will be given by the vector sum

Equation 6-20:

$$\vec{M}_d = [(\vec{F}_d + \vec{F}_L)(L_{em} + L_{ex}/2) + \vec{F}_b(L/2)] \times \vec{l}$$

where $\vec{l}$ is the unit vector along the axis of the buried log and positive in the direction away from the buried tip. The resisting moment $\vec{M}_r$ will act opposite the driving moment and will be given by the vector sum

Equation 6-21:

$$\vec{M}_r = [(\vec{F}_{soil}(1/2)L_{em} + \vec{F}_p(2/3)(L_{em} + \vec{F}_{av}L_c] \times \vec{l}$$

where $\vec{F}_{av}$ is the restraining force due to anchors (if there are any) as defined above, and L_c is the appropriate moment arm about the buried tip of the embedded log.

Vertical Large Wood Placed as Piling

Logs or metal beams may be driven vertically through the large wood structure as it is built so that they act as pilings to resist horizontal driving forces. If a log with a rootwad is buried vertically with the rootwad at the bottom, the pullout resistance will be increased several-fold relative to a log without a rootwad (Abbe and Brooks 2011). Pilings must be placed deeply enough to provide adequate safety factors even after burial depth has been reduced by scour. Therefore, scour analysis must precede geotechnical analysis for vertical piles.

Applicable methods selected under advisement from a geotechnical engineer should be used to determine the number of pilings, piling depth. and other properties needed. Knutson and Fealko (2014) suggest use of Brom's equation[7] for computing lateral resisting forces due to a group of vertical piles.

Equation 6-22:

$$F_{gh(piles)} = N\left(\frac{\frac{1}{2}L_{em}^3 d_p K_p(\gamma_s - \gamma_w)}{(h_{load} + L_{em})}\right)$$

where N is the number of piles, L_{em} is the length of the pile buried below the bed (allowing for scour), d_p is the pile diameter, h_{load} is the distance above the scoured bed that the load is applied, and all other variables are as previously defined. A trial and error approach may be used to adjust piling parameters to obtain the value of $\vec{F}_{gh}$ that will produce $\vec{F}_{sh} \geq 2$ in Equation 6-12 above. It is important to look at the ultimate pile strength (shear and moment) versus the applied loads to ensure that the pile material is structurally sound and will not snap or shear off during the design event. Piling strength is often the limiting factor, and consideration of this factor can result in a higher number of required piles.

6.6.10 Planting Vegetation

Because instream wood is tightly linked to the riparian forest (*see Chapter 4, Geomorphology and Hydrology Considerations*), ecosystem recovery is often aided by planting woody vegetation concurrent with wood addition projects (sometimes referred to as

[7] Brom's equation assumes a maximum allowable deflection of the pile at the ground of 0.002 to 0.006 radians. Assuming rotation about the buried pile tip, this assumption implies that a pile embedded 3 meters (10 feet) below the channel bed would have a theoretical maximum displacement of 1.8 centimeters (0.7 inches) at the channel bed.

"revegetation"). Plantings are usually flood-tolerant, pioneering species that may be propagated by large (~1- to 10-centimeter [0.4- to 4-inch] diameter) cuttings. In some cases, small living trees may be transplanted by excavating root balls and incorporating the living material and associated soil in the placed wood or adjacent to it. Cuttings may be placed in banks adjacent to wood placements, on nearby bars, or planted in sediments that deposit on or within large structures after the first few high flows. A wide variety of planting techniques and practices are available; full treatment is beyond the scope of this manual. *Additional guidance is provided in Chapter 8, Regulatory Compliance, Public Involvement, and Implementation,* and by the Federal Interagency Stream Restoration Working Group (FISRWG 1998), NRCS (2007f), and Fischenich (2001).

CAVEAT

Key Engineering Considerations for Plantings
(NRCS 2007f)

- Protection of plantings from erosion during period of establishment.
- Ability of established plant materials to withstand hydraulic loadings imposed by high flows.
- Protection of plantings on banks from undercutting.
- Effects of slope instability on plantings on high, steep banks.
- Effects of mature vegetation on reach hydraulics and sediment transport.
- Site conditions (soil fertility; shade; frequency, timing, and duration of inundation).
- Potential damage to plants by beaver, muskrat, deer, or other herbivores.
- Problems due to invasive exotic species.
- Availability of plant materials from local sources.

6.6.11 Constructability Assessment

Preliminary designs should be subjected to a constructability assessment (*also see Chapter 8 for guidance on constructability*). Key issues for such an assessment include the compatibility of the design with site geology, hydrology, hydraulics, and biota. For example, stream channel substrate must allow for pile driving or excavation if required for construction of restraint systems. Posts may be used for restraints if site substrate allows excavation of post holes, but bedrock is an obvious limitation.

In deeply incised channels, consideration must be given to the challenge of access to the channel bed from high banks. Certain types and sizes of equipment may be able to reach the channel from top banks, but it will often be necessary for equipment to operate within the channel during low flow periods. Temporary ramps may be needed to allow movement of equipment and materials from the top bank/floodplain down into the incised channel (Figure 6-16).

Figure 6-16. Construction of Temporary Ramp for Access to Channel for Large Wood Structure Construction in Little Topashaw Creek, Mississippi

One of the key decisions that affects both design and construction is whether to construct in the dry using some type of berm or coffer dam to allow site dewatering or with ordinary water levels, otherwise referred to as "in the wet."

Project economics are heavily influenced by haul distances for wood, ballast rock, and other materials, so sources and haul routes must be carefully planned, and the types of equipment to be used must be selected and specified.

Limitations on heavy equipment use are provided by site hydrology and hydraulics, environmental restrictions (e.g., water quality considerations, migratory or other seasonal windows), and potential conflicts with recreation and navigation.

6.7 Special Considerations for Urban Streams

There are special considerations for the evaluation and design of large wood structures in an urban setting due to the constrained nature of many of such sites; the extreme modifications to water, sediment, and wood loading; and potential impacts on public infrastructure and safety. Crossing structures (bridges, culverts, and pipelines) are more prominent in urban settings, and while newly constructed crossings should be designed with consideration of passage of large wood (Lassettre and Kondolf 2012), existing crossings are likely to retain large wood, and risks should be carefully assessed. Figure 6-17 illustrates built projects in urban settings. The following are some key parameters to consider in the design of large wood structures in the urban environment.

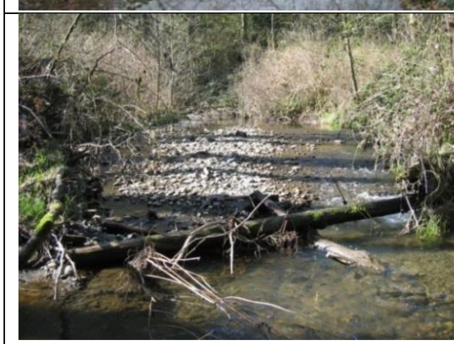
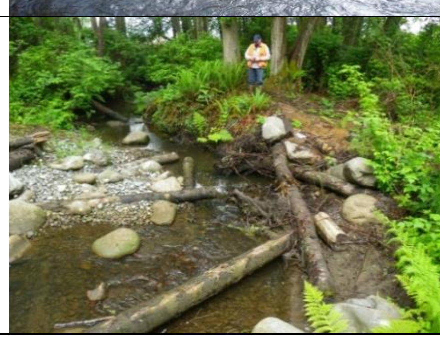
6.7.12 Design Discharge

It is common for Q_{100} to be the design flow in urban settings due to the need for stability within tightly constrained, high-risk project settings. Due to the prevalence of impervious surfaces (40% or more), the prevalence of turf grass, and storm drainage infrastructure that rapidly delivers water to streams, peak flows are elevated in urban areas. Designers are challenged to produce structures with the capacity to withstand high flows while still providing habitat enhancement during lower flows. Design is further complicated by the tendency of urban channels to be disconnected from adjacent floodplains due to floodplain fill or channel entrenchment. In such channels it is typical for the water width-to-depth ratio to decrease with increasing flows, resulting in increasing velocities and shear stresses as the flows increase up to and beyond Q_{100}. Hydraulic modeling is particularly critical to quantify the forces acting on the large wood structures and the stream bed and bank materials. As described above, assessing the response of added large wood and channel boundaries to hydraulic loading is a key task within the design process.

If the spatial limits of the project can be expanded, it may be possible to maintain instream flow conveyance even with large wood added or to restore floodplain function beside or within the incised channel to regain lost floodwater storage. Floodplain restoration can produce a more natural aesthetic through floodplain vegetation and use of softer bioengineering techniques such as soil wraps, coir logs and vegetated flood swales.

Where floodplain restoration cannot be achieved and forces remain high within the project reach, more non-deformable bank stabilization may be required around large wood. This may include boulder placement, nondegradable geotextiles for bioengineering, and/or cobble backfill within the wood structures to resist erosion of the native soils where burial has been used as the primary anchoring technique. Structure heights may be up to or above the level of Q_{100} where bank stabilization is being installed at high-risk, constrained sites.

Figure 6-17. Examples of Large Wood Projects in Urban Settings of the Pacific Northwest

Before	After	Description
		Reestablishing pool-riffle morphology using hand-placed logs and gravel addition in entrenched channel.
		Bed and bank stabilization and instream habitat enhancement with large wood installed as part of fish passage culvert replacement with adjacent houses and utilities in entrenched channel.
		Large wood installation as part of channel realignment and floodplain/wetland restoration for flood relief in former agricultural site.
		Installation of large wood in plane-bed gravel channel to restore pool habitat through constriction scour.
Before photo not available.		Installation of large wood to raise bed elevation to reengage floodplain, reestablish channel sinuosity and provide instream habitat.

Before	After	Description
Before photo not available.		Installation of whole tree spanning ¼ of river channel to promote deposition of sediment along channel edge and increase center-channel scour

(Photos by Mike Hrachovec)

Though many cities are implementing stormwater management techniques intended to reduce both the flood peaks and the amount of fine sediments delivered to urban channels, such as Low Impact Development (LID) techniques, it will be many years before these projects are prevalent enough within most watersheds to result in measureable reductions in flood peaks in urban channels.

6.7.13 Floodplain Regulation

Many urban settings are under constraints imposed by FEMA floodplain regulations, which require a “no-rise” condition within the channel. In these cases the project must be designed so that hydraulic analysis of existing and proposed conditions demonstrate that the proposed large wood installation does not increase flood stages within the project reach or upstream. In these situations excavation of channel or floodplain cross-section may be required to provide flood storage equal to or greater than that portion of the cross-section occupied by the large wood, incorporating into the proposed model conditions the additional channel roughness imposed by the large wood. These constraints, when imposed, will often drive the development of project alternatives and the final design. An LOMR or Conditional Letter of Map Revision (CLOMR) prepared by a Certified Floodplain Manager to demonstrate the project is in compliance with FEMA regulations may be required.

Exceptions to this policy include an exception issued by Region X of FEMA that allows the “no-rise analysis” to be replaced by the judgment of a qualified professional such as staff of the Rural Conservation and Development or the NRCS. “The qualified professional should, at a minimum, provide a feasibility analysis and certification that the project was designed to keep any rise in 100-year flood levels as close to zero as practically possible and that no structures would be impacted by a potential rise.” Additional provisions of the policy include maintenance considerations and further analysis to address river dynamics (FEMA 2009).

6.7.14 Existing Utilities

It is critical to fully understand the constraints placed on the project by the presence of existing utilities (power, sewer, gas, storm drainage, water) by obtaining the horizontal and vertical location of all utilities at the start of design. In many cases these utilities will provide a limit of excavation that will influence where large wood can be installed as well as appropriate anchoring methods. In some cases, anchoring with bole burial may not be feasible due to location of utilities within the bank. The relocation of utilities to allow installation of large wood requires involvement of a civil engineer as well as review and concurrence by the utility owner.

6.7.14.1 Water and Sewer Lines

A general rule and utility requirement is to limit excavation to areas at least 3 meters vertically and horizontally away from major sewer and water lines. In some circumstances exceptions to this rule may occur, but such cases may require costly temporary shoring and stabilization and additional geotechnical analyses. It is very common for sewer and water lines to cross through and under urban stream corridors. Channel incision driven by urbanization frequently results in exposure and breakage of water and sewer lines buried under the channel. Restoration of utility service will often require mitigation in the form of placement of large wood within the channel. In these circumstances, placement of large wood must be designed in a way such that erosion or deposition triggered by the large wood does not threaten the restored utility crossing. Minor water lines (less than 20 centimeters [8 inches] in diameter) can occasionally be routed around the project area, depending on the number of lateral service connections affected. The re-routing of larger (more than 31 centimeters [12 inches] in diameter) sewer lines is typically expensive due to gravity flow constraints and multiple lateral connections, but it may be feasible to lower elevations of smaller sewer lines to allow installation of large wood where sufficient gradient exists to connect to the receiving sewer trunk line. An additional exceptional situation is revision of the base flood elevation to reflect levee setbacks or other physical changes that have occurred subsequent to the current base flood elevation determination. Base flood elevation revision is typically a costly process.

6.7.14.2 Gas Lines

Often it is feasible to relocate minor (less than 10 centimeters [4 inches] in diameter) gas lines to accommodate large wood placement, typically with directional drilling of the lines around the zones where large wood is to be installed.

6.7.14.3 Power Lines

The main constraint with power lines is the limitation of overhead height, which will affect the type of equipment used to move the large wood into position and install it. Presence of power poles within the proposed project's channel or floodplain corridor is a common constraint, though it may be feasible to relocate the power poles to a different location to permit installation of the large wood.

6.7.15 Sediment and Debris

In urban settings the incoming sediment supply may be much lower in quantity and finer than under predevelopment conditions. In urban settings, sediment sources may be cut off by revetments or retaining walls and impervious surfaces, with a shift from gravel substrate to a sand/silt-dominated substrate associated with road runoff including street sanding and soils from residential yards. In some cases a bimodal sediment size distribution develops, with higher proportional quantities of both fine sediments (sand/silt) and larger materials (bricks, broken concrete) with little gravel or cobble present. Large wood installations must be designed to accommodate these materials; for example, anticipating infill within the voids between logs by fine materials. Additionally, the designer should recognize that conditions conducive to bed degradation may exist, and gravel backfill must be sized for stability under design conditions.

Incoming debris from storm conditions can consist of trash, human-made objects of all types, yard waste, log rounds, tires, and construction debris, as well as branches, leaves, logs, and even whole trees. In tightly constrained settings, it is prudent to avoid structures that fully span the channel, as incoming debris can accumulate and exacerbate flooding. A general rule for reach layout is to position structures on alternating banks at longitudinal intervals of at least one to two channel widths to avoid impairing flow conveyance. When analyzing conveyance impacts, it is prudent to consider large wood structures as impermeable and not allocate channel capacity for flow that may flow through or under the large wood structure.

6.7.16 Existing and Historic Structures

Existing and historic structures will impose lateral limits to installation. Excavation limits must be designed to avoid destabilization of structure foundations. In many cases the soils between the stream channel and historic structures may be poorly consolidated fill, and it may be difficult to obtain representative borings. In constrained sites, soil retention measures such as sheet piling may be required to allow installation of large wood. High groundwater tables and saturated soils create the hazard of soil slumping during excavation to install large wood; in these situations, involvement of a geotechnical engineer is prudent. Where there is any likelihood of past human habitation within the project area, archaeological investigations should be scheduled early in the project to identify sensitive areas and features and required avoidance or mitigation of impacts.

6.8 Integrating Landscape Architecture

Landscape architecture is the profession that applies artistic and scientific principles to the research, planning, design, and management of both the natural and built environments (American Society of Landscape Architects 2013). In these two environments, the functional outcomes achieved from this process are often distinct and disparate but will need to overlap and coexist in multiuse landscapes. Accommodating these interactions during the planning and design process will help create projects that meet ecological objectives and that can also be safely enjoyed by the public. Large wood structures in these multiuse landscapes must be designed properly to benefit aquatic organisms and at the same time provide an opportunity for both active and passive human interaction.

6.8.1 Landscape Integration

Integrating large wood into larger habitat restoration projects takes additional planning and presents unique design and construction challenges. The horizontal and vertical elements of large wood structures sometimes require excavation with heavy machinery.

GUIDANCE

Depending on the timing of installation, several post-installation actions may need to take place to ensure other elements of the restoration project or surrounding environment are not adversely affected.

- If the structures are installed in a newly graded landscape once installation is complete, the soil should be returned to the design finish grade and compaction specification to ensure proper drainage and sufficient soil cover over elements of the structure anchored in the bank. This will help ensure there is sufficient rooting zone for plantings and cover for irrigation lines that may cross the buried portions of the structures.
- Any areas or soil around the work area that were not excavated and backfilled should be uncompacted as necessary and stabilized to reduce erosion.
- If large wood structures are installed in areas around existing vegetation or other sensitive resources, precautions should be taken to avoid adverse effects on these areas. This could include exclusion fencing, onsite monitors, and working within prescribed seasonal work windows.

6.8.2 Public Use Considerations

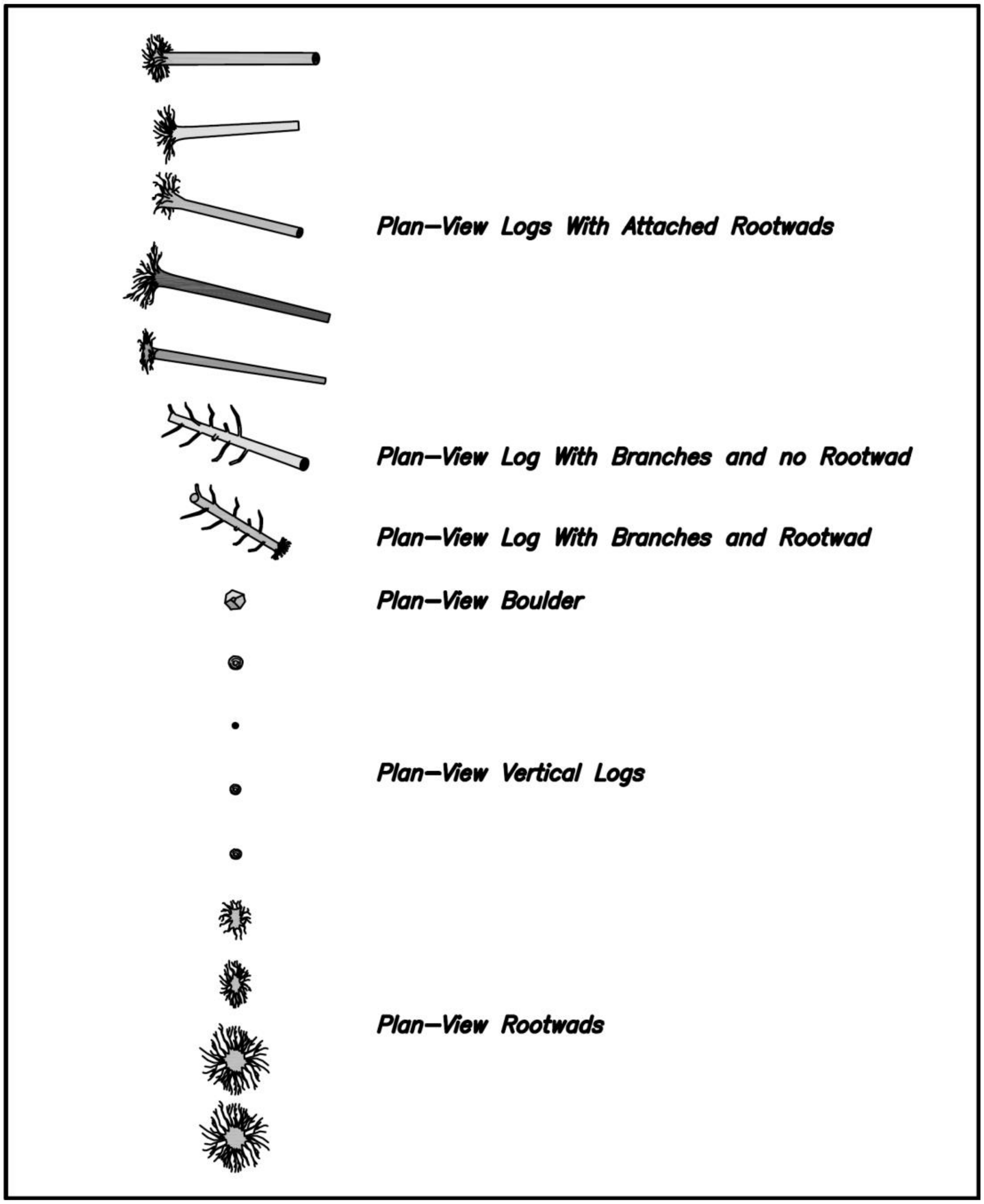
Large wood structures often represent the focal point of stream restoration and enhancement projects. Aesthetically they represent the seldom-seen macro-scale successional processes that occur naturally in forests adjacent to riverine systems. Wood structures represent a link between terrestrial and aquatic ecosystems, and the microclimates they create are frequently heavily utilized by aquatic organisms for refugia and foraging. Placed large wood can provide opportunities for the public to see these functional outcomes occurring. Because large wood habitats are often attractive to fish, they provide opportunities for fishing or snorkeling.

To maximize the educational and passive recreation opportunities presented by large wood structures, trails and interpretive exhibits should be sited close when possible. Interpretive exhibits can explain the ecological functions and benefits offered by large wood structures, and situating the exhibits next to trails will maximize their exposure to the public. In areas where the public will interact with large wood structures, adequate precautions should be taken to ensure the public can safely do so and reduce the potential liability for the landowner. Warning signs should be placed near the installations, indicating that the slippery and uneven surfaces as well as the unpredictable hydrodynamics on and around the structures persist and that climbing or standing on them should be avoided. Depending on seasonal water elevations, submerged or partially submerged structures can also present a hazard to boaters. Local boat rental companies should be notified about these hazards so they can inform customers as appropriate. Signage or other notifications should be posted at put-in locations and launch ramps to inform boaters about the structure locations and the potential hazard they represent to watercraft.

6.8.3 Graphic Standards

Figure 6-18 illustrates some common symbols that can be used in restoration construction drawings to illustrate the size, extent, and location of large wood structures. Regardless of the symbol type, large wood pieces and structures should always be drawn to scale to convey the size and extent of each placement to the design team, community stakeholders, and construction contractors. Construction details for individual structures should be developed on a project-by-project basis so that structures are engineered properly for existing site conditions and prevailing hydrology.

Figure 6-18. Large Wood Structure Graphic Standards



6.9 Uncertainties and Research Needs

1. Much of the existing knowledge base is derived from the Pacific Northwest. Regional differences in climate, hydrology, geomorphology, large wood loading processes, wood species, wood sizes, and aquatic ecology are significant; therefore, it is likely that some of the principles developed to date are not universally applicable. There is a need for development of regional data and expertise.
2. Ideally, large wood placements foster conditions where wood contributions from riparian zones and floodplains sustain target-loading levels without further intervention. A basis is needed to estimate the time required for natural regrowth of riparian and floodplain forests to sustain instream wood levels, particularly for warm, humid regions where wood decay rates are most rapid.
3. More information is needed about the role of vertical and inclined timber piling in stabilizing engineered logjams and collecting natural wood, including guidelines for pile sizing, embedment, species, and condition (e.g., using trees that are not certified as pile quality).
4. More modeling and data is needed on the role of "racking wood" on the stability and performance of engineered structures.
5. More modeling and data and guidance is needed regarding the spatial layout and sizing of engineered logjams within migrating channels
6. More information is needed on use of live trees as instream large wood.
7. Wood placements/structures have been designed to produce certain hydraulic effects related to habitat character or erosion control. Accordingly, considerable research has targeted hydraulic effects of wood, but little is known regarding the properties of wood placement that control trapping efficiency of fluvially transported wood.
8. Effects of ice and ice-related events on instream wood, wood contributions to channels, and the stability of placed wood is poorly understood.
9. Approaches for computing forces on wood structures due to ice, floating debris collisions, bedload collisions, waves, and mud glows are needed.
10. Additional information is needed on the interaction between ice, instream wood, and channel erosion and sedimentation.
11. Existing technology for computing forces due to wind waves and waves produced by boat wakes should be adapted for large wood design.
12. Continued development of multidimensional hydrodynamic and sediment transport models is needed to facilitate reach-scale design and comparison of alternatives. User-friendly interfaces and utilities to facilitate selection of input values for coefficients, for example, are needed to facilitate adoption and use of these tools by practitioners.

6.10 Key Points

1. Use of large wood in fluvial systems is not a new practice, but is becoming more common with more of a focus on restoring physical and temporal complexity.
2. Large wood is generally used with a goal of assisting recovery of a degraded system to a state where it naturally sustains levels of large wood loading commensurate with the target ecosystem requirements.
3. Wood is not intended to be static like most engineering structures placed in channels. It decays, shifts, accretes sediment and other wood and organic matter, and may be colonized by plants. It is not considered a failure if it produces the desired channel and habitat characteristics even if is not stationary.
4. Engineered (introduced, placed. or otherwise managed) wood is most common in the Pacific Northwest. Wood is a major component in lotic ecosystems nationwide, but higher wood decay rates, more extreme hydrologic variation, absence of boulders and cobbles, presence of ice, and human encroachments into stream corridors may make instream wood engineering much more complex in other regions.
5. Large wood introduction is not feasible in all settings. Applicability is sharply limited by site geomorphology, availability of wood, and adjacent infrastructure.
6. Levels of effort appropriate for engineering wood projects vary from desktop, pencil and paper exercises to multidimensional hydrodynamic and geomorphic modeling. Level of effort should be proportional to the stream and project size and relative risk associated with failure.
7. Hydrologic considerations include selection of a design event that will produce the greatest forces on the wood structure and assessment of wood influences on physical aquatic habitat across the range of flows and seasonal requirements for species/life stages of interest.
8. Design of wood projects is a multi-disciplinary endeavor. This is reflected in the stamping of plans by not just the professional engineer, but others with key design input such as the professional geologist (with geomorphology expertise).
9. Design includes reach layout, or determining locations and configurations for placed wood. Reach layout may be driven by habitat or erosion control requirements. Habitat may be viewed at a local scale (increasing pool habitat or woody substrate) or at much larger scales (sediment retention, island formation, or inducing channel planform evolution). Erosion control includes both bed and bank erosion.
10. Following reach layout, designers should determine the dimensions of each structure. Usually, this process follows experience and rules-of-thumb, but multidimensional computer models and physical models may be justified for higher risk projects.
11. Design includes specifying the size, species, and other characteristics of wood materials. In general, larger wood is in short supply and is often too costly to import. Decay-resistant species are preferred. Environmental impacts of wood harvest should be considered.
12. Except for extremely simple projects, hydraulic analysis should include assessment of the flow conveyance, sediment transport capacity, and velocity and shear stress at design discharge for the existing channel and for the channel after large wood structure construction.

13. Flow forces on large wood include buoyancy, lift, and drag. A free body diagram may be used to visualize the interactions among these forces and restraining forces of friction, gravity, and restraints such as ballast, buried members, or anchors.

14. Restraints should be designed so that safety factors exceed a predetermined minimum.

15. Plans and designs may include provisions for planting vegetation that provides additional stability and accelerates ecological recovery.

16. Design should include an assessment of constructability that deals with issues of access, availability of materials, construction techniques and equipment, safety concerns, and environmental restrictions.

17. Projects in urban areas face additional constraints due to utilities and other infrastructure in the stream corridor, perturbed hydrology, historic structures, and floodplain regulation.

6.11 References

Abbe, T. B. 2000. *Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System*. Ph.D. dissertation. University of Washington, Seattle, WA. 222 pp.

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers: Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, and C. Petroff. 1997. Design of Stable In-Channel Wood Debris Structures for Bank Protection and Habitat Restoration: An Example from the Cowlitz River, WA. Pages 809–816 in S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, F.D. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi, Oxford, MS.

Abbe, T. B, A. P. Brooks, and D. R. Montgomery. 2003b. Wood in River Rehabilitation and Management. Pages 367–389 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003c. Integrating Engineered Log Jam Technology into River Rehabilitation. In D. R. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies, University of Washington, Seattle.

Ahmad, M. 1951. Spacing and Projection of Spurs for Bank Protection. *Civil Engineering and Public Works Review.* March:172–174; April:256–258.

Allen, H. H., and J. R. Leech. 1997. *Bioengineering for Streambank Erosion Control*. Technical Report E 97-8, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

American Society of Landscape Architects (ASLA). 2013. *American Society of Landscape Architects (ASLA)*. Available: http://www.asla.org. Accessed: August 27, 2013.

Arneson, L. A., L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper. 2012. *Evaluating Scour at Bridges*. Hydraulic Engineering Circular 18, FHWA-HIF-12-003, National Highway Institute, Federal Highway Administration, Arlington, VA.

Bilby, R. E., J. T. Heffner, B. R. Fransen, F. W. Ward, and P. A. Bisson. 1999. Effects of Immersion in Water on Deterioration of Wood from Five Species of Trees Used for Habitat Enhancement Projects. *North American Journal of Fisheries Management* 19(3):687–695.

Bolton, S., A. Watts, T. Sibley, and J. Dooley. 1998. A Pilot Study Examining the Effectiveness of Engineered Large Woody Debris (ELWD™) as an Interim Solution to Lack of LWD in Streams. *EOS, Transactions of the American Geophysical Union* 79(45):F346.

Borg, D., I. Rutherford, and M. Stewardson. 2007. The Geomorphic and Ecological Effectiveness of Habitat Rehabilitation Works: Continuous Measurement of Scour and Fill around Large Logs in Sand-Bed Streams. *Geomorphology* 89(1/2):205–216.

Braudrick, C. A., and G. E. Grant. 2000. When do Logs Move in Rivers? *Water Resources Research* 36(2):571–583.

Brooks, A. P. 2006. *Design Guidelines for the Reintroduction of Wood into Australian Streams*. Land & Water Australia, Canberra.

Brooks, A. P., T. Howell, T. B. Abbe, and A. H. Arthington. 2006. Confronting Hysteresis: Wood Basin River Rehabilitation in Highly Altered Riverine Landscapes of South-Eastern Australia. *Geomorphology* 79(3/4):395–422.

Castro, J., and R. Sampson. 2001. *Incorporation of Large Wood into Engineering Structures.* Natural Resource Conservation Service Engineering Technical Note Number 15. U.S. Department of Agriculture. Boise, ID.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997a. Response of Juvenile Coho Salmon and Steelhead to Placement of Large Woody Debris in a Coastal Washington Stream. *North American Journal of Fisheries Management* 17:947–963.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997b. Response of Juvenile Coho Salmon and Steelhead to the Placement of Large Woody Debris in a Coastal Washington Stream. *Transactions of the American Fisheries Society*. 118:368–378.

Cederholm, C. J., L. G. Dominguez, and T. W. Bumstead. 1997c. Rehabilitating Stream Channels and Fish Habitat Using Large Woody Debris. In P. A. Slaney and D. Zaldokas (eds.), *Fish Habitat Procedures*. Watershed Restoration Program, Ministry of Environment, Lands and Parks, Vancouver, British Columbia.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Comiti, F. and Mao, L. 2012. *Recent Advances in the Dynamics of Steep Channels. Gravel-bed Rivers: Processes, Tools, Environments*, pages 351–377.

Copeland, R. R. 1983. *Bank Protection Techniques Using Spur Dikes*. Paper No. HL-83-1. Hydraulics Laboratory. U.S. Army Waterways Experiment Station. Vicksburg, MS.

Cramer, M. L. (ed.). 2012. *Stream Habitat Restoration Guidelines*. Copublished by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service. Olympia, WA.

Cramer, M., K. Bates, D. Miller, K. Boyd, L. Fotherby, P. Skidmore, T. Hoitsma, B. Heiner, K. Buchanan, P. Powers, G. Birkeland, M. Rotar, and D. White. 2002. *Integrated Streambank Protection Guidelines*. Washington State Aquatic Habitat Guidelines Program, Washington State Department of Fish and Wildlife. Olympia, WA.

Curran, J. C. 2010. Mobility of Large Woody Debris (LWD) Jams in a Low Gradient Channel. *Geomorphology* 116:320–329.

D'Aoust, S. G. and R. G. Millar. 2000. Stability of Ballasted Woody Debris Habitat Structures*. Journal of Hydraulic Engineering* 126(11):810–817.

Derrick, D. L. 1997. Twelve low-Cost, Innovative, Landowner Financed, Streambank Protection Demonstration Projects. Pages 446–451 in *Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, and Restoration*. Center for Computational Hydroscience and Engineering, University of Mississippi.

Drury, T. A. 1999. *Stability and Pool Scour of Engineered Log Jams in the North Fork Stillaguamish River, Washington*. Thesis, Master of Science in Civil Engineering. University of Washington, Seattle.

Elliot, R., D. Froehlich, and R. MacArthur. 2012. *Calculating the Potential Effects of Large Woody Debris Accumulations on Backwater, Scour, and Hydrodynamic Loads*. Pages 1213–1222 in Proceedings of the World Environmental and Water Resources Congress 2012. Reston, VA: American Society of Civil Engineers.

Erskine, W. D., M. J. Saynor, A. C. Chalmers, and S. J. Riley. J. 2012. Water, Wind, Wood, and Trees: Interactions, Spatial Variations, Temporal Dynamics, and their Potential Role in River Rehabilitation. *Journal of Geographical Research* 50(1):60–74.

Eslamian, S. 2014. *Handbook of Engineering Hydrology.* Boca Raton, FL: CRC Press.

Federal Emergency Management Agency (FEMA). 2009. *NFIP Floodplain Management Guidebook: A Local Administrator's Guide to Floodplain Management and the National Flood Insurance Program.* Fifth Edition, Federal Emergency Management Agency Region 10. Bothell, WA.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Restoration Implementation, Monitoring, and Management. Chapter 9 in *Stream Corridor Restoration: Principles, Processes and Practices*. National Technical Information Service, U. S. Department of Commerce, Springfield, VA. Also published as NRCS, U.S. Department of Agriculture (1998) *National Engineering Handbook* (NEH), Part 653. Washington, D.C.

Fischenich, C. 2001. *Stability Thresholds for Stream Restoration Materials*, Publication No. ERDC TNEMRRP-SR-29. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fischenich, C., and J.V. Morrow, Jr. 2000. *Streambank Habitat Enhancement with Large Woody Debris.* Publication No. ERDC TN-EMRRP-SR-13. U.S. Army Engineer Research and Development Center.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins (eds.). 1998. *California Salmonid Stream Habitat Restoration Manual*. 3rd ed. California: California Department of Fish and Game, Inland Fisheries Division, Sacramento.

Forest Products Laboratory. 2010. *Wood Handbook—Wood as an Engineering Material*. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI.

Freschet, G. T., J. T. Weedon, R. Aerts, J. R. van Hal, and J. H. Cornelissen. 2012. Interspecific Differences in Wood Decay Rates: Insights from a New Short-Term Method to Study Long-Term Wood Decomposition. *Journal of Ecology* 100:161–170. doi: 10.1111/j.1365-2745.2011.01896.x.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. *North American Journal of Fisheries Management* 12 182–197.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1996. Distribution and Hydraulic Significance of Large Woody Debris in a Lowland Australian River. *Hydrobiologia* 318:179–194.

Gotvald, A. J., N. A. Barth, A. G. Veilleux, and C. Parrett. 2012. *Methods for Determining Magnitude and Frequency of Floods in California, Based on Data Through Water Year 2006.* U.S. Geological Survey Scientific Investigations Report 2012–5113. Available: http://pubs.usgs.gov/sir/2012/5113/.

Gurnell, A. M., H. Piegay, F. J. Swanson, F. J. and S. V. Gregorys. 2002. Large Wood and Fluvial Processes. *Freshwater Biology* 47(4):601–619.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

He, Z., W. Wu, and F. D. Shields, Jr. 2009. Numerical Analysis of Effects of Large Wood Structures on Channel Morphology and Fish Habitat Suitability in a Southern U.S. Sandy Creek. *Ecohydrology* 2 (3):370–380. doi: 10.1002/eco.60.

Herrera Environmental Consultants, Inc. 2006. *Conceptual Design Guidelines: Application of Engineered Logjams.* Prepared for Scottish Environmental Protection Agency, Galashiels, United Kingdom.

Hertzberg, R. 1954. Wave-Wash Control on Mississippi River Levees. *Transactions of the ASCE* 119(2688):628–638.

Hilderbrand, R. H., A. D. Lemly, C. A. Dolloff, and K. L. Harpster. 1998. Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects. *North American Journal of Fisheries Management* 18:161–167.

Hyatt, T. L., and R. J. Naiman. 2001. The Residence Time of Large Woody Debris in the Queets River, Washington, USA. *Ecological Applications* 11(1):191–202.

ICF International. 2010. *Instream Woody Material Installation and Monitoring Guidance Manual.* Sacramento Area Flood Control Agency, Sacramento, California.

Interagency Advisory Committee on Water Data (IACWD). 1982. *Guidelines for Determining Flood Flow Frequency*. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia. 183 p.

Jia, Y., S. Scott, Y. Xu, and S. S. Y. Wang. 2009. Numerical Study of Flow Affected by Bendway Weirs in Victoria Bendway, the Mississippi River. *Journal of Hydraulic Engineering* 135(11):902–916.

Johnson, A. W., and J. M. Stypula (eds.). 1993. *Guidelines for Bank Stabilization Projects in the Riverine Environments of King County*. King County Department of Public Works, Surface Water Management Division. Seattle, WA.

Johnson, P. A., R. D. Hey, M. Tessier, and D. L. Rosgen. 2001. Use of Vanes for Control of Scour at Vertical Wall Abutments. *Journal of Hydraulic Engineering* 127(9):772–778.

Kail, J., D. Hering, S. Muhar, J. Gerhard, and S. Preis. 2007. The Use of Large Wood in Stream Restoration: Experiences from 50 Projects in Germany and Austria. *Journal of Applied Ecology* 44:1145–1155.

Keown, M. P., N. R. Oswalt, E. B. Perry, and E. A. Dardeau Jr. 1977. *Literature Survey and Preliminary Evaluation of Streambank Protection Methods*. Technical Report No. WES-TR-H-77-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Klingeman, P. C., S. M. Kehe, and Y. A. Owusu. 1984. *Streambank Erosion Protection and Channel Scour Manipulation Using Rockfill Dikes and Gabions*. Water Resources Research Institute, Oregon State University. Salem, OR.

Knutson, M., and P. Fealko. 2014. *Pacific Northwest Region Resource and Technical Services—Large Woody Material Risk Based Design Guidelines*. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.

Kruys, N., B. G. Jonsson, and G. Stahl. 2002. A Stage-Based Matrix Model for Decay-Class Dynamics of Woody Debris. *Ecological Applications* 12(3):773–781.

Kuhnle, R. A., C. V. Alonso, and F. D. Shields Jr. 1999.Volume of Scour Holes Associated with 90-degree Spur Dikes. *Journal of Hydraulic Engineering* 125(9):972–978.

Kuhnle, R. A., C. V. Alonso, and F. D. Shields Jr. 2002. Local Scour Associated with Angled Spur Dikes. *Journal of Hydraulic Engineering* 128(12):1087–1093.

Lagasse, P. F., P. E. Clopper, J. E. Ortiz-Page, L. W. Zevenbergen, L. A. Ameson, J. D. Schall, and L. G. Girard. 2009. *Bridge Scour and Stream Instability Countermeasures Experience, Selection and Design Guidance Volumes 1 and 2.* HEC-23, Third Edition. Federal Highway Administration. Washington, D.C.

Lagasse, P. F., P. Clopper, L. Zevenbergen, W. Spitz, and L. G. Girard. 2010. *Effects of Debris on Bridge Pier Scour*. Federal Highway Administration. Washington, D.C.

Lassettre, N. S., and G. M. Kondolf. 2012. Large Woody Debris in Urban Stream Channels: Redefining the Problem. *River Research and Applications* 28.9 (2012):1477–1487.

Lester, R. E. and A. J. Boulton. 2008. Rehabilitating Agricultural Streams in Australia with Wood: A Review. *Environmental Management* 42(2):310–326.

Merten, E., J. Finlay, L. Johnson, R. Newman, R., H. Stefan, and B. Vondracek. 2010. Factors Influencing Wood Mobilization in Stream. *Water Resources Research* 46:W10514.

Miles, P. D., and W. B. Smith. 2009. *Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America*. U.S. Forest Service, Newtown Square, PA.

Montgomery, D. R., and T. B. Abbe. 2006. Influence of Logjam-Formed Hard Points on the Formation of Valley-Bottom Landforms in an Old-Growth Forest Valley, Queets River, Washington, USA. *Quaternary Research* 65:147–155.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1995a. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995b. Pool Spacing in Forest Channels. *Water Resources Research* 31:1097–1105.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Nanson, G. C., M. Barbetti, and G. Taylor. 1995. River Stabilisation due to Changing Climate and Vegetation During the late Quaternary in Western Tasmania, Australia. *Geomorphology* 13.1(1995):145–158.

Natural Resources Conservation Service (NRCS). 2007a. Streambank Soil Bioengineering. Technical Supplement TS 14I in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

Natural Resources Conservation Service (NRCS). 2007b. Use and Design of Soil Anchors. Technical Supplement TS 41E in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

Natural Resources Conservation Service (NRCS). 2007f. Stream Hydrology. Chapter 5 in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

Oregon Department of Fish and Wildlife (ODFW). 2010. *Guide to Placement of Wood, Boulders, and Gravel for Habitat Restoration*. Oregon Departments of Forestry and Fish and Wildlife. Salem, OR.

Oregon Department of Transportation (ODOT). 2011. *Hydraulics Manual, Engineering and Asset Management*. Unit Geo-Environmental Section. Salem, OR.

Petersen, M. S. 1986. *River Engineering*. Englewood Cliffs, NJ: Prentice-Hall.

Piégay, H., and J. P. Bravard. 1997. Response of a Mediterranean Riparian Forest to a 1 in 400 Year Flood, Ouveze River, Drome-Vaucluse, France. *Earth Surface Processes and Landforms* 22(1):31–43.

Pokrefke, T. J. (ed.) 2013. *Inland Navigation: Channel Training Works*. ASCE Manual of Practice 124. American Society of Civil Engineers. Reston, VA.

Quinault Indian Nation (QIN). 2008. *Salmon Habitat Restoration Plan for the Upper Quinault River.* Quinault Indian Nation Department of Fisheries. Taholah, Washington. Prepared by T. Abbe and others.

Roni, P., K. Hanson, and T. Beechie. 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management* 28(3):856–890.

Ruiz-Villanueva, V., M. Stoffel, H. Piégay, V. Gaertner, and F. Perret. 2014. Wood Density Assessment to Improve Understanding of Large Wood Buoyancy in Rivers. Pages 2503–2508 in A. Schleiss, G. De Cesare, M. Franca, and M. Pfister (eds.), *River Flow*. London, England: Taylor and Francis.

Saldi-Caromile, K., K. Bates, P. Skidmore, J. Barenti, and D. Pineo. 2004. *Stream Habitat Restoration Guidelines: Final Draft.* Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. Olympia, Washington.

Sauer, V. B. 1974. *Flood Characteristics of Oklahoma Streams Techniques for Calculating Magnitude and Frequency of Floods in Oklahoma, with Compilations of Flood Data Through 1971.* U.S. Geological Survey Water-Resources Investigations Report 73–52. 307 p.

Scheffer, T. C. 1971. A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground. *Forest Products Journal* 21(10):25–31.

Shields, F. D., Jr. 2007. *Scour Calculations.* Technical Supplement 14B in Stream Restoration Design. National Engineering Handbook Part 654. USDA-NRCS. Washington, D.C. CD-ROM.

Shields, F. D., Jr., and C. V. Alonso. 2012. Assessment of Flow Forces on Large Wood in Rivers. *Water Resources Research* 48(4):W04156.

Shields, F. D., Jr., and C. J. Gippel. 1995. Prediction of Effects of Woody Debris Removal on Flow Resistance. *Journal of Hydraulic Engineering* 121 (4):341–354.

Shields, F. D., Jr., and A. D. Wood. 2007. *The Use of Large Woody Material for Habitat and Bank Protection*. Technical Supplement 14J in Stream Restoration Design, National Engineering Handbook Part 654. USDA-NRCS Washington, D.C. CD-ROM.

Shields, F. D., Jr., A. J. Bowie, and C. M. Cooper. 1995. Control of Streambank Erosion due to Bed Degradation with Vegetation and Structure. *Water Resources Bulletin* 31(3):475–489.

Shields, F. D., Jr., N. Morin, and C. M. Cooper. 2004. Large Woody Debris Structures for Sand-Bed Channels. *Journal of Hydraulic Engineering* 130(3):208–217.

Shields, F. D. Jr., S. S. Knight, and J. M. Stofleth. 2006. Large Wood Addition for Aquatic Habitat Rehabilitation in an Incised, Sand-Bed Stream, Little Topashaw Creek, Mississippi. *River Research and Applications* 22:803–817.

Shields, F. D., Jr., S. R. Pezeshki, G. V. Wilson, W. Wu, and S. M. Dabney. 2008. Rehabilitation of an Incised Stream with Plant Materials: The Dominance of Geomorphic Processes. *Ecology and Society* 13 (2):54.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen. 2000. Bank and Near-Bank Processes in an Incised Channel. *Geomorphology* 35(3):193–217.

Simon, A., A. Brooks, and N. Bankhead. 2012. Effectiveness of Engineered Log Jams in Reducing Streambank Erosion to the Great Barrier Reef: The O'Connell River, Queensland, Australia. Pages 2570–2577 in *World Environmental and Water Resources Congress 2012: Crossing Boundaries*. Reston, VA: ASCE.

Simon, A., R. Thomas, A. Curini, and N. Bankhead. 2014. *Development of the Bank-Stability and Toe-Erosion Model* (BSTEM version 5.4). Available: www.kwo.org/reports_publications/Presentations/pp_Development_of_BSTEM_012811_sm.pdf.

Simpson, W. and A. TenWolde. 1999. Physical Properties and Moisture Relations of Wood. Chapter 3 in *Wood Handbook: Wood as an Engineering Material.* Report FPL-GTR-113. U.S. Department of Agriculture Forest Service. Forest Products Laboratory. Madison, WI.

Smith, D. L., J. B. Allen, O. Eslinger, M. Valenciano, J. Nestler, and R. A. Goodwin. 2011. Hydraulic Modeling of Large Roughness Elements with Computational Fluid Dynamics for Improved Realism in Stream Restoration Planning. *Geophysical Monograph Series* 194:115–122.

Subramanya, K., 2008. *Engineering Hydrology*. New York: McGraw-Hill. 434 pp.

Svoboda, C. D. and K. Russell, K. 2011. Flume Analysis of Engineered Large Wood Structures for Scour Development and Habitat. Pages 2572–2581 in *Proceedings, World Environmental and Water Resources Congress*, ASCE, Reston, VA.

Sylte, T., and C. Fischenich. 2000. *Rootwad Composites for Streambank Erosion Control and Fish Habitat Enhancement*. U.S. Army Corps of Engineers. Vicksburg, MS.

Thompson, D. M. 2002. Channel-bed Scour with High Versus Low Deflectors. *Journal of Hydraulic Engineering* 128(6):640–643.

Thompson, D. M., and Stull, G. N. 2002. The Development and Historic Use of Habitat Structures in Channel Restoration in the United States: The Grand Experiment in Fisheries Management. *Géographie physique et Quaternaire* 56(1):45–60.

Turnipseed, D. P., and V. B. Sauer. 2010. *Discharge Measurements at Gaging Stations: U.S. Geological Survey Techniques and Methods Book 3*, Chapter A8, U.S. Geological Survey.

U.S. Army Corps of Engineers, 1981. *The Streambank Erosion Control Evaluation and Demonstration Act of 1974*. Final Report to Congress, Main Report. Washington, D.C.

U. S. Army Corps of Engineers. 1992. *Engineering and Design: Bearing Capacity of Soils*. EM 1110-1-1905. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U. S. Army Corps of Engineers. 1994. *Engineering and Design: Hydraulic Design of Flood Control Channels.* EM 1110-2-1601. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U. S. Army Corps of Engineers. 2005. *Engineering and Design: Stability Analysis of Concrete Structures.* EM 1110-2-2100. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U.S. Department of Agriculture (USDA), Agricultural Research Service. 2013. *Bank Stability and Erosion Model*. Available: http://www.ars.usda.gov/Research/docs.htm?docid=5044&page=1.

Valverde, R. S. 2013. *Roughness and Geometry Effects of Engineered Log Jams on 1-D Flow Characteristics.* M. S. Thesis, Civil Engineering, Oregon State University, Corvallis.

Vanoni, V. 1975. *Sedimentation Engineering, ASCE Manuals and Reports on Engineering Practice—No. 54*. American Society of Civil Engineers, New York, NY, pp. 531–538.

Viessman, W. J., and G. L. Lewis. 2003. *Introduction to Hydrology.* Prentice Hall. 612 pp.

Wallerstein, N. P., C. V. Alonso, S. J. Bennett, and C. R. Thorne. 2001. Distorted Froude-Scaled Flume Analysis of Large Woody Debris. *Earth Surface Processes and Landforms* 26:1265–1283.

Wohl, Ellen. 2013. Floodplains and Wood. *Earth-Science Reviews* 123:194–212.

Wood, A. D., and A. R. Jarrett. 2004. *Design Tool for Rootwads in Streambank Restoration.* Paper 042047, Annual International Meeting, Ottawa. American Society of Agricultural Engineers. St. Joseph, MI.

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Chapter 7
RISK CONSIDERATIONS

Channel spanning logjam in the Deschutes River of central Oregon providing a complex range of habitat conditions and cover (Tim Abbe, March 2013).

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7.1 Purpose

This chapter provides an overview of how to assess risk when introducing and managing wood in stream restoration and management. Risk is a major concern with many stakeholders based on real and perceived threats that wood may pose or because infrastructure was never designed for wood conveyance. This is not surprising given over a century of channel clearing led by local, state, and federal government agencies. Inappropriate placements and poorly designed structures can introduce unacceptable risks. Risk also applies to ecological effects caused by design alternatives that do more harm than good. Every project should consider a range of alternatives that always includes a no-action scenario. An objective risk assessment not only provides insight to how and where things can go wrong, but provides justification on why restoration is needed.

7.2 Introduction

The design and placement of large wood structures and riparian reforestation has been recognized as a beneficial element of stream and river restoration strategies (Roni et al. 2014a). Historically, large wood was naturally abundant and strongly influenced fluvial morphology in virtually every river and stream network where riparian forests were present. In the past 100 to 200 years, large wood has been actively removed from streams for a variety of reasons, such as: to increase channel flood capacity, improve channel navigability, and improve safety to the general public. Although most of the initial wood reintroduction projects in North America were well intentioned, some projects had limited success due to the insufficient understanding of the fluvial processes, and the forces to which the structures would be subjected, how the project would influence these processes, and how changes in those processes would affect habitat. In the past 30 years, the importance of large wood to geomorphic processes, habitat complexity, and ultimately, the health of aquatic habitat has become better understood. This has led to federal, state, local, tribal, and private citizens placing large wood in streams in the form of ELJs and large wood placements. These endeavors are an effort to restore channel processes, create habitat for the purposes of enhancing geomorphic and habitat processes, and restoring flood-protection measures that will enhance fluvial processes while also protecting infrastructure and property.

While the placement of large wood is an important component of river restoration strategies, many of the rivers and streams have significant constraints such as civil and private infrastructure, private property ownership, and a host of recreational activities within the river corridors. These constraints are commonly damaged by natural fluvial processes and are at risk from flooding and erosion, resulting in significant public and private investments in river-training structures and flood-control projects.

Current river and floodplain management practices acknowledge that there are inherent risks associated with any river that could negatively affect recreation opportunities, commerce, infrastructure, and existing buildings in a flood or channel migration zone. Since the European settlement of North America started, large financial investments have been made in the United States to reduce flood risks and improve navigation through the removal of large wood, dam building, channel confinement, channel training, and flood-control projects, which have singly and in combination greatly simplified aquatic habitat and disrupted natural fluvial processes. It is important to recognize that extensive natural wood accumulations can coexist with existing infrastructure. For example, large accumulations of wood in Long Tom Creek in Venata, Oregon, occur adjacent to the annual Oregon Country Fair (Figure 7-1). The wood probably increases the frequency of floodplain inundation during the fall and winter, but holding the Country Fair during the summer has avoided this potential issue. In the Upper Yakima River near the town of Easton, Washington, a channel-spanning logjam just 100 meters (328 feet) from Interstate 90 has obstructed flows for decades without threatening the highway, due to natural development of new side channels (Abbe et al. 2003a).

Figure 7-1. Natural Logjam on Long Tom Creek near Venata, Oregon

The simplification of rivers and streams has also led to public misconceptions of riparian systems and their natural fluvial processes. As addressed in previous chapters, a healthy and productive river is complex on multiple levels. The “mess” many people perceive when seeing wood accumulating in a river channel is quite the opposite from an ecological perspective. With any fluvial project, managing risk must also include gaining an understanding of and managing people’s perceptions. By helping the public understand fluvial science and the historic context, project sponsors and practitioners can expect greater public support for future projects. For instance, wood accumulations, once common in streams, were very effective at dissipating energy, slowing down flows, trapping sediment, engaging floodplains, and creating vast wetlands. These naturally occurring events moderated downstream flooding and reduced channel incision (i.e., the natural or anthropogenic downcutting of a river that occurs in the long-term erosion of a landscape). In many watersheds the clearing of wood and channel straightening has increased the speed at which floods move downstream and the stream’s erosive power to create incised channels that are disconnected from their floodplains, further exaggerating downstream flooding. Channel incision can threaten infrastructure buried under, going over, or near existing channels. It is imperative to consider that the failure to correctly restore wood in channels can also pose significant risks. Too often risk assessments are one-sided, simply focusing on traditional definitions of risk and the historic perceptions of wood. Restoration of fluvial systems using large wood should always consider the risk of not restoring the system correctly, and, in most cases, it can be demonstrated that restoration provides the greatest long-term benefits and reductions in risk. Much of this chapter focuses on factors to consider in assessing risks of reintroducing wood to streams from the perspective of flooding, erosion, and public safety. Evaluating risk in river restoration has received increased attention, and some sort of risk assessment is typically included in many restoration projects. Thorne et al. (2014b) describe the project risk screening matrix, including the RiverRAT guidelines published by the National Oceanic and Atmospheric Administration (http://restorationreview.com/).

The initial and essential step in conducting the risk assessment is to document the existing, inherent, or background risks found within the stream or river in question. This is particularly important given that the assessment is intended to show whether or not the addition of large wood will introduce risks not found in the system or will increase existing risks. Natural wood can pose direct and indirect risks. Direct risks are those that create a direct impact, such as a person who is entangled in wood situated in flowing water. Indirect risks are those where wood contributes to a problem, such as wood blocking a culvert, which in turn leads to flooding. Both of these risks can exist where wood is naturally entering streams. For example, natural logjams still occur throughout North America and pose a significant hazard to unprepared boaters (e.g., kayakers, canoeists, rafters, and fishermen) and have been contributing factors in fatalities, injuries, and close calls. In all such instances, the people involved assumed personal responsibility for the risks associated with entering the river. The persistence of the traditional view that “clean” rivers are safer contradicts the reality that in some circumstances wood provides benefits that slow flows down, limit channel incision, and create safer conditions for the public on the whole. The widespread perception that wood is a hazard will have to be addressed by many restoration projects, increasing the time and cost of implementation. At the same time, many user groups are strong advocates for restoring river corridors to the benefit of aquatic species and allowing the natural channel-forming processes to continue. Additionally, user safety is a goal for these advocates, where large wood is seen as a hazard, suggesting many current river users and advocates are unaware of the influence large wood historically had on properly functioning fluvial processes and aquatic habitat conditions.

It is also important to consider that the river environment is inherently dangerous because of large wood delivery and the dynamic behavior of channels as they continually adjust their form, alignment, and character through changes in water and sediment delivery.

Wood poses little threat when boaters are careful to inspect the channel prior to floating it to identify potential obstructions and where to line or portage boats around a hazard. Where wood is placed in recreational rivers, warning and educational signage is sometimes required by local authorities. Education, such as signage at boat ramps and information supplied to user groups, leads to less risk, and, conversely, little or no information leads to greater risks. By educating communities about the importance of large wood placements and the conditions they create, a safer environment can be attained. This can be partially achieved by providing local user groups with interpretative kiosks at entry points and posting warning signage where instream structures are located. Regardless of these educational efforts, there may continue to be concerns about placing wood in channels even though project sponsors and designers have done their due diligence and have conducted public meetings, performed other means of outreach, and included signage as part of the project. To address these concerns and also meet the professional engineering design standards, some level of risk assessment should be incorporated into the standard of practice for wood design and managing streams. It should also be recognized that restoring rivers to their natural state will change the way they look to the public. After decades of clearing wood from streams it can be expected that restoration professionals will need to work with local communities and recreational users.

Accurately predicting the geomorphic response of restoration projects or changes in stream management can influence relationships with stakeholders and local communities which affect future projects and underscore the importance of having well qualified geomorphologists involved with design. In many cases, large wood placements have been designed to achieve the maximum geomorphic and habitat benefit, which has in some instances resulted in conflicts with the general public and recreational users. In 2010, public concerns over large wood placements in the Entiat River watershed in Washington State led to construction delays and added coordination costs. Ultimately, maintaining and improving the safety around large wood placements requires careful planning, public education, and outreach to reduce conflicts. Urban rivers and streams may pose extra consideration because of infrastructure, private property, upstream effects, downstream effects, and recreational uses or aesthetic considerations. The most common failure of large wood placements during early attempts has been the wood simply washing away and the failure to achieve the intended effects at the reach scale (Frissell and Nawa 1992). But advancements in the understanding of wood stability and engineering instream structures have dramatically increased the performance of wood placements (Nooksack Tribe 2013).

The design life of wood structures continues to be a common question that risk assessments address, particularly the mechanical failure of a structure during a particular design flow. Force balance calculations (*see Chapter 6, Engineering Considerations*) should be done to ensure any structure has the desired stability. These calculations should not only account for buoyancy and drag, but how the structure is designed to deal with bed scour (Figure 7-2).

Scour is one of the most common failure mechanisms of instream structures, both in traditional river engineering and restoration. Wood structure design should also assess design life with respect to decay. Wood that remains submerged can last indefinitely, so wood placed below base flow will have a much longer design life than wood subjected to wetting and drying. Some types of wood such as cedar are naturally more resistant to decay, so that should be taken into account in estimating design life. Some permitting agencies may not require projects to clearly describe the measures to retain wood placements, but may require an assessment of the fate of wood should it be washed downstream (e.g., will it threaten downstream infrastructure?).

In the restoration context, large wood placements should have a design life sufficient to restore habitat conditions, achieve the project objectives, and sustain long-term recovery of the system. This is typically the time needed to reestablish riparian trees large enough to create functional (stable) instream wood and natural processes to deliver the wood into the river (e.g., bank erosion, wind throw associated with severe weather). In other cases the design life of large wood placements may be subjective, based on typical design life of existing infrastructure, or subject to such stochastic events as major ice dam breaks.

Figure 7-2. Scour Undermining Downstream Corner of an ELJ on Upper Quinault, Washington

To summarize, managing all streams involves some level of risk, including leaving the system and current processes in their current condition. Placing anything, including wood, into a stream immediately incurs risk as the object could be washed away, which may negate the purpose for which it was intended and pose downstream risks. Stable large wood structures induce changes that can be beneficial or create undesired results. It is important that large wood designs carefully consider project goals, define acceptable risk, determine the critical factors contributing to unacceptable risks, and develop designs that achieve project goals within acceptable risks. Therefore, the simple act of conducting a risk assessment helps to reduce the chances of an adverse effect.

RISKS

Using Wood in Stream Restoration

- Loss or washout of wood placement that results in failure to achieve restoration goals.
- Washout of wood placement that would threaten downstream infrastructure:
  - Bridge pier scour
  - Bridge or culvert blockages causing flooding
- Large wood structures triggering unintended geomorphic changes in a river corridor which damage adjacent infrastructure, property, or habitat (e.g., structure intended to protect a bank could cause unintended erosion of an adjacent or opposite bank).
- Large wood structures raise water elevations above existing regulatory mandates (e.g., the FEMA 100-year flood).
- Large wood structures collecting sufficient debris to increase flooding or create hazardous conditions.
- Large wood structures altering sediment transport characteristics within the reach, resulting in local aggradation or scour affecting flooding or infrastructure failure.
- The presence of large wood structures encouraging beaver activity in the area leading to formation of beaver dams, with subsequent flooding impacts on adjacent properties or creation of fish passage barriers.
- Large wood used in bank stabilization rotting out over time, leaving a “soft spot” in the road prism or hillside that would then be exposed to future slope instability.

7.3 Defining and Assessing Risk

Assessing risk can be relatively simple when there is little or no consequence to failure, or it can entail complex quantitative analyses of stability, hydraulics, channel response, human behavior, and monetary costs. Any risk assessment is inherently subjective given the many factors that influence streams, so a great deal depends on professionals familiar with fluvial processes and historical knowledge of regional streams in unmanaged forest settings and in disturbed settings. An assessment can be as simple as using empirical guidelines to size and then place functional wood into a remote stream. This scenario assumes that there would be no adverse consequences because the stream is located in a protected watershed with little to no development or recreation. Conversely, a sophisticated assessment can include detailed engineering, flood scenarios, wood transport, wood decay rates, and other analyses, to clearly evaluate all reasonable scenarios that could occur. Potential changes in both the natural and built environment, such as climate change and increased development, introduce uncertainty and may require more detailed analysis and predictions to adequately assess risk. Rivers themselves have inherent dangers where the variability in river conditions are constantly changing and evolving. As such, risks for any given project are situation-specific and should be evaluated relative to the watershed and user groups associated with the project, stream type, project context, and project components.

Risk assessments are increasingly being incorporated into stream restoration and river management to better ensure that projects have considered potential adverse consequences. Standard engineering practices typically include a risk assessment involving a structure’s stability and safety. In stream restoration practice, large wood placements have been a primary driver for completing risk assessments because of the concern about public safety associated with instream structures that many people are not familiar with, do not understand, or see as a potential threat.

Risk is ubiquitous within the river environment given channel responses to changes related to water, sediment, and the delivery of natural large wood. The purpose of any risk assessment is not to eliminate risk but to objectively evaluate the potential risk elements and assess how a particular large wood placement or project can be designed and installed to address and alleviate those risks. It is also important to note that there can often be a significant risk to continued geomorphic and habitat degradation if large wood is not reintroduced to a stream or river, and this should be considered in every risk assessment. This highlights the importance of having a professional geologist with expertise in fluvial geomorphology involved with design and risk assessments, including approving plan sets and reports. A primary purpose of a risk assessment is to assure the design team, stakeholders, and local community that the short- and long-term effects of the project have been considered, and the expected benefits of the project outweigh the potential consequences.

Risk is most commonly defined as the product of the probability of a certain event occurring with the consequences of that event. This is expressed as the following equation.

$$Risk = P(h)x\sum(C)$$

Where:

P(h) = Probability of a specific event or combination of events occurring.

∑(C) = Summation of the consequences of event occurring, typically presented as a monetary cost.

If there are no negative consequences of a particular event occurring, then there is no risk. If the consequences are very severe, then even an event with low probability of occurrence may pose more risk than is acceptable. Critical to evaluating risk is how events and consequences are defined. For instance, the 100-year recurrence flood has a 1% probability of occurring in any given year. The 100-year flood is then associated with particular consequences to have meaning, such as flooding areas that will have economic damages (consequences). In the case of large wood placement, if it is known that a large wood structure would fail during a 100-year flood event, then consequences must be assigned to the structure's failure. This could be as simple as the economic loss associated with how much it cost to build the wood structure or additional factors such as the wood accumulating on a bridge pier. Assuming a large wood structure has a 50% probability of surviving the 1% probability flood event, then the large wood structure has a 0.5% (0.5 x 0.01 = 0.005) probability of failing in any given year. If the structure does fail, the consequences also may have a particular probability. For instance, if the structure fails, there will be some probability from 0 to 1 of wood accumulating on a bridge pier that would pose a problem. If that probability was 1%, then the actual probability of wood causing a problem at the bridge would be 0.005% (0.005 x 0.1 = 0.00005) in any given year. If the consequences are $100,000 in emergency maintenance then the total risk would be $5 per year summed over 50 years, which would be $250. But if wood on the bridge resulted in a failure requiring a $5,000,000 bridge replacement, then the cumulative risk would be $500 per year, or $25,000 over 50 years.

Risk also must be computed for the no-action alternative and can often result in identification of greater risk to both ecological and socioeconomic conditions than restoration involving wood placement. This is especially true in the case of habitat restoration when the no-action approach results in further degradation of habitat that leads to higher costs to restore in the future. A no-action alternative can also put infrastructure at risk, particularly in cases of channel incision that undermines bridge foundations, buried pipelines, or road embankments. Channel incision has been shown to result in the loss of floodplain connectivity and associated side channels and wetlands. Geomorphic assessments can quantitatively define incision and the impact on both habitat and infrastructure, and provide input on how wood can be used to treat the problem.

For example, assume a geomorphic assessment found that there is a 90% probability that 100 acres of floodplain wetland will be disconnected and lost in the next 20 years if incision is allowed to proceed. In 20 years the incision will also expose a pipeline that would then need to be lowered at an estimated cost of $1,500,000. Stabilizing the stream channel is estimated to cost $2,000,000 if done today. If done in 20 years, the project will be more challenging because of the deeper channel, which together with predicted cost inflation is estimated to be at least $3,500,000, and not recover the wetlands. The estimated replacement or mitigation cost of the wetlands is $10,000/acre, adding an additional $1,000,000 cost if the wetlands are not protected. The total cost of a no-action scenario is $4,500,000—and $6,000,000 if the pipeline has to be lowered. This simple example clearly shows the value of stopping the incision as soon as possible.

In evaluating restoration risks, it is important to understand the ecological trajectory of the project site. In some situations where riparian forests are protected, a stream may gradually be restored under the no-action scenario. In these cases of "passive restoration," the question to ask is how long will recovery take and is that acceptable with regard to goals such as restoring habitat for endangered fish. Recovery metrics must be defined, such as the stream reaching a specified wood loading, a volume per channel length, or number of functional pieces per channel length (e.g., Fox and Bolton 2007). Risk is evaluated by taking the probability of not achieving the desired goal within a specified time, multiplied by the cost of placing that wood at that time. Like other risk assessments, this requires estimating future costs.

With regard to human safety, even passive restoration has risks. As trees fall into rivers they will create potential hazards, so even managing for passive restoration may need to address the benefits and risks of natural snags and logjams to prevent their removal. Historic management incurred costs to remove snags. Currently many parts of the country remove large quantities of wood after major storms and floods, much of which could be left to provide substantial ecological benefits with little risk. Current management leaving wood may have no costs associated with removal, but may entail costs for public outreach and education.

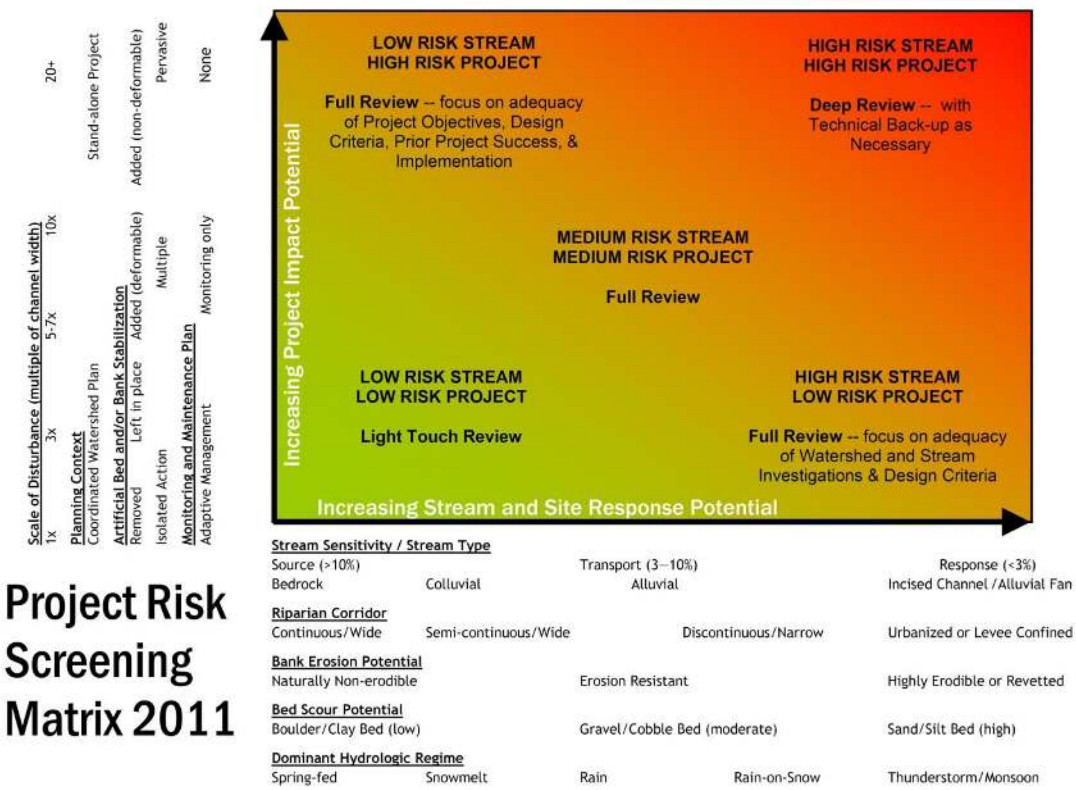
Not all wood placements are equal. Properly engineered wood placements should not pose a risk to downstream infrastructure because they will be stable and act to trap mobile wood that may otherwise put infrastructure at risk. Poorly designed wood placements can pose a major risk if the material were to plug a culvert and trigger a road washout. Conversely, properly engineered wood placements could lower risk to the culvert by capturing mobile wood and sediment prior to reaching the culvert. The engineered wood placements will be more expensive, but will lower risk. Because risk increases at sites upstream of inadequately designed infrastructure, so will project costs. Most culverts were never designed considering sediment transport, much less wood transport. Restoration should always consider upgrading infrastructure as a critical element to achieving restoration goals.

7.3.1 Quantitative and Qualitative Risk Assessment

A risk assessment should be completed for every large wood placement and restoration project, regardless of the size and scope. Risk assessments can either be quantitative or qualitative depending on the level of background risk, acceptable limits of risk, available data, and project resources. Given the subjective nature associated with key risk elements, most often risk assessments begin qualitatively and proceed to a quantitative stage if initial findings warrant further detailed assessments. A thorough risk assessment may even provide an economic study to assess the positive or negative monetary effects from a large wood project. By using a project-screening matrix developed by RiverRAT (Skidmore et al. 2011), practitioners can evaluate the relative level of thoroughness needed for a specific project (i.e., a high response stream with a high impact potential likely warrants a more thorough risk assessment than a low response stream with a low-impact potential; see Figure 7-3).

To complete a quantitative risk assessment, the probability of certain events (e.g., a flood of particular discharge, depth, and velocity capable of moving wood placement) are evaluated then multiplied by the consequences of those events (impact of wood placement moving), and summed for each alternative. The most common method used is to equate a monetary value or loss to risk elements of interest events, and then sum all risk elements for each alternative considered (e.g., replacement cost of a bridge failing, property value loss due to an eroding bank, economic impacts of the loss of a commercial fishery). Assessing the value or loss of any risk elements can be very subjective, and a certain degree of objectivity should be used to provide reasonable assessments. Niezgoda and Johnson (2007) and Jones and Johnson (2015) provide examples of cost-based risk assessments.

Figure 7-3. RiverRAT Screening Matrix



Source: Thorne et al. (2014b).

7.3.2 Elements of Risk Assessment

Defining risk and identifying the appropriate risk elements to consider is specific to each project. However, the processes of assessing risk should not significantly vary between projects.

GUIDANCE

Main Components of a Risk Assessment

1. Description of key risk concerns: (A) human development (e.g., infrastructure, recreation, and flooding) and (B) ecology (e.g., preventing further habitat degradation, failing to achieve restoration goals)
2. Description of channel morphology and stability (e.g., is channel incising or aggrading?)
3. Description of existing or current fluvial and habitat conditions, including presence and type of wood currently in the system
4. Description of historic changes to the system and how they influenced risk concerns (e.g., channel clearing, recreational boating)
5. Description of risks associated with the no-action alternative
6. Description of existing infrastructure such as downstream bridges or culverts and how they could be impacted by wood
7. Description for how the proposed large wood placements will affect these processes and key risk elements

A risk assessment should begin with a description of the existing project site, key watershed processes, and adjacent fluvial morphology (Table 7-1). Typically, this portion of the assessment forms the basis for the no-action alternative. Common risk elements for each component are shown in Table 7-2. Elements of risk assessments should be completed by licensed professionals in each relevant science—typically a geologist with expertise in fluvial geomorphology, bank and hillslope stability, and hydrogeology; a biologist with expertise in aquatic habitat and species; and civil engineering professionals with expertise in hydraulics, structural stability, and construction management. Because all of these fields have a wide range of specific skills, each professional is mandated to practice within their area of expertise or under the guidance of someone who has that experience. Consequently, anyone performing large wood design should have education, knowledge, and experience in all the relevant fields.

There are situations where wood is not appropriate; natural wood rarely occurs within confined bedrock channels (canyons) because wood is more easily transported to such locations due to high flow depths and velocities, and channels with little resistance. Additionally, because there is no bank erosion in bedrock channels, there is little to no wood recruitment. Where historic incision (due to human disturbance) has transformed alluvial channels to bedrock, wood may play an important role in restoring an alluvial channel. Such sites will involve greater risk and more intensive engineering, but also represent important restoration opportunities. Other channel types where wood may not be appropriate are highly confined urban channels with little or no tolerance for increasing water levels. Understanding linkages between channel evolution and wood accumulations is a key element of any risk assessment involving wood placement or removal.

It is important to understand channel stability and the role wood will have on channel forming processes. Wood can be used to stabilize or destabilize banks. Restoration projects will fall into three different categories regarding channel stability.

1. Dynamic Channel Corridors:
    a. Project sites where channel migration is a natural process, which wood

placements are intended to accommodate.

   b. Project sites where natural channel migration has been halted:

      1) Sites where channel migration does not occur due to regulated flow and sediment regimes where wood is intended to help restore channel migration.

      2) Channelized reaches where restoration includes setting back levees and revetments and wood is intended to restore channel migration.

      3) Sites where wood is intended to locally stabilize banks to protect infrastructure or property within a dynamic reach.

2. Restoration of Disturbed Channels that were stable under their natural condition—many restoration projects have a goal of restoring straightened channels to their natural meandering planform. Wood is often used to stabilize banks until mature riparian vegetation is established that naturally stabilizes the channel banks.

3. Stable or Constrained Channel Corridors—sites where wood placements are intended to stabilize banks and not trigger bank erosion elsewhere.

The Trinity River in northwestern California is an example of a restoration program where water withdrawals have dramatically reduced peak flows and sediment supply. The altered flow and sediment regime has resulted in an unnaturally stable channel devoid of the physical and temporal complexity that once characterized the river. One goal of the Trinity Restoration Program (2015) is to rehabilitate channel forming processes such as bar development and bank erosion. Restoration actions include using engineered logjams to deflect flow and induce turbulence that will help trigger the morphologic response the river once had, where wood is being used to help trigger channel migration in reaches where it can be accommodated. Some reaches of the river underwent significant development because flow regulation so the restoration program must deal with different risk issues for each project reach. Some sites must demonstrate they will not adversely affect existing development, with regard to either bank erosion or flooding. The Trinity River also has recreational and commercial rafting and fishing. Through public meetings with fishing guides and rafting representatives and designs that maintained navigable pathways, the restoration program has received widespread public support, and the ELJs have created popular new fishing holes.

Table 7-1. Important Project Characteristics Defining Existing Conditions and Geomorphic Setting

Element	Considerations
Project Goals	Clearly state the project goals and the role wood placements have in achieving those goals; use metrics to quantify goals if possible.
Project Site	Where is the project area located? What are the main features of the project area? What and where are constraints (e.g., levees, bridges, buried pipelines)?
Project Reach	How do upstream and downstream reaches influence the project site?
Watershed Water, Sediment, Wood Loading	Are peak flows increasing? Is sediment supply expected to be relatively constant (e.g., upstream dam or landsliding)? Development, logging, agriculture, and climate change can significantly alter these conditions and influence a project.
Stable Wood	Are there stable wood accumulations in the project reach? If so, what are their characteristics (size and shape of key pieces)? How much wood is enough; how much is too much?
Mobile Wood	How much wood is moving through the project reach, and how will it influence the project? What will consequences be of wood accumulations within the treatment reach?
Geology	What are the characteristics of the riverbed and river banks? What is depth of alluvium? What is bedrock material made of (e.g., glacial clay or hard rock?)
Habitat	What are current habitat conditions? Is there high-value habitat in the project reach that could be affected?
Channel Migration	Is the channel actively migrating? If so, what are the average rates of migration? Are there avulsion risks?
Channel Confinement	Is the channel confined by levees, revetments, or incision?
Existing Large Wood	What is the frequency and function of existing large wood in the project area? Will the project significantly increase the frequency of large wood in the project reach?
Floodplain Connectivity	Do flows frequently access the floodplain?
Riparian Condition	What are the size, species, and distribution of trees in the project reach and channel migration zone, and are they available for potential recruitment?
Historical Context	Was large wood historically present? What were its likely effects?
Future Context	Will large wood loading remain constant? How will climate change effect fluvial habitat processes?
Channel Bed Material	What is the size and gradation of channel material? Has an armor layer formed?
Channel Bank Material	What is bank stability and resistance to erosion? Will wood placements trigger bank erosion on either side of channel? (Refer to Simon and Collison 2002; Simon et al. 2000.)

Table 7-2. Important Elements for Consideration in Risk Assessment

Element	Considerations
Infrastructure	Are there bridges or culverts downstream of the project area? Do they have in-channel piers? What is their ability to convey large wood?
	Are there levees or revetments adjacent to or downstream of the project area? What is their condition? Were they designed to withstand extreme floods?
	Are there buried utilities in the project area? How deep are they buried? If the channel avulses or migrates are they likely to be exposed?
	Are there public or private roads within the adjacent floodplain? If so, are they overtopped frequently and by how much flow depth?
Property	Is the adjacent floodplain public or private property? How will large wood placements affect flood depths on adjacent properties?
	Where is the project area located in relation to property boundaries?
	What structures (houses, outbuildings, recreational facilities) exist within or downstream of the project area?
	Is the channel actively eroding or migrating? How will large wood placements affect erosion and migration rates? Would channel migration into adjacent properties be perceived negatively?
	Are there avulsion pathways through adjacent properties? How will large wood placements affect the likelihood of a major channel avulsion? Would a major avulsion through adjacent properties be perceived negatively?
Habitat	What will happen if no project is completed? Will habitat conditions for the species of interest improve or decline?
	How will large wood placements affect habitat conditions in the short (1 to 5 years) to long term (5 to 50 years)?
	Will there be temporary impacts during the construction process? Will those create any permitting issues?
	How will large wood placements affect future large wood recruitment?
Public Safety	Would failure of infrastructure (described above) cause a threat to human safety or welfare?
	Would erosion, channel migration, or avulsion (described above) cause a threat to human safety or welfare?
	Does the reach experience recreational use? If so, what is the experience level of the normal user? Are most users accustomed to large wood hazards?
Construction	How does the local regulatory environment view large wood installations? Will local policies and/or viewpoints affect how the large wood placements are located and constructed?
	How will the large wood placements be constructed? How will sediment and turbidity be minimized?
	Will de-watering be required? If so, is a de-watering plan feasible? What are the contingencies if the plan's de-watering method proves to be infeasible?
	When will the large wood placements be constructed? Is there a risk of high flows during the construction window? If so, what would the consequences be?
	Can a flood event (e.g., summer rainstorm) pose a threat to construction? What is the probability and how can risk be minimized?

Element	Considerations
	Is there a regulatory “fish-window” or timeframe the project will need to be constructed within? If so, is that timeframe sufficient to complete construction for all elements?
	Will the construction methods generate significant noise that will affect nesting birds or wildlife, particularly threatened or endangered species?
	Is buried wood expected within the excavation area during pile driving? If so, what is the plan or contingencies for how to handle?
	Is bedrock expected in the excavation area during pile driving? If so, what is the plan or contingencies for how to handle this?
	What level of design is being developed for the large wood placement? Has the contractor built large wood placements? How will change-orders be handled during the construction process?
	How will the contractor access the site and are there constraints on that access posed by landowners, length of access route, traffic control, wetlands, stream channels, or soft soils?

7.3.3 Professional Liability

In many regions where large wood placements are installed, property owners, designers, contractors, sponsors, counties, and regulatory agencies are professionally liable for damages caused by these placements (Andrus and Gessford 2007). To minimize liability associated with damages related to large wood placements, practitioners are advised to conduct rigorous and defensible analyses of the risks associated with each project (Tonglao and Eckberg 2012). This analysis should include hydraulic and geomorphic information that will evaluate how the large wood placement would affect flow patterns, and verify that the predicted changes are not likely to result in significant damages to adjacent property owners (Tonglao and Eckberg 2012). In practice, liability is assumed by the design professionals while sponsors and property owners often pursue indemnification agreements to protect themselves. Washington and Oregon have passed legislation granting immunity to private property owners to remove barriers to aquatic habitat restoration.

GUIDANCE

Key Tenets of Recent Washington Legislation

1. The project was designed by licensed professional engineers and geologists experienced in riverine restoration.
2. The project was designed to withstand the 100-year flood.
3. The project is not located within 0.40 kilometer (0.25 mile) of an established boat launch.
4. The project is designed to allow adequate response time for recreational users to safely evade large wood placements.
5. Large wood placements larger than 3 meters (10 feet) long and 0.3 meter (1 foot) in diameter include tagging of individual pieces that will last for at least 3 years.

While these requirements represent specific guidelines for the State of Washington, it is reasonable to expect similar legislation in other states as the design and implementation of wood-based restoration activities becomes more frequent.

Locating and designing large wood placements is a multidisciplinary exercise that requires involvement of trained professionals that include professional engineers, licensed geologists, fisheries scientists, and wetland/ riparian scientists to ensure long-term success (Tonglao and Eckberg 2012). Project sponsors and regulatory agencies are encouraged to require stamped and signed plans from every key discipline involved as part of the review process.

The design of large wood placements should, at a minimum, include licensed professionals and scientists with river and wood expertise. The final design package (plans, specifications, and estimates) should be stamped by a professional geologist and engineer. The geologist ensures that designs have taken into account an understanding of site conditions, geomorphic processes, and responses. The engineer certifies that designs have the desired stability, are buildable, provide sufficient detail for the contractor, and include inspection criteria for ensuring the project is constructed per the design. Due to the charge of civil engineers to "to use their knowledge and skill for the enhancement of human welfare and the environment" and "engineers shall hold paramount the safety, health and welfare of the public…in the performance of their professional duties" (Tonglao and Eckberg 2012) they are often, and in some circumstances, required (SRFB 2013) to be responsible for the design of large wood placements. Furthermore the development of large wood placement designs generally falls into the standard definition of the "practice of engineering" as follows.

> Practice of engineering means any professional service of creative work requiring engineering education, training, and experience and the application of special knowledge of mathematical, physical, and engineering services to such professional services or creative work as consultation, investigation, evaluation, planning, design, and supervision of construction for the assuring compliance with specifications, in connection with any public or private utilities, structures, buildings, machines, equipment, processes, works, or projects.

Other professionals, such as geologists, maintain similar definitions and guidelines. In Washington, any analysis report describing surface and subsurface water flow and earth materials is supposed to be stamped by a professional licensed geologist. Geology specialty licenses include engineering geology (e.g., rock and soil mechanics, hillslope stability, and stabilization of excavated areas) and hydrogeology (e.g., ground and surface water modeling, solute transport, water quality).

7.3.4 Defining Risk on Your Project

Each risk assessment will be unique to each project given the historical context, restoration goals, site constraints, recreational use, and public concerns. However, as noted above, the assessment process should not vary significantly between projects, though the scale of the efforts may be quite different. A risk assessment is only finalized once a project is completed and deemed to be functioning properly. The critical stages for the risk evaluation are completed at critical stages during the lifecycle for the project. An early evaluation is completed during the project concept phase with details on a variety of analyses performed during the project development phase, while a final evaluation is completed during the post-project review and monitoring phase. Each phase of the evaluation process is described below.

7.3.4.1 Project Conception

This phase of risk assessment begins with engaging local and regional stakeholders at the onset of the project to provide an opportunity for input. Initiating the process with stakeholder engagement reduces the chances for costly changes near the end of the design process, and it also engages the community in a way that engenders support for large wood projects. Following public input and developing extensive site knowledge, project sponsors and designers should develop a list of key risk elements (a partial list is included in Table 7-2) to consider during the project development and post-project phases.

7.3.4.2 Project Development

Risk elements identified during the project conception phase should be considered in the project development phase. Alternatives should be developed that consider the geomorphic and habitat restoration goals, and how each alternative could affect the identified risk elements. Effort should also be made to minimize risk, while maintaining intended geomorphic and habitat benefits to the maximum extent possible. Following development of alternatives, an analysis of hydraulic, hydrologic, scour, and stability factors can be performed to evaluate the effects on geomorphic and habitat processes, flooding, erosion, and sediment transport. This information will aid in evaluating the relative risks and benefits of each alternative. At the end of the project development phase, the results of the risk assessment should be documented and presented to the local and regional stakeholders.

7.3.4.3 Post-Project Monitoring

During the development of a large wood project, there is potential to encounter difficulties requiring adjustments to the design elements, schedule, and funding requirements. During the construction phase most challenges arise due to unforeseen site conditions, short construction timeframes, materials that do not meet specifications, and inexperienced contractors. The purpose of this phase of the risk assessment is to ensure that the key assumptions and design elements were completed and the large wood placements are performing as intended. The majority of the risk assessment for this phase can be completed during the post-construction punch-list with the contractor and project sponsor. A punch-list is simply a checklist of important actions that can be clearly accounted for with regard to when they were completed, by whom, and as intended. During the development of the punch-list items, each large wood placement should be inspected and evaluated for compliance with the final plans and specifications, while any deviations that create a high-risk situation should be addressed before the contractor demobilizes from the site. Following the post-construction walk through, large wood placements should be inspected on an annual, multiyear timeframe to ensure the structures are performing as intended and a high-risk situation has not developed. If during periodic monitoring a high-risk situation is observed, sponsors should consider an adaptive management protocol to reduce risk and improve public safety. Situations that could warrant high risk could include natural large wood that has racked on large wood placements creating a strainer condition or a channel spanning logjam that increases unacceptable flooding or erosion.

CROSS-REFERENCE

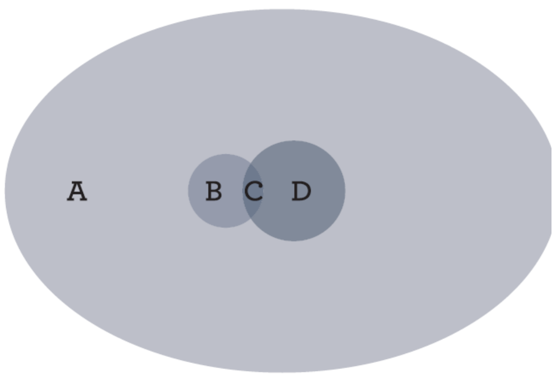
Chapter 9, *Assessing Ecological Performance*, describes the adaptive management process in detail.

7.3.4.4 Special Considerations for Recreational Users

Safety attributes of ELJ and large wood placements specific to recreational users can be divided into two categories: reach and structure-specific assessments. Reach categories include definition of the recreational use, access, and reach-scale geomorphic factors. Structure-specific categories include structure location, structure type and characteristics, and avoidance potential of each specific structure (i.e., line of sight distance, path around structure, including portage, and response time). These categories, as they relate to public safety and the engineered placement of large wood, are further explained in the following section.

The American Whitewater Association (2012) suggests assessing how individual wood accumulations function both ecologically and as a hazard to recreational boaters, suggesting that hazardous wood is typically just a fraction of the total wood loading (Figure 7-4).

Figure 7-4. Relative Quantity of Wood Within a Reach, the Subset with High Geomorphic and Habitat Benefits, and the Subset that Causes Public Safety Concerns



A. All wood in stream reach.
B. Portion of wood causing high-risk recreational hazards in stream reach.
C. Portion of wood that is both ecologically most functional and causes high-risk recreational hazards.
D. Portion of ecologically most functional pieces of wood in stream reach.

Source: American Whitewater Association (2012).

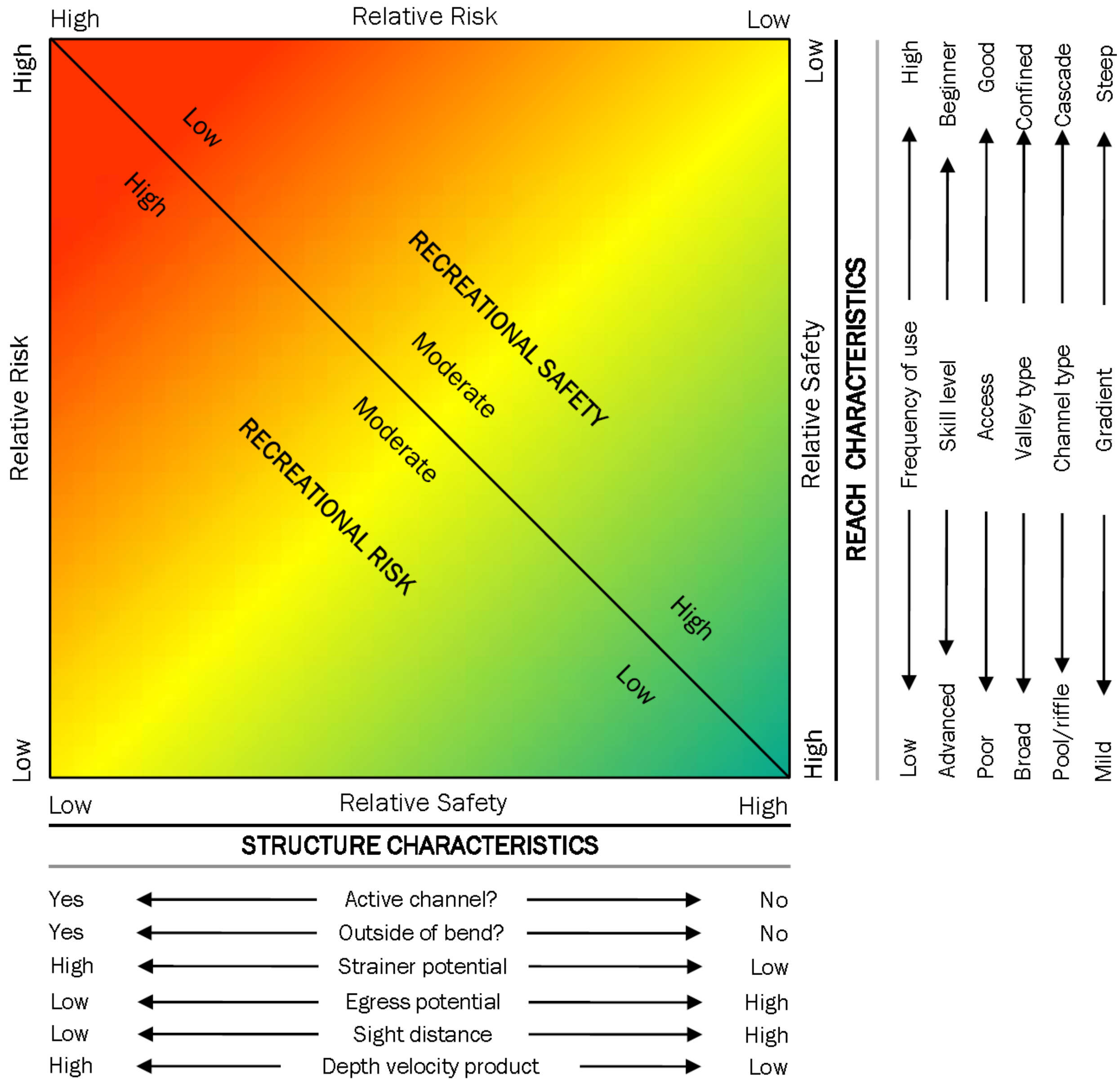
A more detailed risk matrix was developed in Washington State that considers both structure and reach characteristics (Figure 7-5). Similar risk matrices could be created by expanding or considering different risk elements specific to a project. Risk matrices are not recommended to evaluate a precise risk level but for evaluating the general effects relative to the no-action and project alternatives. When evaluating the safety of large wood or ELJ placements, it is important to note a low-risk structure can be placed in a high-risk environment creating a hazardous scenario, and a high-risk structure can be placed in a low-risk environment and not significantly affect the safety of recreational users.

7.3.5 Reach Factors

7.3.5.1 Recreational Use

An important consideration when assessing public safety impacts on recreational users associated with large wood placements is determining the various recreational uses, the primary use period, frequency of use, and the general skill level of the primary user group. Most recreational rivers in North America experience seasonal use based on weather and flows. Summer is typically the highest use time and may correspond to relatively high flows (particularly in regulated rivers with irrigation flow releases) or low flows. Expert whitewater enthusiasts can be an exception; their most intensive use is typically during periods of high flow, such as fall and winter in the Pacific Northwest. While recreational use in some form is possible on most rivers in North America, not all rivers experience a high frequency of use. The flow range occurring during the majority of that use period is also important and is defined in the assessment as the *recreational flow range*. When considering recreational use categories, there are often outliers or extremes to many of the categories described. When performing a recreational risk assessment it is recommended to focus on the majority or typical value for the specific category and omit outliers or extremes.

Figure 7-5. Risk Assessment Chart



Source: Embertson and Monahan (2011).

The skill level of recreational users is an important consideration when completing a reach assessment. Large wood in the river environment is very common in certain physiographic regions (albeit significantly more rare than historic norms), and avid recreational users may be accustomed to dealing with hazards associated with large wood (Figure 7-6). For instance, expert and advanced user groups will generally not be challenged navigating safely around large wood given their experience with naturally occurring wood. However, safely avoiding ELJs or large wood may be more difficult for beginner-to-intermediate user groups. Therefore, skill level and frequency of use are important factors to consider because structures placed in reaches frequented by beginner to intermediate users will pose a greater risk to those users than structures placed in reaches frequented by expert users.

Figure 7-6. Natural Wood Accumulation in Idaho

Source: American Whitewater Association (2012).

7.3.5.2 Access

The ability to access a given reach can significantly influence many of the recreational factors discussed above. Reaches with poor access will generally have a low frequency of use and are well suited as locations for the placement of ELJs and large wood to maximize habitat enhancement. Locating large wood and ELJ structures near known access points can also be considered a higher risk due to the frequency of use in the immediate area. When determining normal access points it is important to note that the type of access varies for different types of recreational use. More sophisticated, experienced user groups can often use road and highway pullouts with steep wooded banks and relatively little to no calm water along the channel bank. Less-experienced recreationalists require larger access points and boat ramps to the water edge to aid in carrying heavy equipment and loads. Consulting with known private or commercial users groups is often the easiest way to locate common recreational access points and to assess the experience level and frequency of access by different user groups.

7.3.5.3 Geomorphic Factors

Reach-scale characteristics described in a geomorphic risk assessment can also aid in assessing recreation-based public safety. Wood naturally plays a role in many channel types throughout a drainage network (e.g., Keller and Swanson 1979; Hickin 1984; Triska 1984; Abbe and Montgomery 2003; Montgomery et al 2003; Wallerstein and Thorne 2004). A fluvial geomorphic analysis should compile a spatial and temporal database that includes: valley morphology, channel planform and confinement, bed (surface and subsurface) and bank materials, sediment supply, channel gradient, riparian conditions, artificial structures (e.g., levees, revetments, diversions, weirs, dams, bridges), pool frequency, rates of channel migration, evidence of channel incision or aggradation, flood frequency, flow regime, flow depths and velocities, and estimates of natural wood quantities (*refer to Chapter 4, Geomorphology and Hydrology Considerations*).

The valley type within a reach can help identify safety issues that could arise associated with instream wood. For instance, large wood in a confined bedrock canyon would pose a greater risk to recreational users than placements in a broad alluvial valley where a user would likely be able to portage (get out and walk around) wood that posed a possible hazard.

Channel types can be used to evaluate potential risk by providing information on hydraulics, bed material, and the influence of wood. Montgomery and Buffington (1997) provide a process-based classification of channel types found within a channel drainage network primarily based on gradient and confinement. Both of these factors can help identify the degree to which a recreational user might be challenged to navigate safely through a given reach and the hazards of wood accumulations. Large wood placements in a reach with a confined bedrock, cascade, or step pool morphology (Montgomery and Buffington 1997) should be considered higher risk because these channel types are inherently more difficult and dangerous than other channel types due to the flow velocities, transitions between subcritical and supercritical flow, and channel confinement that makes it difficult to reach safe ground. In contrast, placements in a reach with pool-riffle or plane-bed morphology are generally lower risk because these channel types are easier for recreational users to navigate or portage in order to avoid large wood placements. Any wood placements in rivers with recreational boaters should maintain a sufficient portion of the channel for safe navigation.

The average channel gradient within a reach can both help identify the inherent difficulty for a recreational user and estimate the relative speed with which a recreational user approaches the large wood or ELJ placement. A steep-gradient reach should be considered higher risk than a low-gradient reach for similar reasons as the channel type described above. A steep-gradient reach generally has a high approach velocity, reducing the reaction time of a recreational user to large wood or ELJ placements. Consequently, high-gradient reaches should be considered higher risk than lower-gradient reaches.

The channel stability of a given reach is also an important geomorphic reach characteristic. Most structures placed in the river environment are located such that they do not pose a significant safety hazard following construction. However, if the river channel migrates or dramatically changes position, a significant safety hazard could result due to changes in the channel location, flow direction, and potential accumulation of large wood on the ELJ or other structure. The likelihood of this occurring in a dynamic and active reach is higher than in a less dynamic, slow-reacting system. ELJs or large wood placements in a dynamic geomorphic reach should be considered higher risk than those located in a slow-reactive system.

Large wood is very common in river environments within certain physiographic regions in North America (Figure 7-4). Almost any stream flowing within forested banks will have wood inputs. Because bank erosion is a major recruitment mechanism, forest channels with alluvial bank heights greater than root depth of trees typically have large quantities of wood. In rivers and streams where there are existing accumulations of large wood, recreational users are generally aware of the inherent risk in that area. The addition of large wood or ELJ placements as part of habitat improvement projects should clearly demonstrate the scientific justification of placements and how they could affect recreational users. Education and signage can help to mitigate the recreational effects of the placement of wood. In some cases it may be wise to close the river to recreational use. In cases where recreational areas will be maintained, wood placement should both mimic natural wood accumulations and maintain a navigable path for boaters. Placing structures in sites downstream of natural large wood reaches should be considered lower risk if boaters have to navigate those reaches before encountering a restoration reach.

To estimate natural wood loading, it is common to use reference conditions determined by Fox and Bolton (2007). As part of a study of over 150 stream segments, unmanaged basins were surveyed for wood quantities and volumes in Washington State. The results were segregated into bankfull width classes, forest zones, and percentile of classes listed. The most important thing to consider for wood and boaters is whether flow goes around the wood ("deflector") or through it ("strainer"). Wood design in recreational rivers should focus on deflector structures, which are easy to navigate because flow goes around them. They also tend to create downstream eddies that provide a safe refuge or pull-out point for boaters.

7.3.6 Large Wood Structure Factors

7.3.6.1 Structure Location

The location of large wood and ELJ structures in a stream channel and floodplain is an important consideration when assessing the recreational safety of a particular structure. The primary consideration related to the location of structures is the amount of engagement of the structure with the wetted channel during the expected recreational flow range, and whether the structure is located along the outside of a channel bend.

The more a structure is engaged in the wetted channel, the more likely it is that the structure poses a risk to the safety of recreational users. Structures that are not engaged in the wetted channel during the expected recreational flow range pose a much lower risk to the safety of recreational users. For instance, many large ELJ structures are often constructed on dry gravel bars and out of the low-flow channel due to permitting and constructability constraints and may not significantly engage with the channel during the recreational flow range. These structures pose a much lower risk to recreational users than structures constructed in the wetted channel that are fully engaged with the low-flow channel.

As flow moves through a channel bend, floating objects will tend to move toward the outside of a bend. Recreational users navigating through a channel bend have a harder time avoiding structures placed along the outside of a sharp channel bend than structures placed along the inside of a broad channel meander. But if there is sufficient roughness (e.g., wood) along the outside of a bend it will introduce strong secondary vortices along the bank that not only dramatically reduce near-bank velocities, but effectively push the thalweg away from the bank (Blanckaert et al. 2010; Konsoer 2013). Structures placed along the outside of a channel bend should be considered higher risk to recreational users than structures placed in a linear reach or on the inside of a channel bend. The degree to which a recreational user is influenced by local hydraulic patterns is a function of the user's maneuverability. For instance, a recreational "tuber" has a low maneuverability and, therefore, would be more influenced by hydraulic patterns (and at a higher risk) than an intermediate to advanced whitewater kayaker who is more maneuverable.

7.3.6.2 Structure Characteristics

The characteristics of different large wood and ELJ structures have varying degrees of risk to recreational users (Table 7-3). Structure characteristics of most concern are those that create a "strainer" condition that could trap a person or boat. A strainer condition occurs when a piece or pieces of large wood in a structure allow water to pass under, over, or through the piece or pieces. The force of the moving water through the strainer can trap or pin a person or their recreational craft against the large wood and create a dangerous scenario (i.e., potential drowning). The most common strainer condition is a single piece of large wood that extends out perpendicular to the channel bank and direction of flow, at or below the water surface.

Large wood placed in a rootwad bank protection method can commonly form a strainer condition if scour and channel migration is not considered during the design and placement process. A strainer condition is not as common for ELJs but can occur if the structure is not backfilled with alluvium to prevent flow through the structure, if individual log pieces extend out beyond the general limits of the structure, or if the structure shifts and unravels over time. While a strainer can create a dangerous condition for recreational users, strainers can also increase channel complexity, cover, and habitat variability all of which are beneficial for many types of aquatic.

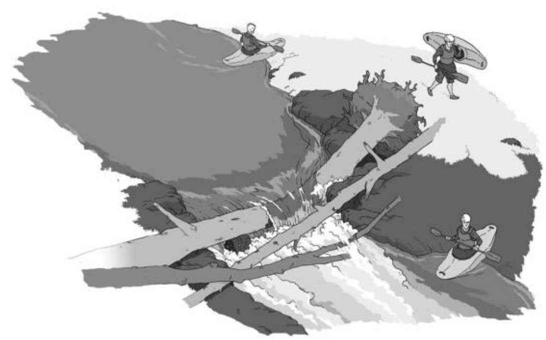
Large wood and ELJ placements designed to emulate natural wood assemblages create flow hydraulics that are more familiar to recreational users and pose a lower risk than nonnatural structure types (e.g., log crib wall, tethered log structures). Abbe et al. (2003a) classified instream woody debris accumulations observed on the Queets River in three distinct types: grade control, revetment, and flow deflection. A summary of the different types, brief descriptions, and relative recreational risks is provided in Table 7-3.

For the purpose of this assessment, a subjective relative risk rating is provided for each structure type, based on the intended function of the structure (Table 7-3). In this assessment, the only structure qualifying for a low rating was a step-type structure, because its design standard requires a high level of embeddedness in the channel bed and also provides the low-risk flow profile over the structure. Valley-type structures receive a high-risk rating due to their size, the chaotic assemblage of woody material within each structure, and the presence of flow through the structure. Bar apex structures may be assigned a low to moderate rating in cases where there is a clear navigational path around them and a higher risk if navigation is unclear or obstructed. Variability in rating should focus on ease of navigation around the structure, and take into account such things as structure location in the channel, approach line of sight distance, flow velocity, angle of flow deflection, and proximity to calm water (e.g., eddies) to rest or pull out. Ratings are influenced by location along the outside of a channel bend (higher risk), sight distance (often poor), and tendency to create a sweeper/ strainer condition (higher risk).

Avoidance Potential

If recreational users can safely avoid large wood or ELJ structures by either portaging around the structure or paddling well away from the structure, the relative risk of that structure is lower than if portaging or paddling away from the structure is difficult (Figure 7-7). Key factors when considering avoidance potential are egress potential, sight distance, approach velocity, and the combined values of depth and velocity at the approach to the structure (depth and velocity product).

Figure 7-7. Egress and Portage



Source: American Whitewater (2012).

The egress (exit) potential of a structure can be defined as the ability of a recreational user to exit the channel upstream of the structure in order to walk around the structure. An egress point is a specific location where a recreational user could exit the channel upstream of the large wood or ELJ. Conversely, an ingress point is a location where a recreational user could enter or re-enter the channel. Steep bedrock canyons or an incised channel with steep banks generally have poor egress potential. Broad alluvial valleys with frequent gravel mid-channel and point bars generally have good egress potential.

Table 7-3. Relative Risk of Instream Wood to Recreational River Users

Type	Description	Relative Recreation Risk
Step	Single log structure spanning the channel width and forming a scour/plunge pool immediately downstream. Flow generally proceeds over the structure.	Low to moderate in small streams where boating is uncommon or there is adequate submergence to eliminate vertical drop and recirculating plunge pool. A large drop and standing wave increases risk.
Valley	Multiple log structure with a width greater than the bankfull width and accompanying a significant portion of the valley width. Flow through and over the structure.	High
Bankfull Bench	Multiple log structure located along the outside of channel bend, with a width less than the bankfull width, and creating a bench surface. Flow generally proceeds along the structure.	Moderate
Flow Deflection	Multiple log structure located along the outside of channel bend, with a width less than the bankfull width that accumulates wood over time. Flow generally approaches normal to the structure and is then deflected away at a moderate to severe angle via parallel log members.	Low to high, depending on how much of the channel width is obstructed and response time (line of sight and velocity).
Bar Apex	Multiple log structure located at the head of mid-channel bar, with a width less than the bankfull width, creating a stable depositional zone downstream. Flow generally approaches normal to the structure and is then deflected away at a small to moderate angle.	Low to moderate where the navigational path is around the structure. Moderate to high where the navigational path around the structure is unclear or obstructed.
Meander	Multiple log structure located along the outside of channel bend, with a width less than the bankfull width, and creating a bench surface. Flow generally proceeds along the structure.	Moderate to high

The sight distance of a structure can be defined as the maximum distance from which a recreational user will be able to see the structure when approaching along the thalweg of the channel. The lower the sight distance, the less time a recreational user will have to develop a plan for how to avoid the structure and react appropriately. Structures with more sight distance are safer than structures with less sight distance. Because many ELJ structures are constructed to be equal to or above the peak flood water surface, the effects of the channel profile can generally be ignored. However, in certain circumstances the effect of the channel profile may be an important consideration when determining the available sight distance.

The mathematical product of flow depth, *D*, and velocity, *V*, referred to as the wading safety factor, is used to evaluate the potential for a recreational user to walk away or "self-save" within a stream. Researchers at Colorado State University conducted flume tests to identify the depth and velocity of flow at which a person could safely maneuver and stand in moving water. Subjects participating in the study became unstable at product numbers that ranged from 8–23 square meters per second. Results were found to be dependent on body stance, position, and type (Abt et al. 1989). Given the broad range of results, the study concluded safe wading conditions should not exceed a product of 10. To evaluate the wading safety factor specific to large wood or ELJ structures, the expected flow depth and velocity upstream from field observations or hydraulic modeling is commonly utilized. Flow depth and velocity should be determined upstream of the structure (about 8–15 meters [26–49 feet]; Abt et al. 1989) and outside the expected scour hole influence. The wading safety factor (depth and velocity product) is defined as follows.

$$WadingSafetyFactor = V * D$$

where:

V = Flow Velocity (meters/second)

D = Flow Depth (meters)

Note that the drag force acting on a wader will be proportional to the wader's submerged area normal to flow.

7.4 Bridges and Culverts

Mobile wood moving down streams can be an issue with human-made crossings that constrict the channel, such as small bridge spans or culverts. A risk assessment should always include a description of downstream crossings and whether the project would increase risk exposure. If the wood placements are stable and designed to catch mobile wood debris, then the restoration will reduce risk to downstream crossings. Efforts to restore wood by putting in mobile pieces should be carefully thought through because this process could elevate downstream risks. Well-designed large wood placements can help downstream infrastructure (Abbe et al. 2003a; Abbe and Brooks 2011). Whenever possible, channel crossings (culverts or bridges) should be used to accommodate the transport of wood material (e.g., Cafferata et al. 2004; Flanagan 2004, 2005). There has been extensive research regarding the risk wood material poses at bridge crossings, with specific concern for conveyance and bed scour (e.g., Diehl 1997; Lagasse et al. 2010). Recent flume research found that scour risk is reduced if the wood accumulation on a bridge pier extends the full depth of flow, while it increases if there is flow beneath the wood (Lagasse et al. 2010).

CROSS-REFERENCE

Additional information on the effects associated with bridges and climate change can be found in Chapter 5, *Watershed-Scale and Long-Term Considerations*.

7.5 Uncertainties and Research Needs

1. Regional data is needed regarding the ecosystem role of wood and impacts of wood removal.
2. Regional data on existing wood loading, specifically the location, size, and mobility of large wood pieces, is needed.
3. Predictive models need to be designed to identify wood transport and deposition reaches in stream systems.
4. Outreach should be conducted to educate residents, recreational users, flood districts, and public works departments on the value of instream wood and best practices for wood placement and stream management. Awareness and education on wood is one of most important means of reducing risks over time.
5. Guidelines should be developed for culvert design with respect to sediment and wood conveyance.
6. Guidelines should be developed for wood management (what to leave or remove) following major storms or floods.
7. Regional legal guidelines are needed with respect to the liability of wood placement in, or its removal from, streams.
8. Hydraulic models need to be developed that show the influence of instream wood loading on flood stage and discharge throughout a channel network.
9. Predictive models should be developed to evaluate how a wood placement may influence the accumulation of wood and its impacts.
10. Regional data should be compiled on channel incision attributed to removal of instream wood removal.
11. Regional and species data need to be compiled on wood longevity (decay) and its influence on wood stability and function.
12. Regional models are needed that predict the time wood projects must last to establish mature riparian forests and self-sustaining conditions.
13. Guidelines should be developed for establishing geomorphic corridors needed to sustain physical and ecological processes and minimize risks to human development.

7.6 Key Points

1. Risk is the product of the probability of an event occurring times the consequences the event will have with regards to impacts on habitat, public safety or property.
2. Snags and logjams are natural elements of streams throughout the United States and thus represent an inherent risk that recreational users accept when entering the system.
3. For over a century, local municipalities and the federal government have cleared streams of wood and riparian trees to foster navigation and flood conveyance. Although channel clearing has been scaled back in many systems, it has left many people with a simplified perception of

streams that is not consistent with natural conditions and an expectation of channel maintenance that is unrealistic both economically and environmentally.

4. The loss of instream wood has led to major geomorphic changes and severe ecological impacts in most streams throughout the country. Failure to rehabilitate wood loading and the functions it provided poses a serious risk to further ecosystem degradation.
5. Clearing wood from streams can result in channel incision that increases the risk to infrastructure such as buried pipeline crossing, bridge piers and abutments, road embankments, and water intakes.
6. Instream wood and riparian vegetation diffuse flood peaks and lower flood peaks downstream; therefore, large-scale stream clearing increases the risk of downstream flood discharge and staging.
7. When municipalities take direct actions to clear wood from streams, their liability may be increased if the practice is not sustained.
8. Wood accumulations also can raise water elevations, which can increase the frequency and magnitude of overbank inundation. This provides very beneficial ecosystem services but can be problematic in areas where development has encroached into flood-prone areas.
9. Riparian forests are integral to restoring and sustaining wood to stream ecosystems, yet estimates of human impacts on riparian areas range from over 50% (Swift 1984) to 95% (Brinson et al. 1981). This further underscores the risk posed by no-action alternatives.
10. Most stream crossings (i.e., culverts and bridges) have not been designed to accommodate the passage of wood material. Actions that increase wood flux into inadequate crossings will increase the risk of blockages that could compromise the facilities or increase upstream flooding. Risk can be addressed by upgrading infrastructure to accommodate wood material.
11. In streams with high recreational boating usage care should be taken to ensure engineered wood placements do not create strainers and that there is sufficient line of sight and response time to provide navigable passage.
12. Wood placement projects in rivers with recreational users should include public engagement and education, particularly with local communities, emergency service providers (e.g., fire and law enforcement departments with search and rescue teams), and river user groups (e.g., rafting companies, fishing guides).

7.7 References

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, K. Fetherston, and E. M. McClure. 1993. A Process-Based Classification of Woody Debris in a Fluvial Network: Preliminary Analysis of the Queets River, Washington. *EOS*, *American Geophysical Union Transactions* 73(43):296.

Abbe, T. B., J. Carrasquero, M. McBride, A. Ritchie, M. McHenry, and K. Dublanica. 2003a. *Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington*. Proceedings of the Georgia Basin/Puget Sound 2003 Research Conference, Vancouver, B.C., March 31–April 1, 2003, T. Droscher (ed.). Puget Sound Action Team, Olympia, WA.

Abt, S. R., R. J. Wittler, A. Taylor, and D. J. Love. 1989. Human Stability in a High Flood Hazard Zone. *American Water Resources Association. Water Resources Bulletin* 25(4):881–889.

American Whitewater Association. 2012. *Integrating Recreational Boating Considerations into Stream Channel Modificatin & Design Projects*. Written by Kevin Colburn, National Stewardship Director. Illustrations by Chad Lewis. Figure 8.4, page 13. Available: http://www.americanwhitewater.org/content/Document/fetch/documentid/1006/.raw.

Anderson, D. B. 2006. *Quantifying the Interaction between Riparian Vegetation and Flooding: from Cross-Section to Catchment Scale*. University of Melbourne.

Andrus, B., and J. Gessford. 2007. *Understanding the Legal Risks Associated with the Design and Construction of Engineered Logjams*. Skellenger Bender Attorneys. Seattle, WA.

Beechie, T. J., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N Mantua. 2012. Restoring Salmon Habitat for a Changing Climate. *River Research and Applications* 29:939–960.

Blanckaert, K. A. Duarte, and A. J. Schleiss. 2010. Influence of Shallowness, Bank Inclination and Bank Roughness on the Variability of Flow Patterns and Boundary Shear Stress due to Secondary Currents in Straight Open-Channels. *Advances in Water Resources* 33(9):1062–1074.

Booth, D. 1991. Urbanization and the Natural Drainage System: Impacts, Solutions, and Prognoses. *The Northwest Environmental Journal* 7, 93-118.

Brinson, M. M., B. L. Swift, R. C. Plantico, and J. S. Barclay. 1981. *Riparian ecosystems: Their Ecology and Statu*s. FWS/OBS-81/17. Office of Biological Services. United States Department of the Interior Fish and Wildlife Service., Washington D.C.

Cafferata, P., T. Spittler, M. Wopat, G. Bundros, and S. Flanagan. 2004. Designing Watercourse Crossings for Passage of 100-Year Flood Flows, Wood, and Sediment. California Forestry Report No.1. California Department of Forestry and Fire Protection. Available: http://www.fire.ca.gov/php/rsrc-mgt_forestpractice_pubsmemo.php.

Cannon, S. H., and J. DeGraff. 2009. The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change. Pages 177–190 in K. Sassa and P. Canuti (eds.), *Landslides—Disaster Risk Reduction*. Berlin Heidelberg: Springer-Verlag. Available: <http://landslides.usgs.gov/docs/cannon/Cannon_Degraff_2008_ Springer.pdf>.

Cannon, S. H., J. E. Gartner, M. G. Rupert, J. A. Michael, A. H. Rea, and C. Parrett. 2010. Predicting the Probability and Volume of Postwildfire Debris Flows in the Intermountain Western United States. *Geological Society of America Bulletin* 122(1-2):127–144. doi:10.1130/B26459.1.

Colburn, K. 2011. Integrating Recreational Boating Considerations into Stream Channel Modification and Design Projects. *American Whitewater* (2011).

Diehl, T. H. 1997. *Potential Drift Accumulation at Bridges*. Publication FHWA-RD-97-028. U.S. Department of Transportation, McLean, VA.

Embertson, L, and J. Monahan. 2011. *Public Safety Assessment of Habitat Enhancement Projects Fobes and Skookum Reach Restoration Projects South Fork Nooksack River*. GeoEngineers, Bellingham Washinghton. March 1, 2011.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Federal Highway Administration (FHWA). 2001. *Evaluating Scour at Bridges*, Fourth Edition. Hydraulic Engineering Circular No. 18. Publication No. FHWA NHI 01-001. Available: http://www.stream.fs.fed.us/fishxing/fplibrary/FHWA_2001_Evaluating_Scour_at_Bridges.pdf.

Federal Highway Administration (FHWA). 2005. *Debris Control Structures Evaluation and Countermeasures*. Hydraulic Engineering Circular No. 9. Publication No. FHWA-IF-04-016. Available: <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/>.

Federal Highway Administration (FHWA). 2012. *Climate Change & Extreme Weather Vulnerability Assessment Framework*. FHWA Publication No: FHWA-HEP-13-005.

Fischenich, C., and J.V. Morrow, Jr. 2000. *Streambank Habitat Enhancement with Large Woody Debris.* Publication No. ERDC TN-EMRRP-SR-13. U.S. Army Engineer Research and Development Center. Available: <http://el.erdc.usace.army.mil/elpubs/pdf/sr13.pdf>.

Flanagan, S. A. 2004. *Woody Debris Transport Through Low-Order Stream Channels of Northwest California – Implications for Road-Stream Crossing Failure*. M.S. Thesis. Humboldt State University, Arcata, CA. Available: http://www.bof.fire.ca.gov/board/msg_supportedreports.html.

Flanagan, S. A. 2005. *Woody Debris Transport at Road-Stream Crossings. Stream Notes*. Rocky Mountain Research Station. U.S. Forest Service. Fort Collins, CO. October 2005. Available: http://www.stream.fs.fed.us/news/streamnt/pdf/SNOct_05.pdf.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. *North American Journal of Fisheries Management* 12:182–197.

Ghosn, M., F. Moses, and J. Wang. 2003. *Design of Highway Bridges for Extreme Events*. NCHRP (National Cooperative Highway Research Program) Report 489. National Transportation Board. Washington D.C. Available: http://www.national-academies.org/trb/bookstore.

Hamlet, A. F., M. M. Elsner, G. S. Mauger, S.-Y. Lee, I. Tohver, and R. A. Norheim. 2013. An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. *Atmosphere-Ocean*, 51(4):392–415.

Hammer, T. R. 1972. Stream Channel Enlargement due to Urbanization. *Water Resources Research* 8:1530–1540.

Hickin, E. J. 1984. Vegetation and River Channel Dynamics. *Canadian Geographer* 28(2):111–126.

Hollis, G. E. 1975. The Effects of Urbanization on Floods of Different Recurrence Intervals. *Water Resources Research* 11:431–435.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds.). Cambridge, UK, and New York, NY: Cambridge University Press.

Jones, C. and P. Johnson. 2015. Risk Assessment for Stream Modification Projects in Urban Ssettings. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*, Part A: Civil Engineering. 10.1061/AJRUA6.0000815, 04015001.

Keller, E. A., and F. J. Swanson. 1979. Effects of Large Organic Material on Channel Form and Fluvial Processes. *Earth Surface Processes* 4:361–380.

Knox, J. C. 1993. Large Increases in Flood Magnitude in Response to Modest Changes in Climate. *Nature*, 361(6411):430–432.

Knox, J. C. 2000. Sensitivity of Modern and Holocene Floods to Climate Change. *Quaternary Science Reviews*, 19(1):439–457.

Konsoer, K. M., J. A. Zinger, and G. Parker, G., 2013. Bankfull Hydraulic Geometry of Submarine Channels Created by Turbidity Currents: Relations Between Bankfull Channel Characteristics and Formative Flow Discharge. *Journal of Geophysical Research – Earth Surface* 118:1–13. doi: 10.1029/2012JF00242.

Lassettre, N.S., and G.M. Kondolf. 2003. *Process Based Management of Large Woody Debris at the Basin Scale, Soquel Creek, California*. Report Presented to California Department of Forestry and Fire Protection and Soquel Demonstration State Forest. Available: http://www.fire.ca.gov/resource_mgt/downloads/reports/LWDinSoquelCreek.pdf.

Lagasse, P. F., P. Clopper, L. Zevenbergen, W. Spitz, and L. G. Girard.2010. *Effects of Debris on Bridge Pier Scour*. Federal Highway Administration. Washington, D.C.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-Reach Morphology in Mountain Drainage Basins. *Geological Society of America Bulletin* 109:596–611.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Niezgoda, S., and P. Johnson. 2007. Case Study in Cost-Based Risk Assessment for Selecting a Stream Restoration Design Method for a Channel Relocation Project. *Journal of Hydraulic Engineering* 133(5):468–481

Nooksack Tribe. 2013. *ELJ Assessment*. Deming, WA.

Roni, P., T. J. Beechie, G. R. Pess, and K. M. Hanson. 2014a. Wood Placement in River Restoration: Fact, Fiction and Future Direction. *Canadian Journal of Fisheries and Aquatic Sciences.*

Rose, S. and N. E. Peters. 2001. Effects of Urbanization on Streamflow in the Atlanta Area (Georgia, USA): A Comparative Hydrological Approach. *Hydrological Processes* 15:1441–1457.

Salmon Recovery Funding Board (SRFB). 2013. *Manual 18 Salmon Recovery Grants*. Washington State Recreation and Conservation Office. Salmon Recovery Funding Board. January.

Simon, A., and A. J. C. Collison. 2002. Quantifying the Mechanical and Hydrological Effects of Riparian Vegetation on Stream-Bank Stability. *Earth Surface Processes and Landforms* 27(5):527–546.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen. 2000. Bank and Near-Bank Processes in an Incised Channel. *Geomorphology* 35(3):193–217.

Skidmore, P. B., C. R. Thorne, B. L. Cluer, G. R. Pess, J. M. Castro, T. J. Beechie, and C. C. Shea. 2011. *Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals*. U.S. Department of Commerce. NOAA Tech. Memo. NMFS-NWFSC-112.

Swift, B. L. 1984. Status of Riparian Ecosystems in the United States. *Water Resources Bulletin* 20:223–228.

Thorne, C., J. Castro, B. Cluer, P. Skidmore, and C. Shea. 2014b. Project Risk Screening Matrix for River Management and Rrestoration. *River Research and Applications,* April 2014, DOI: 10.1002/rra.2753.

Tonglao, P., and D. Eckberg. 2012. *FAQ's about Wood Placements in Rivers*. March Bulletin, Skellenger Bender Attorneys, Seattle, Washington. Available: http://www.hallandcompany.com/php_uploads/resources/library/2012%20March%20Bulletin%20-%20FAQ%27s%20About%20Wood%20Placements%20in%20Rivers%20%283%29%202012.pdf.

Trinity River Restoration Program. 2015. Main Web Page. Available: http://www.trrp.net/. Accessed: February 28, 2015.

Triska, F. J. 1984. Role of Large Wood in Modifying Channel Morphology and Riparian Areas of a Large Lowland River under Pristine Conditions: A Historical Case Study. *Verhandlungen-InternationaleVereinigung für Theorelifche und Angewandte Limnologie* 22:1876–1892.

U.S. Climate Change Science Program (CCSP). 2008a. *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (S. H. Julius and J.M. West [eds.], J. S. Baron, B. Griffith, L. A. Joyce, P. Kareiva, B. D. Keller, M. A. Palmer, C. H. Peterson, and J. M. Scott [Authors]). U.S. Environmental Protection Agency. Washington, D.C. 873 pp.

U.S. Climate Change Science Program (CCSP). 2008b. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. G. Ryan, S. R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, B. Peterson, and R. Shaw). U.S. Department of Agriculture. Washington, D.C. 362 pp.

U.S. Climate Change Science Program (CCSP). 2008c. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* A Report by the U.S. Climate

Change Science Program and the Subcommittee on Global Change Research (M. J. Savonis, V. R. Burkett, and J. R. Potter [eds.]). U.S. Department of Transportation. Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2014. *Green Infrastructure*. Available: http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm.

U.S. Global Change Research Program (USGCRP). 2009. *Global Climate Change Impacts in the United States*. Edited by T. R. Karl, J. M. Melillo, and T. C. Peterson. Cambridge, MA: Cambridge University Press.

Wallerstein, N. P., and C. R. Thorne. 2004. Influence of Large Woody Debris on Morphological Evolution of Incised, Sand-Bed Channels. *Geomorphology* 57:53–73.

Warner, M. D., C. F. Mass, E. P. Salathé Jr. 2012. Wintertime Extreme Precipitation Events along the Pacific Northwest Coast: Climatology and Synoptic Evolution. *Monthly Weather Review*, 140(7):2021–2043.

Washington Department of Fish and Wildlife (WDFW). 2012. *Stream Habitat Restoration Guidelines*. Washington Department of Fish and Wildlife, Olympia, Washington, 2012.

Chapter 8

REGULATORY COMPLIANCE, PUBLIC INVOLVEMENT, AND IMPLEMENTATION

Photo credit: Ken DeCamp

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8.1 Introduction

This chapter discusses the way federal, state, and local regulations influence the placement, operation, and long-term operation of large wood. It describes the regulatory background, offers potential scenarios under which the regulations may apply, and provides potential best management practices designers and installers should consider.

Secondly, the chapter focuses on public outreach during a large wood project, describing how to best inform the public of project goals, design, and construction and maintenance to ensure their understanding and support.

Finally, the bulk of the chapter describes the implementation process itself. Large wood project implementation is crucial because even the best planning and design can be entirely negated by shoddy construction work. If a project is poorly implemented so that the design intent or intended outcomes are compromised, actual or perceived project failure may make it difficult to pursue future large wood projects. Skills for implementing large wood projects draw from typical logging work, heavy construction, and, more specifically, stream restoration methods, but also include a suite of practices and techniques not required for other types of projects. Accordingly, contractors working with instream or floodplain wood for the first time will encounter a learning curve that will tax the vigilance and communication skills of inspectors and designers. For example, contractors may not appreciate the importance of retaining tree crowns and rootwads on boles for certain types of wood construction. Others may have limited or no experience in transporting large wood, earthmoving in a stream corridor, dewatering, or affixing cables to large wood. Handling and successful installation of plant materials requires specialized expertise. Safety is of paramount importance during implementation, and the project team must comply with applicable laws and regulations as well as ordinary common sense.

The first step in implementation is synonymous with the last step in design: a constructability assessment.

CROSS-REFERENCE

For an overview of all of the steps involved in a large wood project, see Chapter 2, *Large Wood and the Fluvial Ecosystem Restoration Process*. For more on constructability assessments, see Chapter 6, *Engineering Considerations*.

Two overriding considerations in constructability assessment are cost efficiency and minimization of collateral environmental damage. Although some disturbance to the stream corridor is necessary for large wood projects, implementation should be conducted to ensure that project benefits are not outweighed by impacts. Those who implement restoration projects would do well to adopt an ethic that requires them to avoid projects that risk doing more harm than good. Examples of constructability issues include the following (NRCS 2007c; Cramer 2012):

- Safety for construction personnel.
- Permits and agreements.
- Constraints due to existing infrastructure and utilities.
- Material availability.
- Equipment availability and capability.
- Site and staging area access for various types and sizes of equipment.
- Labor requirements.
- Dewatering requirements and trafficability for equipment.
- Sequencing and seasonal restrictions that include, but are not limited to, these:
    - Optimal periods for material sourcing and vegetation establishment.
    - Trafficability properties associated with wet or frozen soils.

    - Migratory/breeding period constraints.
    - Turbidity control and in-water work windows.
    - Flooding and site dewatering issues.
- Measures to protect habitat and water quality, such as these:
    - Limiting impact zones by working from banks, platforms, or gravel bars.
    - Using special equipment.
    - Avoiding sensitive soils and vegetation.

After the constructability assessment, initial steps in project implementation include the following (Federal Interagency Stream Restoration Working Group [FISRWG] 1998):

- Scheduling implementation events and obtaining required permits.

CROSS-REFERENCE
For guidance on permits and regulations, see Chapter 2, *Large Wood and the Fluvial Restoration Process*, and sections below dealing with *Regulatory Compliance* and *Public Involvement.*

- Informing landowners and other stakeholders.
- Securing site access and easements.
- Locating utilities.
- Confirming sources and quality of large wood, plant materials, and other materials.
- Prebid meeting (making the prebid meeting attendance required for all bidders increases the odds of receiving qualified bids and reduces the potential for change orders).
- Contractor selection. Due to the inherent complexity and uncertainty of site conditions and wood materials in many restoration projects, it is highly advised that contractor selection not be based solely on low bids, but also on contractor experience, qualifications, and construction approach. This will increase the odds of receiving qualified bids and reduce the potential for quality control issues and change orders.
- Contract type. Using the right contracting mechanism for the project is an important element during the planning process. There are considerable differences between standard fixed-price and time and material type contracts. It is difficult to define exact scopes of work for large wood projects and therefore flexibility is required for construction. See Appendix A-1 and NRCS (2007c) for additional detail on types of federal contracts available for large wood projects.

Usually designers will prepare plans (drawings) and specifications that govern construction activities. The level of detail provided in plans and specifications depends on the type of contract, as explained in Appendix A-1. Typical specifications will contain sections dealing with the following:

- Mobilization and demobilization
- Pollution and erosion control
- Removal of structures (if necessary)
- Site preparation (haul roads/staging areas)
- Large wood sources and harvesting
- Large wood transport
- Excavation
- Fill
- Quality control
- Large wood placement
- Site closure and cleanup
- Revegetation

GUIDANCE

Regional Considerations in
Large Wood Project Implementation

Each of the key constructability issues listed below displays variation across regions. People implementing large wood projects may turn to case studies and personal communications with experts from other regions, but should remain aware of regional differences, including the following:

- *Total funding available*. Costly approaches such as helicopter transport of wood or importation of logs with rootwads from a distant harvest site are not feasible in many regions with less funding support for restoration work.
- *Size and type of wood available*. Large, decay-resistant logs are simply not found or are not economically accessible in some parts of the Midwest and Southeast.
- *Flow seasonality*. Regions with snowmelt hydrology and less intense storms tend to present different risk profile with respect to high flows during construction.
- *Environmental protection*. The rigor required of contractors working adjacent to and within streams in terms of sediment and turbidity control, fish exclusion, temporary crossings, and dewatering protocols varies widely from state to state and even from stream to stream.
- *Wood restraint.* Acceptability of the use of natural ballast and wood entanglement rather than pilings, wood burial, and attachment of wood to fixed points using cables, chain, or hardware varies.
- *Revegetation*. The impact of exotic plant species, ice, and herbivores on planted vegetation can be extreme in some areas.
- *Contractor expertise*. The availability of capable, experienced contractors is much greater in regions with strong restoration funding and a history of large wood projects.

Methods for measuring quantities for payment are often specified if required by the type of contract selected.

Typical drawings contain sheets showing the project location (maps), plan and profile drawings of large wood placements and structures (either typical for each type of placement or detailed for each site), details for haul roads and staging areas, and locations and details for revegetation and plantings.

In addition to typical safety concerns for a construction project within a stream corridor, large wood projects incur other hazards. Logs may shift in unforeseen and potentially lethal ways. Wood breakage may result in rapid movement of heavy objects or ejection of dangerous fragments. Cable breakage or slippage can create extreme danger to personnel due to rapid rebound. Additional discussion of safety issues is provided below and guidance of a general nature is provided by USACE (2008).

GUIDANCE

Types of Contracts for Large Wood Construction

Fixed-Price Contracts—Place the maximum risk and full responsibility on the contractor for all costs and resulting profit or loss associated with the work. This type of contract provides the maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden on project sponsors. A fixed-price contract requires the contractor to understand, in detail, what is to be constructed before bidding to do the work. This requires a design that includes detailed drawings, specifications, and a bid schedule containing a bid item for each major item of work. The designer must provide a cost estimate by bid item so that the cost of the work can be estimated and the contracting officer can assess the reasonableness of the bids. Most fixed-price contracts are awarded after contractors have submitted a sealed bid in response to an Invitation for Bids (IFB). The IFB includes the drawings and specifications for the work and specific contract requirements. The design effort and level of detail may be the same for simplified fixed-price contracts as it is for formal fixed-price contracts.

Cost-Reimbursement Contracts—Suitable for use when the cost of the work cannot be estimated with sufficient accuracy to use a fixed-price contract. The cost of the work is estimated for the purpose of obligating funds; however, a detailed cost analysis is not required. The contractor must have an accounting system adequate for determining incurred costs that are reimbursable. This type of contract requires significantly more oversight during the construction phase to document that efficient construction methods and efficient cost controls are being used. It provides little incentive for the contractor to control costs and perform effectively and imposes a much larger administrative burden on the contractor and project sponsors.

Incentive Contracts—Link the contractor's profit to performance by establishing reasonable and attainable targets that are clearly communicated to the contractor. These contracts are designed to motivate the contractor to achieve certain goals such as completion by a target date. Incentive contracts discourage inefficiency and waste. They can be fixed-price incentive contracts or cost-reimbursable incentive contracts. These types of contracts are normally used for performance-based service contracts and rarely for construction work.

Time-and-Materials Contracts—Used to procure supplies or services on the basis of direct labor and materials costs. Time-and-materials contracts should be used only when it is not possible to accurately estimate the extent or duration of work or to anticipate costs with any degree of confidence. With this type of contract, there is no incentive to the contractor to control costs, significant sponsor oversight is required, and a much larger administrative burden is imposed on the sponsor.

Labor-Hour Contracts—A variation of the time-and-materials contract, differing only in that materials are not supplied by the contractor.

Equipment Rental Contracts—Used in instances when it is not feasible or desirable to prepare detailed drawings and specifications. Require substantial construction oversight and impose an additional administrative burden on the sponsor.

8.2 Regulatory Compliance and Public Involvement

Most restoration activity decisions must address environmental policy. This section describes the types of federal, state, and local regulations that control or may influence the initial placement and long-term operation and maintenance of large wood. It also describes some hypothetical scenarios under which the various regulations may apply and strategies for compliance. Potential safety issues associated with placing large wood in areas where recreational activities are common are also discussed, along with a recommended process for addressing these issues. Finally, the need for outreach to the public, whether driven by regulatory requirements or planning principles, is discussed.

There are many federal, state, and local regulations that could apply to the installation of large wood within a stream or river. Although federal regulations apply throughout the United States, others obviously vary among the states and local jurisdictions. Information provided about state and local regulations is intended to serve as examples of what may be applicable and should be considered individually for each project. The primary regulations relevant to the installation of large wood are discussed below.

8.2.1 Federal Regulations

Actions involving modification of channel structure and instream habitats (e.g., placement of large wood) will most likely involve activities in navigable waters or waters of the United States and involve the discharge of fill material, triggering the need for compliance with Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act, administered by USACE. The extent of the action will dictate if a Nationwide Permit can be utilized or if an individual permit is required.

In some cases, the installation of large wood may be considered "vegetation" and, if within the footprint of federal flood control levees, is subject to USACE Engineering Technical Letter 1110-2-583, Guidelines for Landscape Planting and Vegetation Management at Floodwalls, Levees, Embankment Dams, and Appurtenant Structures. This may limit the locations in which large wood can be installed.

Any alterations or modifications to existing USACE projects, such as federal flood control levees, must request and be granted permission from USACE pursuant to Section 14 of the Rivers and Harbors Act of 1899 (Title 33 of the United States Code [USC], Section 408)—hereinafter referred to as Section 408—for the alteration of a federal work (e.g., levee).

Because actions that include installation of large wood will most likely occur in areas where species that are federally listed as threatened or endangered or that are candidates for listing may be present, compliance with the federal Endangered Species Act (ESA) (in coordination with the U.S. Fish and Wildlife Service [USFWS] and the National Marine Fisheries Service [NMFS]) may be required. A current list of species protected under the ESA should be obtained from the regulating agencies in order to begin the compliance process.

Separate from federal agency involvement in proposing the project (e.g., placement of large wood), which would itself require National Environmental Protection Act (NEPA) compliance, involvement of USACE and/or USFWS and NMFS may trigger the need for NEPA compliance, and may trigger the need for compliance with the Fish and Wildlife Coordination Act when actions involve the modification of surface water. Federal agency involvement may trigger the need for compliance with Section 106 of the National Historic Preservation Act if the action would occur in an area where properties are listed, or are eligible for listing, on the National Register of Historic Places.

Actions in this category will most likely occur in or affect wetlands, triggering the need for compliance with Executive Order 11990 (protection of wetlands). They may also be located within a floodplain and require compliance with Executive Order 11988 (floodplain management).

8.2.2 State and Local Regulations

Because actions would involve activities with the potential to mobilize contaminants in surface waters and require compliance with Section 404, state certification under Section 401 of the Clean Water Act will usually be required. Because such actions could result in the temporary discharge of waste affecting surface water, many may require compliance with state Waste Discharge Requirements.

Over 90% of states have some form of endangered species act. They vary widely with some just prohibiting either the "taking" of or trafficking in an endangered species to more comprehensive processes for species listing, management, protection, and recovery. It is essential to know the details of the applicable state program in order to ensure proper compliance. Alabama, North Dakota, West Virginia, and Wyoming are the states that currently do not have their own state-level endangered species acts. Because these actions may occur in areas where species that are state-listed as threatened or endangered or that are candidates for state listing may be present, compliance with any applicable state endangered species acts may be required.

These actions are also likely to involve changing a streambed or altering streambed material, triggering the need for compliance with various state fish and wildlife code and/or regulation. For example, in California a Section 1600 Streambed Alteration Agreement with the California Department of Fish and Wildlife is required. Many other states have similar requirements.

Compliance with state and local flood management agencies and reclamation districts may also be required, especially for actions in state-designated floodways, floodplains, and shorelines. If both a state and local agency exist, they are often used to working in tandem, and early coordination with both agencies is recommended. The local reclamation district (sometimes called a levee maintenance district) is often responsible for the maintenance of local waterways and will have a keen interest in large wood projects and how they may influence their ability to conduct maintenance in the long term.

Requirements for state and local authorizations will trigger the need for state-level environmental compliance in those states with applicable laws (e.g., the California

Environmental Quality Act [CEQA]). The following states have some form of environmental impact assessment laws: California, Connecticut, Delaware, Georgia, Hawaii, Indiana, Maryland, Massachusetts, Michigan, Minnesota, Montana, New Jersey, New York, North Carolina, South Dakota, Virginia, Washington, and Wisconsin.

In many cases the environmental effects associated with the placement of large wood are expected to be minimal and the environmental benefits are expected to be high. In some cases, this may help speed the processing and issuance of these permits and requirements. On the other hand, these projects can be complicated and subject to more than a dozen regulatory compliance processes. Therefore, the timeframe for receiving agency authorizations can vary greatly and should be initiated as soon as adequate information about the project has been developed.

Table 8-1 elaborates further on the preceding narrative by posing questions that serve as a basic regulatory compliance decision analysis tool.

Table 8-1. Large Wood Regulatory Compliance Decision Analysis

Do the Following Apply?	*If Yes, Compliance is Required With:*
Federal Compliance	
The action is considered a federal agency proposal.	National Environmental Policy Act (NEPA)
The action is located in waters of the United States, including wetlands, and/or the action is located in navigable waters of the United States; and the action is considered a discharge of dredged or fill material; or the action would affect facilities designed, built, or managed by USACE.	Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act
The action would alter a federal project, such as a federal flood control levee.	Section 408 (33 USC 408)
The action is considered a major construction activity, and species listed as threatened or endangered under the federal ESA may be found in the project area; the action may affect the listed species (Section 7). The action may result in the “take” of a species listed as threatened or endangered under the ESA (Section 7 or 10).	Section 7 or 10 of the ESA
The action is considered a federal agency proposal and proposes to control or modify surface water.	Fish and Wildlife Coordination Act
The action is considered a federal agency proposal and affects a river within the National Wild and Scenic Rivers system.	National Wild and Scenic Rivers Act
The action is considered a federal agency proposal and is located within or may affect a floodplain.	Executive Order 11988 – Floodplain Management
The action is considered a federal agency proposal and is located within or may affect wetlands.	Executive Order 11990 – Protection of Wetlands
The action is considered a federal agency proposal and may affect minority or low-income populations.	Executive Order 12898 – Environmental Justice

Do the Following Apply?	*If Yes, Compliance is Required With:*
The action is considered a federal agency proposal and may affect Native American religious practices.	American Indian Religious Freedom Act of 1978
The action may affect Indian Trust Assets.	Indian Trust Assets
State or Local Compliance	
The action involves a state or local agency action and is considered a project for such purposes.	State Environmental Impact Assessment Laws (e.g., CEQA, Washington's State Environmental Policy Act [SEPA])
The action involves a federal license or permit that may affect state water quality, and the action would result in a discharge of a pollutant into waters of the United States.	Section 401 of the Clean Water Act
A species listed as candidate, threatened, or endangered under the California Endangered Species Act may be present in the project area or the action may result in the "take" of a state listed species.	Fish and Game Code – California Endangered Species Act
The action involves any activity that will divert or obstruct the natural flow or change the bed, channel, or bank of any river, stream, or lake; the action involves the use or alteration of any streambed material; the action occurs within the annual high-water mark of a wash, stream, or lake.	State Streambed Alteration Agreement (e.g., Section 1600 of California's Fish and Game Code)
The action occurs in tideland; submerged land; the bed of a navigable river, stream, lake, bay, estuary, inlet, or strait; swamp land, or overflowed land; the action would affect water-related commerce, navigation, fisheries, recreation, open space, or other public trust uses.	State agency overseeing sovereign lands of the state (e.g., California State Lands Commission requires a land use lease)
The action would affect existing state flood control project facilities, including levees, dams, reservoirs, and floodways and flood control plans.	State or local agency overseeing any state/local plan of flood control (e.g., California's Central Valley Flood Protection Board, local reclamation and/or levee districts)
The action would involve grading, building or modifying structures, special or conditional uses, modification or approval of general or specific plans (local or regional), and/or zoning ordinance amendment.	City or county approvals and entitlements

8.3 Public Involvement and Input

Public outreach during a large wood project may occur for several reasons. In general, outreach will be associated with public noticing required by regulations, public outreach to solicit design input and to build project support, and outreach to inform river users about the presence of large wood to help ensure their long-term safety.

Public noticing is required by several regulations, including federal and state environmental impact assessment laws (e.g., NEPA, CEQA, SEPA, Clean Water Act Section 404). Each of these regulations and the regulating agencies have very specific guidance on the type and content of noticing materials. In addition to meeting the regulatory requirements, this type of outreach can be an effective method of reaching a wide variety of important stakeholders in order to make them aware of the proposed project and solicit their input on a number of matters.

One type of feedback that can result from effective outreach is input on the design of a project. While engineers and aquatic scientists are typically key participants in a large wood design team, input from stakeholders can also be very important. People tend to support what they help build, and early involvement of stakeholders can lead to the most successful buy-in and project support. One of the greatest elements of a successful public outreach program is the development and maintenance of strong relationships with key stakeholders and members of the community, built on and sustained by trust. Opportunities for effective two-way communication are vital to building trust and support.

All aspects of public outreach need to be tailored to engage the community and be the appropriate level of effort for the project—no two projects are alike. Developing a synergy between outreach, engineering, and science ensures a strongly integrated project.

As appropriate and tailored to meet the scope and scale of the project, coordination with a variety of stakeholders—local fire/sheriff/rescue, local flood control entities, rafting companies, fishing guides—will lead to project support. Throughout the development of the preliminary design, the project proponent should engage these stakeholders through project briefings, one-on-one meetings, presentations, and social media and email communication—once again, as appropriate depending on the size and location of the project. These stakeholders should be engaged early and often in order to provide feedback on the preliminary designs and to express their preferences or concerns to the design team. It is important to ensure that the right stakeholders are sitting at the table, that the outreach process is tailored to respect the contribution and time the stakeholders will give to project review and development, and that these stakeholders are provided with regular and meaningful opportunities for engagement in the planning process. Key stakeholders such as those listed above have the potential to be project champions/ambassadors of the project as it becomes reality.

Once a project is constructed, it is important to continue the outreach to inform river users on an ongoing basis about the presence of large wood to help ensure their long-term safety. There are always new river users, so providing permanent, educational sources of information is essential. Appropriate methods include, but are not limited to, signage, websites, and interpretive displays.

8.4 Regulatory Compliance Approaches

8.4.1 Scenario 1: Project Site with an Endangered Species

Consider a large wood project on a stream that supports federally endangered salmon. The project involves a relatively small area and is intended to enhance conditions for rearing and migrating salmon by providing instream structure in an area where it does not exist. Due to the relatively small size of the installation and its purpose (enhancing aquatic habitat), a Clean Water Act Section 404 Nationwide Permit (NWP) is utilized (NWP 27: Aquatic Habitat Restoration, Establishment, and Enhancement Activities). NEPA compliance is addressed through the NWP. The project description clarifies that the project will be constructed/installed when the endangered salmon are not present and NMFS issues a Letter of No Effect under the ESA. Due to the scope and location of this project, no other regulatory approvals are required.

8.4.2 Scenario 2: Erosion Control Project

Another scenario involves a much larger and complex undertaking. Consider a project intended to control erosion that is threatening a flood control levee while at the same time would provide instream structure for endangered salmon through the use of large wood. The river is in California and has been designated as Wild and Scenic under both federal and state acts, and it supports a wide variety of recreational uses and a high number of users. Due to the nature of the project, compliance with a majority of the regulations described in Table 8-1 is required. For example, an Environmental Impact Statement/ Environmental Impact Report is required to satisfy NEPA and CEQA; Biological Assessments are needed to comply with the federal and state endangered species acts; and compliance with Clean Water Act Sections 404 and 401 is needed.

While both of these projects involve the installation of large wood, the differences in the specific circumstances of each result in substantially different regulatory compliance requirements. It is very important to consider, understand, and plan for these types of situations and develop your approach accordingly. A key strategy for successful regulatory compliance is to begin project coordination early and make use of the information gleaned through coordination with regulators, resource specialists, river users, and other relevant stakeholders.

8.5 Construction

Key elements of construction include:

- Construction oversight
- Dewatering and diversion
- Excavation
- Wood placement
- Securing wood
- Finish work

8.5.1 Construction Oversight

8.5.1.1 Risk Management

CROSS-REFERENCE

Chapter 7, *Risk Considerations*, provides detailed guidance on overall project risk assessment and management.

Construction projects often result in litigation due to disputes regarding liability for accidental injuries, cost overruns, project failure, and the like. The distribution of legal liability among owners, designers, and contractors is a highly technical subject, and personnel involved in large wood projects should obtain legal counsel for review of contractual arrangements.

8.5.1.2 Contract Types and Risk

A brief review of some of the types of federal contracts available for large wood projects is provided in Appendix A-1 and NRCS (2007c). Fundamental differences in liability apportionment exist between arrangements where designers act as advisors to the project owner or sponsor and those in which the designer is contracted by the owner or sponsor to perform construction. In the former, the designer creates the design, and prepares plans and specifications, cost estimates, and perhaps schedules and constructability reviews. The designer may also provide inspection services or high level advice during construction, but does not award contracts for construction, materials, or labor. In the latter arrangement (sometimes called design-build), the design-constructor performs the functions listed above but also subcontracts for actual construction. In this case, the design-constructor typically assumes the same risks and responsibilities as the general contractors, including safety.

8.5.1.3 Risk and Project Scale

In theory, risk and project scale are independent as even very small projects in critical locations may incur large risk, while larger projects in remote locations may incur moderate risk. However, because project cost is often a function of scale and projects in remote locations that encounter less potential risk to adjacent infrastructure are likely to affect more valuable habitats, most projects exhibit a tight linkage between risk and scale (geographic and economic).

Small large wood projects may proceed with minimal plans and specifications. Minimal drawings and specifications may be sufficient if a time-and-material or a labor-hour contract is employed, experienced inspection personnel familiar with the design will be on site, and the contractor is experienced and reliable. Simple projects in smaller streams may benefit from reliance on typical sketches of certain types of large wood configurations rather than detailed drawings (e.g., McMillen 2014). Exact locations for large wood may be revised just prior to construction due to events such as channel migration or tree wind throw, or due to constructability logistics; as a result, the original site-specific drawings are often obsolete by the time staking occurs immediately prior to construction.

Although time-and-materials or labor-hour contracts or arrangements are sometimes employed in part or in whole for larger scale projects, the formality of project management should increase with project scale. The number and experience of construction inspectors and the involvement of designers is key in larger scale, high-risk projects. Formal submission of operational, safety and health, pollution control, and other plans by the contractor and documentation of reviews, approvals, and denials by the project sponsor must be more meticulous. Accounting for construction activities, delivery, and disposition of supplies and materials, and hydrologic and geotechnical conditions encountered should also increase with project scale.

8.5.1.4 Risk and Project Management

Key construction oversight tasks involve clearly delineating work zones, access routes, haul roads, and staging areas on the ground and on project documents. Material quality and quantity should be assessed and recorded, and measurements of quantities of large wood material, excavation, fill, plant materials, etc. should be conducted as specified in contract documents. The order of operations should be controlled in a manner that allows the contractor leeway when possible but avoids undesirable impacts. Considerable ingenuity may be required to avoid sensitive habitats, cultural resources sites, highly erodible soils, and soils too wet or soft to support vehicles and equipment.

Daily records should be kept in a log file by the sponsor and/or designated field engineer/scientist when on site to document field conditions, construction progress, compliance with design plans, and conversations with the contractor. Daily logs should include photos from fixed points and plan mark-ups documenting whether the project is being constructed as designed or if changes are needed. These logs can serve as key information to the sponsor and/or designer during any disputes and can limit the potential for unnecessary change orders that increase costs.

8.5.1.5 Material Sourcing

Often large wood construction projects are awarded with little consideration regarding the timing needed for proper wood sourcing. A wood sourcing plan should be developed during the design phase of the project. The wood sourcing plan should specify harvest locations and equipment, hauling and loading equipment, and stockpile or staging locations near placement sites.

Wood sourcing should be a separate phase of the construction contract or secured through a different contract or agreement (see Appendix A-3 for sample large wood harvest and hauling contract language). Some wood material may be harvested on site as a consequence of the excavation, but this rarely produces the required quantity for the project. Offsite sourcing is challenging and may require a timber harvest plan or environmental compliance documents for harvesting in sensitive areas. Hauling can also be a major constraint; see Section 8.5.7, *Typical Construction Equipment*, for a discussion on the appropriate equipment for transporting wood. Large wood stockpiles may require security measures because wood may be vandalized for firewood sourcing.

Effort should be applied to minimize collateral environmental impacts associated with harvest, transport, and stockpiling of large wood. Use of locally derived materials, when available, tends to reduce costs and overall impacts (Figure 8-1). However, strict limits should be placed on the acceptable size, species, condition, and distance from the stream for local large wood. For example, the contract could stipulate “Only live trees more than 8 meters (25 feet) away from the channel top bank may be used,” and “Only downed wood more than 0.3 meter (1 foot) vertically above specified elevation may be used.” Trees with obvious cavities used for nesting may be excluded.

Figure 8-1. Use of Locally Sourced Large Wood

Little Topashaw Creek, Mississippi. Haul Distance from fencerow harvest zone <0.8 kilometer (0.5 mile).

Alternatively, living and downed wood that is suitable for use may be flagged by construction inspectors working with personnel qualified to assess the environmental significance of the materials, and the contractor may be prohibited from using materials that are not flagged.

Because forest products used for restoration projects include soil and biomass, and these materials will likely be placed in flowing water, the potential to spread disease and unwanted species is possible unless proper precautions are taken. Wood materials should be sourced and stockpiled in areas free of disease and invasive species (e.g., root-rot, rust, sudden oak death syndrome, insects, ivy, and pampas grass). In some regions of the United States, inspections by the county agricultural department need to occur and the disease status of forest products signed-off before transporting materials from the harvest location.

8.5.1.6 Material Types

Designers should specify quantities and sizes (diameter and length) of different materials including rootwads, butt logs, slash, tree tops, etc. Most large wood structures contain a few very large key pieces, usually with rootwads attached. The numbers of slightly smaller logs and boles required to construct the body of the large wood structure around the key members is usually much greater (~10x) than for the key members. Even more numerous smaller limbs and slash are used to fill gaps and interstices within the structure. For example, oblique logs are small (15- to 30-centimeter [6- to 12–inch]) diameter logs that are wedged, at off-vertical angles, into the gaps of a logjam. Material types should be specified by DBH, length, with or without a rootwad, and wood species. Material specifications affect costs. For example, a 60-centimeter (24-inch) DBH tree with a rootwad can be an order of magnitude more costly than a 30-centimeter (12-inch) DBH butt log. Harvest plans should allow for procurement of about 25% more large wood than is indicated by design drawings. Large wood material can be placed into the general size categories as shown in Table 8-2.

In addition to the log types listed in Table 8-2, material plans should include quantities for whole tree tops and smaller slash material. Slash is generally too small to be included as large wood material but is an important component in large wood construction. Slash material supplies should allow for significant compaction, and specified volume of slash may be increased by 50 to 75%.

Table 8-2. Size Categories for Large Wood

Nominal length (feet)	Morphology	DBH Range (inches)
32	Log with rootwad	6–12
32	Log with rootwad	12–24
32	Log with rootwad	24–36
20	Butt Log–Racking material and logs sharpened at one end to be used as pins	4–6
32	Horizontal Logs and logs sharpened at one end to be used as structural piles	6–12
32	Butt log	12–24
32	Butt log	24–36

Large wood delivered to the site should be inspected to ensure it meets the species, size, and quality specifications provided in the bid documents. Any pieces not meeting the specifications should be tagged and removed from the site immediately.

Similar concerns attend procurement of boulders and other coarse sediments for anchorage and ballasting. Importation of these materials is likely to be costly, and removal from the base flow channel may create unacceptable impacts.

8.5.1.7 Wood Transport

The cost to harvest and deliver logs with attached rootwads is generally three to four times greater than the cost for similar size logs without rootwads. Rootwad complexity directly benefits fish habitat quality, geomorphic function, and stability of a constructed logjam. Therefore, the importance of retaining as much of the root system as possible cannot be overstated and should be emphasized at each step of the log-handling process (i.e., harvest, loading, transport, stockpiling, and placement).

Furthermore, rough handling can split and/or gouge the bole, which weakens the structural integrity of the log and makes it more susceptible to decay. Several measures can be employed to avoid degrading the habitat quality and premature failure of a logjam due to rough log handling practices.

An excavator equipped with a bucket and hydraulic thumb is typically used as the prime mover of logs, slash, and earth materials for large wood projects. Because a bucket and thumb has limited capabilities to rotate and position logs, contractors can opt to use an excavator with a bucket and thumb for earth-moving tasks and an excavator with a rotating grapple or log shovel for most of the log handling tasks (Figure 8-2a and 8-2b.). Although having both types of equipment is reasonable for large-scale projects, this can be cost-prohibitive for smaller scale projects. Alternatively, contractors can equip an excavator with a detachable heel rack or rotating grapple, or simply attach a set of log tongs, via heavy chain, to the back of the excavator bucket (Figure 8-2c). Any of these options will allow the operator to more efficiently position logs, while minimizing damage to the rootwad, bole, and surrounding environment. However, even when these attachments are available on a job site, most operators need instruction to minimize handling the log by the rootwad and to avoid damaging the material.

8.5.1.8 Change Orders

Change orders during construction can be costly. Some amount of change from the design plans during the construction process should be expected on every large wood project for the reasons previously mentioned.

Figure 8-2. Equipment Useful for Handling Large Wood

(a) Use of excavator with bucket and hydraulic thumb to position log with rootwad. (b) Use of rotating grapple to move multiple small logs. (c) Log tongs used to position rootwad log in tight quarters.

Projects where a certain amount of uncertainty is anticipated should build that expectation into the design plans, contract documents, and discussions with contractors to reduce the potential for costly change orders during the construction process. Common strategies to build flexibility into the contract documents include bidding items lump sum and creating force account items for miscellaneous items (e.g., setting up bid item for contractor to lock in cost of machine and operator time).

8.5.2 Water Management

Large wood placement methods vary greatly from project to project due to site conditions, with economic and regulatory constraints dictating the project approach. Water management is a key component for managing collateral environmental impacts. Construction plans should include stream crossing plans and prescribe wood placement methods. Available approaches may be broadly classified as:

- Working in dry conditions,
- Working in wet, but controlled conditions, and
- Working in existing (wet) conditions, not controlled.

8.5.2.1 Dewatering and Diversion

Working in dry conditions is typically completed in smaller channels, in perennial streams where complete diversion is easily achieved, or on gravel bars in large rivers. It is especially advantageous to work in dry conditions when placing bed control structures, placing vertical posts or pilings, excavating to scour depth, or having to build forms for cast-in-place concrete. When water diversion is needed to ensure dry conditions, available methods include the following:

- Rerouting of the stream through a bypass channel.
- Blocking flows upstream and bypassing water through pipes using pumps (Figure 8-3) or a gravity system.
- Isolating a portion of the site using cofferdams or push-up dikes.

Figure 8-3. Diversion of a Small Stream Around a Construction Zone Through Plastic Pipe

Eel River Headwaters, Massachusetts. Photo courtesy SumCo Eco-Contracting.

8.5.2.2 Wet but Controlled Conditions

In many cases, working in completely dry conditions is not possible. Full dewatering is not always needed or desirable, but isolating a work zone is often required to control downstream turbidity. Working in more controlled conditions where the project area is still wet creates a functional approach to complete the activity (Figure 8-4). This scenario is common in tidally influenced areas, large river systems, estuaries, shorelines, and ponds. While complete diversion is typically not achievable, a variety of methodologies to divert flow and partially or fully isolate the work site from flowing water are listed in the *Guidance* box below. Dewatering or isolation must be complete prior to excavation or large wood placement.

Figure 8-4. Water Management Techniques for Large Wood Projects

(a) Wet but controlled conditions used to isolate turbidity impacts in work zone from main channel. (b) Highway traffic barriers being used to construct a temporary isolation cell prior to wood placement. Photos by Ken DeCamp.

8.5.2.3 Uncontrolled Wet Conditions

While working in dry conditions or semi-dry conditions is desirable, it is sometimes not feasible. Examples where wet construction is warranted include emergency work, placing materials in areas where water is too deep or swift for dewatering or diversion, and work limited to sites along the shoreline (gravel bars). Wet construction also includes situations where equipment is driven across a flowing channel for accessing dry areas on the other side. When working in such conditions, regulatory authorities may require impacts on habitat and water quality be avoided or minimized by fish exclusion (see Section 8.7.2, *Fish Exclusion*), minimizing construction duration, excavation below the water line, operation of equipment in flowing water, and other actions that mobilize suspended sediments.

GUIDANCE

Dewatering and Turbidity Control Techniques

Construction of Push-Up Berms using onsite material is relatively inexpensive and easy. If native material proves to be too porous, has a high clay content, or if there is not enough suitable material on site, a specified mix can be imported and used and exported at the end of the project or repurposed on site. The width and length of the berm will depend on the volume of water that needs to be diverted. Typically, the wider and longer the berm, the more the berm will be more resistant to the forces of the water.

Sand Bagging is the filling of individual bags of woven geotechnical fabric, burlap, or plastic with sand or rounded gravel. The bags come in several colors including white, green, and orange; and, dependent on the situation, can be left in place to degrade or removed at the end of the project. The bags can also vary in size from commonly available small bags (approximately 1-cubic-foot volume) to large “bulk” bags (approximately 1-cubic-yard volume). Typically, the bags are sacked no higher than 1.2 meters (4 feet) or 2–3 courses high because of their non-structural material contents making them susceptible to falling over easily.

Water Filled Bladders or “Aqua Barriers” are portable water-inflated temporary dams and are designed for construction worksite dewatering and/or water diversion work. They are manufactured using high quality industrial-grade vinyl, which provides an economical, effective, and safe alternative to conventional dam methods like sandbags and push-up berms.

Highway Traffic Barriers (precast concrete) normally used as separators for highway construction may be used in combination with turbidity curtains or heavy plastic to isolate work zones. Barriers are available in 81–107 centimeter (32–42 inch) heights and can be butted together to form the necessary isolation length. Plywood can be anchored against the barriers to make them higher. Barriers may be placed and moved using common excavators and loader equipment and chains.

Turbidity Curtains are flexible, impermeable barriers used to trap sediment in water bodies. Curtains are generally weighted at the bottom to ensure that sediment does not travel underneath, and are supported at the top by flotation units that are integrated within the curtain.

Pumps are the most frequently used piece of equipment to re-route water from the construction area. There are a variety of pumps that a contractor may use, dependent on the amount of water that is required/needs to be removed, frequency, volume, regulatory requirements, etc. Pumps can either be run using diesel or regular gas and may be submersible or placed on dry land.

Gravity Bypass may be performed using a combination of some types of cofferdam at the upstream end of the project site, where the cofferdam has an outlet into a flume, pipe, trench, or temporary channel to allow the water to bypass the site using free-flowing conditions.

8.5.2.4 Rewatering

Some projects may require care when rewatering portions of the channel that have been dewatered or placed in slackwater status for large wood construction. When streamflow is returned to these areas, a pulse of turbidity may occur. If such a release of sediment and turbidity violates the applicable permit(s), site rewatering should be done very slowly to minimize scour and resuspension of sediments. The dewatered zone can be flooded and allowed to stand under quiescent conditions for a period of time prior to full restoration of streamflow.

Filtration or sediment retention ponds may be used for mitigating rewatering impacts. Infiltration ponds are simply excavated holes in the floodplain where the substrate is sand or gravel material. A filtration pond can be built so it is hydraulically connected or disconnected to the isolated work zone. The turbid water from an isolated work zone is pumped into the filtration pond to filter out the sediment-laden water by infiltrating into the sediments that make up the pond boundary and discharging by gravity into an off-channel area (backchannel, wetland, slough area).

Another technique is allowing controlled entry of upstream clean water into the isolated, turbid work zone and metering out the turbid water at the downstream end. Controlled opening up of the upstream/downstream isolation area can be done by strategically removing sand-bags or opening up a corner of a barrier. Careful monitoring of turbidity downstream of the work zone is important to ensure environmental regulations are not violated. Because rewatering must be done slowly, time requirements must be considered in the sequencing schedule of the contract.

8.5.2.5 Stream Crossings

In many regulatory environments, construction operations must be planned to avoid impacts associated with fording channels with equipment. An overall stream crossing plan should be prepared within the water management plan to make use of opportunities provided by existing crossings, fording locations with hard bottoms, and strategically located temporary bridges. Temporary bridge construction should be considered to limit impacts when multiple stream crossings are required for equipment access and material staging (Figure 8-5). Temporary bridges may be constructed using log stringers, steel plates, old railroad cars, or large concrete blocks and span from 6 to 30 meters (20 to 100 feet) (combining multiple smaller spans). Costs are dependent on both the length of the required span and design load. If contractors design temporary bridges, they may be required to submit design drawings prior to construction.

8.5.2.6 Sequencing Plan

A sequencing plan detailing water management activities should be developed early in the construction process to facilitate communications among the project stakeholders: designers, sponsors, inspectors, contractors, and regulatory agencies. Water management details should be integrated throughout excavation and large wood placement plans with emphasis on the initial and final stages of those activities. Sequencing plans may address activities such as

- Barrier installation
- Fish removal
- Excavation

- Large wood placement
- Sediment and turbidity control
- Rewatering
- Re-engaging isolated work zones and putting the design feature “on-line” with the active river

Figure 8-5. Examples of Temporary Bridges Constructed for Large Wood Projects

Photos courtesy of Tracy Drury, Anchor QEA, LLC.

8.5.3 Excavation

Some, but not all, large wood designs require excavation of the channel bed or banks to secure placed wood against fluid forces and to prevent undermining by local scour. Excavation may be limited to minor grading to smooth the bed prior to wood placement, excavation of key trenches into the bank for burying boles of key members (Figure 8-6), or excavation of deep pits for burial of key members. In the latter case, key large wood members are placed in pits or holes excavated below projected maximum scour elevation and then partially secured by backfilling around the large wood with ballast. Overlying large wood is secured to the key members, and additional ballast is often placed within the constructed matrix of large wood. Excavated sediments may or may not be suitable for ballast, and, if not, a specified type of backfill material may need to be imported to provide structural stability.

Figure 8-6. Minimal Excavation for Placing First Layer of Large Wood

Little Topashaw Creek, Mississippi

Excavation can present some of the biggest implementation challenges. Excavation approaches vary according to site conditions such as bed material, vegetation, foundation rock, hydrology, and the presence of utilities, infrastructure, and cultural resources.

The use of appropriate equipment and skilled personnel is critical. Using inadequately sized equipment, the wrong type of equipment, or unskilled operation is hazardous to human safety and environmental resources. Additional considerations regarding excavation are listed in the *Guidance* box that follows.

GUIDANCE

Considerations for Excavations for Instream Large Wood Placements

Depth of Excavation—Excavation deeper than 1 meter typically requires laying back side slopes to 1H:1V or less, or use of trench boxes when personnel must enter the pit. Soil stability is critical for deeper excavation due to the risk of sidewall collapse. Excavation depth should be specified during the design phase based on projected scour depth and anchorage requirements. *See Chapter 6, Engineering Considerations*.

Site Hydrology—Dry sites are optimal for excavation. Excavations that intercept the groundwater table are at greater risk for sudden side slope collapse and development of boils. Site dewatering prior to excavation is recommended in high groundwater conditions.

Existing Soils—Coarse aggregate soils, if dry and uncompacted, will require laying back of excavation side slopes to prevent side wall collapse. Stiff, highly compacted sands or sand/gravel mixtures can typically retain steep faces. Geotechnical exploration using borings or trenches are recommended for excavations over 1.5 meters (5 feet) deep.

Backfill—Clay soils are difficult to compact when used as backfill. Sand is highly erodible until stabilized with vegetation. When native soils are not suitable, larger sized materials may be imported. Sometimes existing soils can be blended with some amount of imported aggregate to improve stability for backfilling and compaction.

Location of Equipment—Equipment should not be located at tops of slopes, which are potentially subject to failure unless slope stabilization measures have been implemented, such as use of trench boxes. Equipment should have sufficient boom length to reach at least the bottom of the excavation pit when located safely back from the edge of excavation.

Existing Vegetation—Excavation location should, where possible, be selected to preserve existing mature vegetation, with the edge of excavation remaining outside of the drip line of trees. When designing the project, identify existing mature vegetation both at the excavation site and in the access path to the site.

Depth to Water—Excavation below stream surface or water table level poses challenges in release of turbidity as well as placement of large wood. When placing wood below the water line, equipment must hold the wood in place to resist buoyant forces while additional topping logs, ballast, or backfill is placed on the lower log layers.

8.5.4 Wood Placement

8.5.4.1 Large Wood Configurations

Configuration of emplaced large wood is usually selected in the design phase.

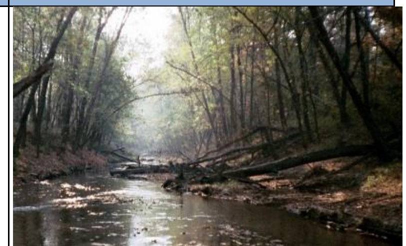
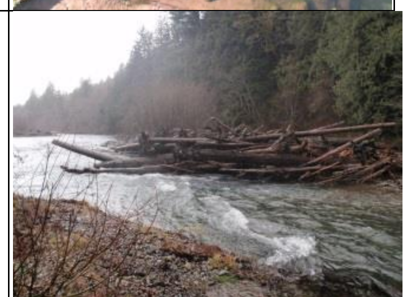
CROSS-REFERENCE

Chapter 6, *Engineering Considerations*, provides detailed information on available options for configuring large wood emplacements.

Large wood configurations in current use vary in complexity from single pieces to complex structures with dozens of large logs, rootwads, and hundreds of smaller pieces (Table 8-3). Pieces with rootwads tend to be more stable (Braudrick and Grant 2001), but are much harder to transport and manipulate. The stability of individual pieces is related to the ratio of their length to channel width,[1] and some scientists have found lengths as great as 2.5 channel widths are needed for long-term stability. Others have found values of this ratio closer to 1.0 for geometrically complex channels with higher rates of natural large wood loading (e.g., Bocchiola et al. 2006).

[1] Stability of individual wood pieces is related to many factors in addition to the length/channel width ratio, and many of these are region- or site-specific. Among these are the presence of rootwads, branches, the ratio of log diameter to depth, channel sinuosity, cross-sectional shape, riparian vegetation, and many other factors. However, relations between mobility and wood length consistently arise in all regions.

Table 8-3. Configurations for Instream Large Wood Placement

Type of configuration	Advantages	Disadvantages	Illustration
Individual large wood piece without rootwad[1]	Less expensive, easier to transport and for hand crews to place, more maneuverable	Less stable, less hydraulic and habitat complexity	
Individual large wood piece with rootwad	More stable, more hydraulic and habitat complexity. Soil in rootwad provides ballast	More expensive, harder to place with hand crews, usually requires heavy equipment to place and operator skill	
Grouping	Added stability by interlocking, added complexity, increased likelihood of engagement	Added cost, generally requires some excavation or anchoring, increased potential for adverse/unanticipated channel response	
Log matrix	High surface complexity and roughness, simple to construct	Aesthetics, limited benefit as bank armoring	

8.5.4.2 Small Wood

Small wood placement is typically installed in smaller systems and provides complexity, diversity, and overhead cover. In these smaller systems, the introduction of a small amount of wood can provide a significant amount of habitat value. Large wood in this context is considered to be 10–30 centimeters (4–12 inches) in diameter and no longer than 6 meters (20 feet). The installation of wood is fairly easy and can be completed by hand crews without the use of large machinery. The wood for these installations can be harvested locally and should be staged no farther than 9 meters (30 feet) from the construction site. Depending on the high flows of the system, the wood can be generally placed on the surface of the channel and intertwined with other wood adjacent to or in the channel to help maintain stability.

8.5.4.3 Oblique Logs

Oblique logs are small (15- to 30-centimeter [6- to 12-inch) diameter logs that are wedged, at off-vertical (oblique) angles into the gaps of a logjam and used to interlock other members and reduce vibration during high flows. Oblique logs are placed in a manner to pin underlying key logs against vertical pilings and under the ballasted weight of overlying key logs. Placement of oblique logs is a strategic part of the construction process and done to complement and not interfere with placement of successive layers of logs, slash, and ballast.

8.5.4.4 Slash

Wood slash refers to branches, limbs, twigs, and other residue left over after a tree is felled (Figure 8-7). Slash may be used for erosion control and as a component of large wood structures, as described in the *Guidance* box that follows. Slash used in large wood projects should be that generated from large wood harvest and transport to the placement site; no extra slash should be extracted.

Figure 8-7. Pile of Slash Available for Use in Large Wood Project

GUIDANCE

Uses for Slash in Instream Large Wood Projects

Base Layer—When placed prior to wood, slash provides prime juvenile fish habitat if submerged (below base flow water surface elevation).

Backfill Retention—A layer of slash underlying backfill helps retain overlying alluvium from bleeding out if undercut by scour.

Soil Amendment—Alternating layers of soil and slash during backfill provides an organic soil amendment that will help retain soil moisture. After slash decays, it provides nutrients but will be a nitrogen sink until it does. In order to place slash layers, place a lift of loose slash at least 61–91 centimeters (24–36 inches) thick and then track or wheel compact with heavy machinery so that the layer is 8–10 centimeters (3–4 inches) thick. Alternate with layers of soil that are 46–60 centimeters (18–24 inches) soil thick.

Final Ground Surface Layer—This layer protects soil surface from sunlight (lowering soil temperatures), increases surface roughness if subjected to overland flow, retains moisture, and limits wind-blown dust.

In Large Wood Structures—Use slash to fill large voids and supplement racked logs. Incorporating slash into the face of the wood structure creates a more hydraulically diverse condition and provides refuge for juvenile fish.

Special Cases—When using dolosse (concrete jacks), steel piles, or other artificial materials, loose slash offers an excellent way to improve aesthetics by covering over exposed artificial elements.

8.5.5 Securing Wood

Properly securing the wood installation is probably the most important task in an instream large wood construction project, and a wide range of approaches are possible (Table 8-4). In most cases, the methods to be used are selected and details specified in the design phase of the project.

CROSS-REFERENCE

Chapter 6, *Engineering Considerations*, provides detailed information on selecting and designing restraints for placed wood.

By properly installing and securing the wood, this will prevent future property damage, loss of life and possible litigation.

Table 8-4. Comparison of Methods for Securing Instream Large Wood

Method	Technique	Advantages	Disadvantages	Illustration
Burial	Trenching/ backfill. See discussion of ballast requirements below.	Precise placement. Embedment in highly cohesive (e.g., lacustrine clay) material has been effective (Southerland and Reckendorf 2010)	Cost of excavation and challenges working below waterline	
Pinning	Rebar/dowels	Inexpensive way to use small wood to create a larger structure; wooden dowels are biodegradable	Holes from rebar create a weak point that tends to rot out. Leaves behind relict steel. Wooden dowels have little strength against rotational forces	
Lashing	Manila rope, cable, chain	Bundle small/mid-size together to act as large members. Quick to install. Manila degrades in few years	If structures wash away, they may not break up and therefore more readily get tangled up in downstream structures. Cable and chain leave relict steel. Loose cable can be safety hazard to boaters.	

Method	Technique	Advantages	Disadvantages	Illustration
Tethering (Nichols and Sprague 2003)	Cable or chain	Simple and low cost	Limited habitat benefit as single logs; also, tethered logs often come to rest above the baseflow level and provide no aquatic habitat at lower stages; added safety risk due to tether, no redundancy for stability	
Mechanical anchors (Shields et al. 2008)	Helical, rotating plate	Large holding force with small anchor	Leaves behind relict steel; difficult holding in some alluvial soils; time consuming to install	
Pile-supported structures[1] (Abbe and Brooks 2011)	Driven or placed in excavated holes and refilled (the latter required for placing piles with rootwads); sharpen piles for quicker driving	Smaller excavation footprint; quick installation, relatively low cost; high stability, adds redundancy when incorporated in larger structures	Subsurface obstruction; piles must be driven deep enough to avoid scour	
Entanglement on bank trees[2]	On-bank trees	No additional anchoring required	Dictated by existing trees; requires large wood that is longer than ~2.5 times the channel width for permanent stability	
Gravity anchorage	Structure (wood + ballast) is heavy enough to resist imposed forces during design flows	No additional anchoring or manufactured materials required; natural appearance	Structure height must be great enough that it is not submerged during design event; not feasible at many sites	

Method	Technique	Advantages	Disadvantages	Illustration
Woven	Hybrid of pile-supported and gravity; horizontal logs are entangled with vertical piling logs; vertical piles used to counteract horizontal forces and ballast to counteract vertical forces	No additional anchoring or manufactured materials required; natural appearance.	Structure height must be great enough that it is not submerged during design event; not feasible at many sites	 Photo by Ken DeCamp
Unanchored	Placing wood directly in system	No anchoring required	Safety concerns, may dislodge in unexpected flows; requires large wood that is longer than ~2.5 times the channel width for permanent stability	

[1] Photo used by permission of Office of Response and Restoration, National Ocean Service, National Oceanic and Atmospheric Administration.
[2] Photo used by permission of Long Tom Watershed Council, Eugene, Oregon.

8.5.5.1 Cable, Chain, and Rope

Restraining devices such as steel cable, chain, and rope are commonly used for either temporary or permanent large wood restraint (Table 8-4). As temporary features, these materials are used during the construction process to secure wood to heavy equipment for transport and installation and to secure wood in a particular location or logjam until additional ballast or wood members are placed. All temporary restraining devices should be viewed with caution due to corrosion and wear and should be inspected by the contractor prior to construction commencing. As permanent features, these materials are used to connect large wood pieces and to connect large wood to anchors, boulders, and trees. Permanent applications of cable, chain, or rope should be carefully considered to ensure that these materials do not create public safety hazards.

8.5.5.2 Mechanical Anchors

Earth anchors in unconsolidated material such as alluvial streambed or banks rely on skin friction and surcharge on the cable and passive earth pressure acting on the anchor—all of which depend on the material remaining static.

If the streambed or bank erodes, an earth anchor will fail. If wood attached to a cable moves, so will the cable and the alluvium around the cable, destabilizing the earth anchor and potentially causing erosion of the streambed or bank. Because of these potential issues, using earth anchors is strongly discouraged, and if they are used, it is recommended to use three or more at each attachment to minimize strain and displacement, similar to cable stays on a tower.

8.5.5.3 Ballast

Large wood structures are often stabilized by filling the spaces within the wood members with alluvium. Because native alluvium (e.g., that removed for excavation in preparation for large wood placement) tends to be mobile at high flows, ballast must often be imported, which can increase costs. Table 8-5 presents some examples of typical ballasts used in wood installations and their advantages and disadvantages. Each technique will vary given specific site conditions and the availability of material. Interstices in large ballast can be filled with finer-grained alluvium washed in using water jets supplied by pumps and hoses. Jetting in the backfill improves consolidation, increases ballast weight, and provides better media to support vegetation planted within the structure.

Table 8-5. Ballast Materials for Instream Large Wood Structures

Ballast	Advantages	Disadvantages	Illustration
Native alluvium[1]	Reuse onsite material lower costs	Can wash out of structures (Shields et al. 2004; Southerland and Reckendorf 2010)	
Imported rock[2]	Select material appropriate for job[3]	Additional cost to purchase and haul in; nonnative to site	
Rock collars	Quick placement and flexible to accommodate multiple log configurations	Poor quality rock can shatter when drilled; match cable strength to ultimate loading	
Dolosse[4]	Complex shape helpful to entrap wood; shape of unit inherently stable; can be colored and textured to imitate wood	Artificial material; aesthetics poor; limited manufacturing locations and sources	

[1] Arrow in photograph indicates alluvium placed as ballast.

[2] Illustration shows Sulphur Creek, Redding, California. Used by permission of John McCullah, Salix Applied Earthcare, Redding, California.

[3] Sizing and selection of imported rock is beyond the scope of this document. Guidance for use of quarry stone riprap for erosion control in stream channel is provided by many authorities including Brown and Clyde (1989), U.S. Army Corps of Engineers (1994), and Escarameia (1998). Natural rounded stone is aesthetically superior to angular riprap for many applications, but tends to be less stable because it does not interlock. Use of rounded stone may call for larger stone or thicker layers of stone.

[4] Illustration used by permission of Pierce County Public Works and Utilities, Surface Water Division, Washington.

8.5.6 Finish Work

An essential element in the process of installing wood is cleaning up the site and completing the finish work and preparing the site for plant material. An important factor when demobilizing from the site is to try and not leave the soil compacted in the construction area itself or the access route to the site. Wet soils and seep areas should be avoided when operating vehicles, and when these areas must be affected, they may be protected with slash, matting, or logs.

Compacted soils are difficult for vegetation to penetrate the compacted soil and become established. If compaction does occur, it is important to scarify the soil with the equipment on site or return to the site and un-compact the soil with a different approach.

8.5.6.1 Soil Amendments and Erosion Control

To ensure successful plant propagation, adding soil amendments can help in the long-term stability for the site. Ideally, the contractor should blend in approximately 46 centimeters of organic material with the native soil. Once the final grade has been established and the site has been planted, the application of arborist chips will aid in the retention of moisture in the soil and can potentially slow erosion on the disturbed area.

Erosion control for the site is a construction activity that requires diligent implementation and constant maintenance to ensure compliance with a variety of regulators. One of the more common applications is the use of erosion control blankets, which will provide 2–5 years of erosion control before the blankets biodegrade. Depending of the degree of erosion probability, the blankets come in a variety of sizes and weights to mitigate the degradation of the site. Typically, the variety of the blankets is contingent on the frequency and size of the woven matrix. To ensure successful implementation of the blankets, the blankets must be securely held down with no bare soil showing. Additionally, a variety of methods to securely hold down the blankets are available, such as using staples and stakes. Stakes and staples are also made using a variety of materials such as wood, metal, and biodegradable material and should be selected based on the site constraints and long-term maintenance considerations.

8.5.6.2 Revegetation

Natural large wood accumulations produce gradual changes in stream corridors by providing sites for terrestrial plant colonization. Heterogeneous floodplains develop as woody plants sprout and mature on sediments trapped on or within large wood formations, trapping and recruiting more large wood and sediment. The weight of trees growing on large wood adds ballast to counteract buoyancy, drag, and lift. Large wood projects often attempt to emulate these natural processes by including provisions for planting fast-growing riparian species in exposed soils and sediments adjacent or within newly constructed large wood structures.

Revegetation may proceed by inserting or burying dormant cuttings of adventitious species such as willow (Salix spp.) (Figure 8-8); using nursery-grown bare root, potted, or burlap-wrapped specimens; or seeding. In some cases plant materials may be harvested or salvaged from stands on the project site, and some projects have successfully transplanted willow tree root balls. Selection of plant species and propagule should include consideration of site hydrology, soil conditions, sun exposure, existing plant material, and long-term maintenance and management goals. Plants should be robust under anticipated hydraulic loads; deeper-rooting species may be needed to withstand higher velocities. Soil tests should precede planting, and amendments and mulches used as necessary. Plants are sensitive to soil density and drainage, so overcompaction and grading that leave plants flooded should be avoided. Moist, well-drained soils are optimal.

Figure 8-8. Planting Willow Cuttings in Recent Sediment Deposits Adjacent to Placed Large Wood Using Water Jetting

Little Topashaw Creek, Mississippi

Soaking cuttings in well-oxygenated water for up to 21 days prior to planting may be helpful (Schaff et al. 2002; Martin et al. 2004). Some evidence indicates that survival rates may be higher for larger-diameter cuttings (Greer et al. 2006). More complete treatment of plant material installation is provided by FISRWG (1998), NRCS (2007d), and Fischenich (2001). Goldsmith et al. (2014) present a series of useful case studies. Key principles include reliance on local or regional expertise and native species. Control of exotic species may be included in the project or may be required to eliminate competition for plantings.

Plant materials impose severe constraints on implementation scheduling (FISRWG 1998). Cuttings should be dormant when harvested and planted, and they should be planted within a day of harvest or completion of the soaking period. Ideally, planting schedules should allow time for establishment and rooting between planting and high-flow season, but this may not be possible.

Plant materials should be kept moist between harvest and planting. Rooted stock is prone to drying, particularly if pots or burlap-wrapped roots are exposed to direct sun. Soaking rooted stock is not recommended, but 1 to 2 hours of immersion immediately prior to planting is a common practice. Bare-rooted or burlap-wrapped stock should be heeled into damp ground or mulch while awaiting final installation. Cuttings must be planted with the same vertical orientation they have grown in, and bundling and marking of cuttings should proceed accordingly.

During the period of establishment, irrigation may be needed. Also, fencing to deter herbivory by wildlife (e.g., beaver) or livestock is often required, although some evidence indicates moderate beaver herbivory is not deleterious to willows (Li et al. 2005; NRCS 2007d). Vandalism is also a potential problem in populated areas (FISRWG 1998).

8.5.7 Typical Construction Equipment

While the use of mechanized equipment allows restoration professionals to complete site work faster and on a larger scale, the use of "light" construction techniques is often required to complete a variety of wood installments. Some installations require access to remote sites that are not accessible by vehicles or are located in environmentally sensitive areas where access is limited and alternative construction methods are required.

8.5.7.1 Light Construction

Hand Placement

Human-powered labor is a useful tool when access is extremely limited or site conditions do not allow vehicles or construction machinery (Figure 8-9). Typical applications are along small, sensitive streams. Of course, hand placement is not adequate for dealing with large quantities of excavation or fill, pieces of wood or rock that are heavier than a few hundred pounds, or working in water more than 0.6 to 1.0 meters (2 to 3 feet) deep.

Figure 8-9. Manual Labor Team Stockpiling Large Wood Prior to Stream Installation

Some workers report good results using draft animals (e.g., Belgian draft horses) to enhance hand labor teams (Figure 8-10). However, use of draft animals requires skilled handlers and access for horse trailers. When the local regulatory agency permits, onsite thinning of wood along the stream banks can be used to drop whole trees directly into the channel. Riley (1998) provides detailed instructions for implementing stream stabilization measures, many of which include wood and plant cuttings with hand labor.

Cable Yarding

Mechanical systems such as overhead cables, grip-hoists, or pulley systems can be useful for transporting wood from staging sites into the stream channel. This practice is referred to as "cable yarding," and may be used to transport wood overhead or drag it along the ground (Figure 8-11). Overhead cable systems can typically be used for lengths of up to 91 meters (300 feet) each, and log weights up to 1,360 kilograms (3,000 pounds) may be accommodated.

Figure 8-10. Belgian Draft Horses Moving Large Wood for Instream Placement

Photo courtesy of the British Columbia Ministry of the Environment.

Figure 8-11. Cable Yarding Large Wood for Transport to Channel

Cable system feasibility depends on site topography, and requires anchor trees or towers at both ends to which the cable tight line can be anchored. Typically, cable yarding is a manual process, but using small machines can speed up the process and facilitate work with larger wood. It is important to note that cable trading can be extremely dangerous and consulting with an expert in the profession prior to starting work is recommended.

Walking Excavators

Walking excavators or "spiders" provide unequaled performance in difficult terrain such as steep slopes or in river beds. The four hydraulically adjustable legs allow for the excavator to position the machine in a variety of ways, unlike other excavators. Some other benefits of walking excavators include very small turning radius, large lifting forces, and compact loading dimensions. Conversely, walking excavators are slow to move, have difficulty moving through soft soil, and are not ideal for transporting materials.

Small Excavators

The use of small excavators or “minis” is particularly useful when the site will not accommodate larger equipment or the scope of the project does not warrant the expense. Minis are typically rubber-tracked and can access remote sites and environmentally sensitive areas with little disturbance. Minis are limited to excavating in soils (not rock) and cannot drag weights greater than about 1360 kilograms (3,000 pounds). They typically are useful for lifting and relocating materials weighing up to about 544 kilograms (1,200 pound)s; this is equivalent to a 6-meter (20-foot) long log with an average diameter of 46 centimeters (19 inches) or boulders with a 76-centimeter (30-inch) average diameter. If materials are larger than this, a larger excavator will typically be required.

8.5.7.2 Heavy Equipment

Characteristics of typical equipment used in large wood work in the Northwest are provided in Table 8-6 below.

Trucks

Dump trucks are used to transport material to and around the site. Wood may be hauled in semi-end dump trucks on highways and in off-road articulated dump trucks elsewhere. Dump trucks come in a variety of sizes and are typically identified by volumetric capacity: five-yard or ten-yard dump trucks are common. When used in large wood placement, a ten-yard dump truck can transport logs shorter than 6 meters (20 feet). Highway hauling restrictions typically limit log length to 10 meters (32 feet).

Trash haulers and trucks with flatbed trailers may be used for logs longer than 6 meters (20 feet) and for logs with large rootwads. Logs are also often delivered via self-loading log trucks. Logs with rootwads do not fit well in logging trucks.

Table 8-6. Examples of Heavy Equipment Used in Large Wood Installation Including Machine and Lift Weights as Appropriate

Machine	Examples	Typical Approximate Machine Weight (1,000 lbs)	Approximate Lift Capacity (1,000 lbs)	Illustration
Tracked excavator with thumb	CAT 330 Kobelco SK300	75	8	
	CAT 350 Kobelco SK400	105		
Rubber tired wheel loader with forks[1]	CAT 930K	30		
Rotating grapple sometimes used on excavator arm instead of bucket with thumb				
Mini excavator				
Tracked-type tractor (bulldozer)	CAT D8R	83		
Walking or “spider” excavator	Schaeff HS 41 M	18	~11	

Machine	Examples	Typical Approximate Machine Weight (1,000 lbs)	Approximate Lift Capacity (1,000 lbs)	Illustration
Log skidder	CAT 525	28	6	
Tracked log loader[2]	Thunderbird 840	100	5	
Low-boy truck, logging truck	A variety of truck types are utilized.			
Crane	National 456A		20	 Photo by Ken DeCamp
Pile driver	Bermingham Foundation Solutions B21 Diesel Hammer	Attachment to crane		
Excavator-mounted vibrator				 Photo by Ken DeCamp

[1] Permission pending for use of image. Obtained from: http://www.cat.com/en_US/products/new/equipment/wheel-loaders/small-wheel-loaders/18262632.html.

[2] Illustration shows log loader with tires, not tracks.

Tracked vs. Rubber Tire Machines

Most types of heavy machinery are available in either tracked or rubber-tired versions. Rubber-tired vehicles are best suited for compact driving surfaces such as well-established access roads. Rubber-tired machines tend to have less effect on native soils and vegetation but can be limited in off-road capabilities. Tracked machinery is best suited for sites with challenging access conditions. Due to the surface area of tracks (relative to rubber tires), tracked machinery also exerts less pressure on native soils.

Excavators

Excavators are the most often-used type of equipment in large wood placement. Excavators come in a variety of sizes, and selection for a given project depends on large wood size. The smaller excavators are more nimble, while larger machines can handle heavier material but are somewhat cumbersome on the site.

Most excavators are tracked, allowing them to travel well on variable terrain. Ground pressure for tracked vehicles is lower than equivalently sized equipment with tires, reducing site damage and soil compaction. For large wood projects, an excavator may be fitted with a bucket with a "thumb," or device that allows the machine to hold onto materials while being placed. Instead of a bucket with a thumb, some machines use a rotating grapple that allows for more precise placement of material.

Log Loaders

Log loaders are an efficient means to transport logs from source or staging areas to construction zones in or near the channel. Most log loaders have a straight arm assembly that is optimized for log handling whereas excavators have a curved arm assembly that is optimized for digging. Tracked and wheeled loaders are available, and both types can traverse rough terrain with little disturbance. Neither require an access road, thus reducing cost and site disturbance.

Bulldozers

Bulldozers are useful for moving large amounts of soil. Dependent of the size of the bulldozer, they can be utilized in large wood placement to excavate the area where the wood jam will be placed, temporarily stage excavated material, and complete the finish grading for many construction sites.

Cranes

Large cranes can be used to move single pieces or bundles of large wood. Cranes are often used to move other large objects such as culverts, pre-cast control structures, machinery, and construction materials. Construction cranes can be mobile or stationary. Crane mobility is related to size and lift capacity with large cranes requiring firm soil conditions and having limited off-road capabilities. Crane rental can be very expensive, and their utilization should be understood early in the design process and built into the construction budget. Stationary cranes typically remain on site for the duration of the project.

Pile Drivers

Pile drivers are usually attachments for cranes that include a heavy weight placed between guides so that it is able to freely slide up and down in a single line. The weight is repeatedly dropped on the head of a pile to drive it into the ground. Pile drivers are useful for placing vertical piles to anchor large wood structures and formations. Piles may be driven into the bed prior to placement of horizontal large wood members or driven through an existing large wood jam or structure. The feasibility of pile driving is strongly tied to subsurface conditions because buried large wood, bedrock, or boulders can severely hamper pile driving.

Pile driving requires less dewatering and disturbance than excavation for large wood structure foundation member burial. Noise levels are similar to that for other types of construction equipment operation when timber piles are used. Piling materials include steel beams, sheet pilings, pipes, or concrete. Only timber piles are recommended for river restoration applications. Piles should be untreated, green-harvested large logs (30–60 centimeters [12–24 inches] in diameter) and often have one end sharpened to a point.

Leads can be one of two types: hanging or fixed. Detailed information on lead systems can be found at: http://www.delmag.com/lead-systems.html.

Hanging leads typically are more versatile and do not need a level surface. **Swinging leads** provide more flexibility, but need a spotter on the ground and a lot of head room for the crane to position them. A typical set of swinging leads is approximately 18 meters (60 feet) long and 60 centimeters (24 inches) square. For driving timber piles for large wood projects, it is recommended to use a hanging lead system for flexibility and to help provide bracing and support for the timber pile itself during driving operations.

Fixed leads are typically only used in situations where increased precision control is needed for detailed positioning by the operator or to reduce ground support of spotters. The fixed leads are usually mounted to an excavator boom or other rigid controlled machine.

Pile driving equipment can be placed into four categories (Table 8-7): (1) diesel hammers, (2) hydraulic hammers; 3) vibratory hammers; 4) alternative equipment.

Diesel-powered hammers are the most common, and are very efficient and effective at installing timber piles below the river bed, even in difficult conditions like coarse cobble substrate or in flowing water. Diesel hammers operate with a piston-cylinder apparatus using an air-fuel compression-impact-combustion energy combination to drive the piston (hammer) into the timber pile. The recommended diesel hammer for large wood projects is the DELMAG (D-12) hammer due to its size, reliability, and availability. Use of larger hammers may result in impact cracking or shattering.

Hydraulic-powered hammers operate similar to diesel hammers but have cylinders stocked with hydraulic fluid rather than a compressed air-fuel combination. Hydraulic hammers are not as efficient, cost effective, or available as diesel hammers. However, hydraulic hammers can often be less noisy and decrease concerns of air/water pollution.

Vibratory impact drivers (“Vibros”) operate using counter-rotating weights that are powered by hydraulic motors. Although vibratory hammers are often used for driving hollow piles or sheet piles through fine sediments, they are not recommended for large wood projects.

Alternative equipment includes devices designed for mounting on excavators. Use of excavators removes the need for crane mobilization. Excavator-mounted vibratory drivers can work well in finer sediments up to gravel size, but may not function well in cobble. Other alternatives have also been used to drive timber piling, but are not recommended. Among these are conversion of excavator-mounted soil compaction vibrators and direct use of excavator boom to push down timber piles.

Table 8-7. Comparison of Pile-Driving Methods

Hammer	Advantage	Disadvantage	Remarks	More information
Diesel hammer	Commonly available, low cost, high strength to weight ratio, can be used in cobble substrate	Potential environmental issues for air quality, increased noise level	Recommended option for driving timber piles on large wood projects	http://www.delmag.com/diesel-pile-hammers.html delmag.com/technical-data.html
Hydraulic hammer	Decreased noise level, decreased risk to air quality	Decreased strength and efficiency, higher cost	Reasonable alternative to diesel hammers	http://www.apevibro.com/ver2/products/hih/default.asp
Vibratory impact hammer	Very little noise level	Difficult to install per pile—mounting required	This is not recommended	http://www.apevibro.com/ver2/products/vibro/default.asp
Excavator-mounted vibrators	Removes need to mobilize crane	May not work for cobble beds		http://www.movax.com

CASE STUDY

Driving Piles to Secure Large Wood Structures

On the Trinity River in Northern California, restoration practitioners found that the diesel hammer was the most effective at driving timber piles into coarse sediments in moving water. The large wood design called for foundation piles installed approximately 3 meters (10 feet) below grade to allow for scour. Over ten piles needed to be installed as the vertical members to the large wood structure. Excavation and backfilling were not feasible due to regulatory requirements for maintaining navigability and holding the turbidity below 20 NTU at 152 meters (500 feet) downstream.

The construction sequence is illustrated in Figure 8-12.

1. Clean gravel fill was placed in the large wood footprint approximately 0.3 meter (1 foot) above the water level to serve as a staging pad.
2. The planned location for each pile was surveyed and marked on the gravel pad.
3. An excavator was used to dig a pilot hole for each pile through the gravel pad and 0.3–0.6 meter (1–2 feet) into the bottom of the river bed.
4. Piles were inserted in the holes and backfill was placed to hold them vertical.
5. A crane and DELMAG D-12 diesel pile-driver hammer were mobilized to the project site. The crane was positioned strategically to be able to logistically reach each of the piles from one central location. The diesel hammer and fixed leads were lowered onto each timber pile and were driven according to conventional pile-driving protocols, except that the excavator boom was used to stabilize the fixed leads to ensure vertical placement during initial blows for each pile.

The diesel hammer was able to drive the timber piles 3 meters (10 feet) into the river bed through coarse cobble in approximately 30 minutes or less per pile. Positioning the piles prior to crane mobilization allowed the crane and diesel hammer to mobilize, install the piles, and demobilize in one full day. The approximate cost per day for the crane, diesel hammer (D-12), and crew was around $7,500 (2014).

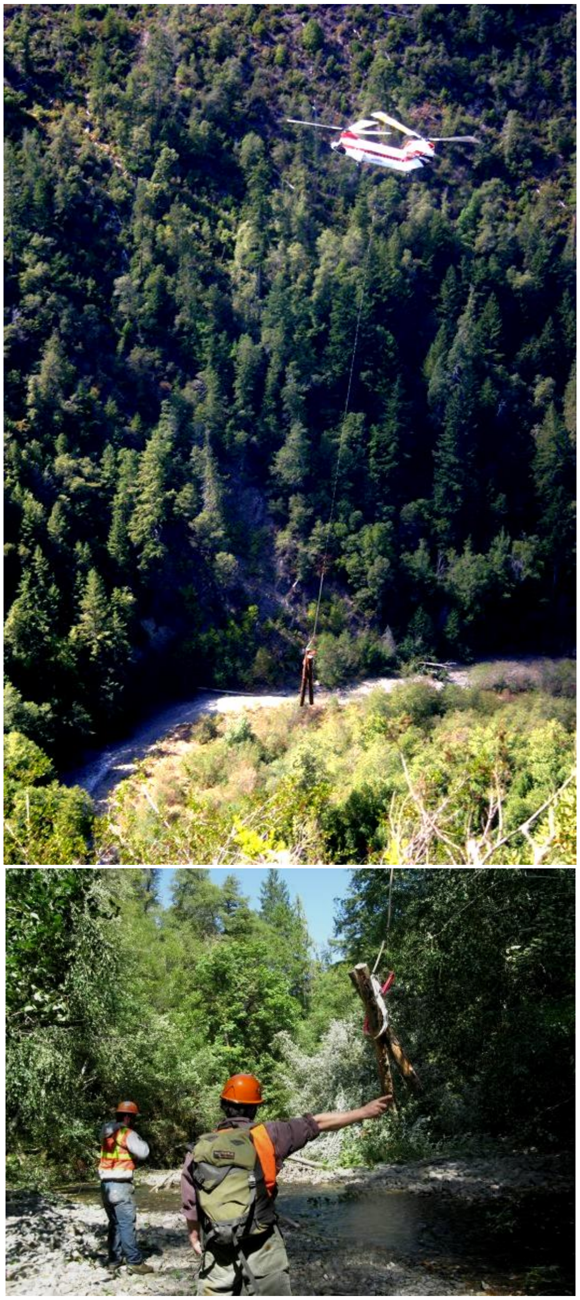
Figure 8-12. Sequence for Constructing Large Wood Structure With Vertically Driven Piles Used to Secure the Structure

Trinity River, California. (a) Gravel pad placed over river bed at site for large wood structure. Holes excavated in pad with track hoe, logs (piles) inserted, and holes backfilled to stabilize piles. (b) Crane for driving piles mobilized to site. (c) Crane driving piles with diesel hammer. (d) Gravel pad removed to allow flow around placed wood and attendant vegetated bar. Completed large wood formation functioning as bar apex jam. All photos by Ken DeCamp.

8.5.7.3 Helicopter Construction

Helicopters ("aerial cranes" or "skycranes") are used to lift heavy loads with long cables or slings and have been used in the logging industry for decades. They are useful for delivering imported wood and other materials and maneuvering wood for final placement (Figure 8-13). Helicopters offer advantages of low site impact and rapid construction. They are especially useful for sites with difficult access and in-water placement. On the other hand, they are relatively high cost, have limited ability to work with extremely large loads, and require increased planning and coordination as well as special safety expertise for the ground crew. Helicopter routes must avoid active roadways and residential areas when transporting material.

Figure 8-13. Use of Helicopter to Transport Large Wood to Remote Project Site



(a) Helicopter delivering wood. (b) Use of hand signals by ground crew to coordinate with pilot.

Timing and Costs

Using helicopters for implementing large wood projects can be highly efficient and cost effective. However, few firms have the required expertise, and they are often unavailable during forest fire season (summer).

GUIDANCE

Improving the Efficiency and Cost-Effectiveness of Helicopter Operations

- Provide a design booklet for the pilot and ground crew. The booklet should be 5.5 by 8.5 inches (or similar) and show basic schematics for each site design and be arranged to show the order of operations for the project.
- Pre-arrange in-flight design terminology.
- Have the wood numbered, laid out and grouped to coincide with the construction sequencing.
- Review the project construction sequencing and safety hazards at daily pre-flight safety meetings.

Requirements for Project Design Drawings

Construction drawings for large wood projects involving helicopters must address several issues that are normally not taken into account. For example, to eliminate lost air time, plans may specify staging areas and refueling stations and contain lists of exact coordinates for the delivery or placement of materials. Additionally, the construction sequence should be defined in detail. This will allow for efficient staging and streamline helicopter operations.

Ground Crew

Ground crews for helicopter placements are an important component. Ground crew personnel are generally provided by the helicopter contractor and are trained in operating and safety procedures specific to this machinery. Crews composed of two to four persons will be stationed at both the loading and unloading areas and responsible for communicating with the pilots, connecting cable chokers to the controller yoke, helping position large wood, and collecting cables at the unloading area. For projects with in-water placements, care should be taken not to exceed depth and velocity criteria for safe wading.

Most helicopter companies working in North America provide the option of moving wood using either chokers or various types of specialized grapples. Grapples are more efficient at moving one or two large logs at a time, whereas chokers can move several smaller logs but require ground crews to hook and unhook the logs. Grapples allow the pilot to select, arrange, and place logs with greater precision compared to chokers, and are safer for ground crews because there is no hooking involved, and the crew can maintain a greater distance from the load and flying debris.

See the next section for other safety considerations associated with helicopter operations.

The large wood project designer (or their representative[s]) should be on the ground, working either in direct communication with the pilots, or through the helicopter company's ground crew, to direct final placements. This role will depend on the designer's experience and physical ability to traverse the terrain, and the helicopter company's safety policies.

8.6 Safety

Successful implementation of safety plans is a hallmark of effective projects and contractors. Personnel implementing instream large wood projects incur hazards associated with logging, construction, and amphibious operations. Such operations often occur in non-ideal weather. The synergy of these hazards heightens the importance of safety issues in implementation. Standard practices such as furnishing first aid kits and training, holding regular safety meetings, and complying with applicable local, state, and federal laws and regulations should be followed and will not be detailed here. A safety and health section from an actual large wood placement contract is provided as Appendix A-4.

Logging has consistently been one of the most hazardous industries in the United States, with a 2010 fatality rate of 73.7 deaths per 100,000 workers, or about 21 times higher than the overall population fatality rate There is a large body of regulations and supporting documents dealing with safety in the logging and construction industries, and no effort will be made here to reproduce all of it. Highlights from key topics will be introduced. The single most comprehensive document in this topic area is *Engineer Manual 385-1-1* (USACE 2008), which governs activities by USACE personnel and contractors and is a valuable information resource for others. Safety guidance for logging operations is provided by the U.S. Occupational Safety and Health Administration (OSHA undated a), the National Institute of Occupational Safety and Health (NIOSH 2012), the State of Idaho (undated), the Washington State legislature (undated), the Southwide Safety Committee (2010), and USACE (2008).

It is advisable to include provisions in large wood placement contracts that require Job Hazard Analyses (JHA) for each distinct phase of work. The JHA should be prepared and submitted by the contractor and approved by the government prior to beginning work on the relevant phase. Furthermore, the contractor may be required to develop a site-specific safety and health plan prior to starting work. The plan should cover all aspects of on- and offsite operations and activities associated with the contract, and include noise monitoring and material safety data sheets for activities requiring hazardous materials. Generic safety plans do not fulfill these requirements. The project safety and health plan should provide a list of the JHA anticipated throughout the project and a statement that additional JHA will be provided as required as the project progresses.

8.6.1 Potential Safety Issues

Public agencies and other responsible and interested parties may be concerned about both public safety and assumption of liability that may be associated with large wood projects.

The level of concern, and, as a result, the level of effort to address potential issues, needs to be driven by the actual level of risk. The number and types of users on any given stream or river can vary dramatically when compared to other rivers. Some rivers have millions of users during a single year while others may have close to none. In either case, public safety should be a strong driver for project design. However, the level of analysis and method of accommodation should reflect the level and types of use. One way to address the public safety concern is to document the pre- and post-project conditions and use the design process to identify all potential hazards, systematically evaluate them, and ensure that the design has minimized the level of risk to an acceptable level.

Public safety in the broader sense, and specifically recreational safety, is a primary consideration during the design and construction phases of instream projects that include the installation of large wood. It is important to consider recreational safety throughout the project development process to ensure that public safety is maintained over the life of the project (MTZ Associates 2000).

Although recreational activities vary greatly among different streams, in general, several types of recreation may occur, such as fishing, swimming, wading, rafting, kayaking, and inner-tubing. In addition, water skiing, personal watercraft use, and recreational power boating are popular activities on some larger rivers, especially during the summer and fall months when water levels are generally at their lowest and large wood structures are most exposed. Incorrect placement of large wood can increase potential safety hazards to recreationists, especially for swimmers, waders, water skiers, and personal watercraft users.

8.6.2 Potential Best Management Practices

Designers and installers should consider best management practices when installing large wood to minimize the potential for compromising recreational safety. Each project site is different, and the site-specific details need to greatly influence if and how these recommendations are incorporated.

GUIDANCE

Best Management Practices

1. Avoid installing large wood in such a way that large, single branches project far out into the river channel where they can create a hazard to boaters; placement of large, rigid woody structures in strong currents has the greatest potential to present a hazardous condition.

2. Where applicable, install trimmed large wood in such a way that finer-textured material projects above the water surface at low flows; this provides recreationists with visual cues of the presence of shallowly submerged structures.

3. Do not install large wood where there is limited opportunity for river users to recognize and avoid submerged structures (i.e., hazards are greatest when there is limited approach visibility).

4. Orient large wood downward toward the water and in a downstream direction (i.e., between 45 and 90 degrees relative to a line running perpendicular to the channel) to minimize hazards to swimmers and waders.

5. Do not place large wood near bridge piers and crossings of other infrastructure because complex velocity patterns are often associated with these structures, and large wood at these sites can create special hazards to recreationists.

6. If materials such as cable or chain are used to secure large wood (e.g., into rock revetment), minimize the length of cable or chain that is exposed above the rock revetment to avoid creating a tripping hazard.

7. Secure cable ends under rock revetment or near trunk sections to minimize exposure of the public to sharp objects.

8. Approach visibility is a critical indicator for river users and should be considered in all aspects of project design, including selection of the location of large wood placement, approach velocities under a variety of flow scenarios, and signage at entry points and sufficiently upstream to warn oncoming river users.

9. In various locations around each large wood structure (e.g., entry points, upstream of the structure), install warning and/or interpretive signage panels to advise the public of presence. Warning signs should be very specific about the risks and strategies for avoidance. Interpretive sign panels should describe the functions of a large wood structure, native fish and fauna that utilize wood structures, and precautions boaters and recreationists should take when near a large wood structure.

8.6.3 Personal Protective Equipment

Personnel involved in large wood construction activities should be protected "from head to toe." Clothing and protective equipment (personal protective equipment [PPE]) is no substitute for hazard control at the source. For example, hearing protection is not to be substituted for functional mufflers on machinery. Employees should wear clothing suitable for the expected weather conditions and work conditions. At a minimum, clothing should include short- or long- sleeved shirts, long pants, leather boots, and hard hats. Employees should be trained in the use and adjustment of protective equipment, and nonfunctional or damaged equipment and attire should be destroyed or discarded. Basic requirements are described by USACE (2008) and are summarized in Table 8-8.

8.6.4 Log Handling

Handling large wood is extremely dangerous. Very large wood pieces are often required as key members, and use of large wood with rootwads is attractive for functionality in many applications. However, the asymmetrical mass distribution of these elements leads to unpredictable behavior when they are being moved about. Clearances between personnel and large wood under transport should be conservatively large to allow for these shifts and movements.

Additional detailed guidelines for log handling are provided within the logging safety sources cited above. In general, these resources describe the necessity for proficient equipment operators, keeping equipment in well-maintained condition (particularly brakes and throttles), using equipment that provides structural barriers such as bulkheads to protect operators, and staging operations to provide visibility to operators. For example, information such as the following should be provided: "Truck drivers shall be in the clear and in view of the log unloader operator before forks are moved into the load or against it, before a lift is made. All persons are prohibited from standing under, or near, the ends of logs being lifted or moved," and "All workers shall be in the clear and in view of the machine operator before a lift is made."

8.6.5 Excavation and Earth Moving

Alluvial soils and sediments are quite heterogeneous. Bearing capacity or slope stability may change drastically between two points separated by only a few feet, leading to hazards for equipment or even personnel on foot (Figure 8-14). Geotechnical stability is also a consideration for excavation, as saturated alluvial soils tend to be weak and prone to slope failure. Safety standards for construction excavation and trenching have been promulgated by OSHA (undated b). Excavation deeper than 1 meter typically requires laying back side slopes to 1H:1V or less, or use of trench boxes when personnel must enter the pit. All trenches 1.5 meters deep or greater require a protective system unless the excavation is made entirely in stable rock (OSHA undated b).

Table 8-8. Personal Protective Equipment and Attire for Large Wood Project Implementation

Category of Gear	Examples	Appropriate Uses and Remarks
Head protection	Hard hats, helmets	Hard hats needed whenever heavy equipment is present
Eye and face protection	Safety glasses, goggles, face shields	Glasses with added shields for side protection; face shields needed for chainsaw operation
Hearing protection	Disposable, preformed, or custom-molded ear inserts, ear plugs, ear muffs	When noise exposure exceeds 85–90 A-weighted decibels (dBA) for a time-weighted 8-hour exposure; see USACE (2008) for exposure limit details and computation
High visibility apparel	Apparel meeting American National Standards Institute/International Safety Equipment Association (ANSI/ISEA) 107-2004 Performance Class 2 requirements	Workers in proximity to heavy equipment or vehicles
Chaps	Protective leg chaps meeting American Society for Testing and Materials (ASTM) Standard F1897	Chainsaw operators; workers potentially exposed to poisonous snakes can be protected with snake chaps or knee-high snake boots
Gloves	Hand gloves designed to protect from cold, poisonous plants, cuts, abrasions, punctures, burns, and chemical irritants	Important when working with metal cables and chainsaws
Personal flotation devices	Inherently buoyant Type III, Type V work vests, or better U.S. Coast Guard–approved personal flotation devices that are international orange (or orange/red) or ANSI 107 yellow-green in color	Whenever working on floating plant or over or adjacent to water such that a drowning hazard exists; see USACE (2008) regarding the use of auto-inflatable devices
Protective footwear	Safety-toed boots meeting ASTM Standards F2412 and F2413	Whenever on a work site

Figure 8-14. Log Skidder Mired in an Isolated Deposit of Highly Plastic Clay in a Stream Bed

Little Topashaw Creek, Mississippi

Great care is needed to ensure safety of personnel working near heavy equipment. High visibility apparel and PPE, scrupulous attention to communication, and maintaining clear lines of sight for operators are essential. For all but the smallest projects, it is advisable to prepare an internal traffic control plan (Roadway Safety Alliance [undated]). Key safety principles for construction site management include the following:

- Separate on-foot workers from equipment as much as possible.
- Design the work space and operations to eliminate/minimize backing and blind spots.
- Train workers and equipment operators on communication methods.
- When necessary, use a spotter so the vehicles do not run over workers or back into other vehicles (Figure 8-15).

8.6.6 Helicopters

Helicopter operations generate safety hazards in addition to those associated with lifting equipment due to the danger of moving propellers, the effects of propeller wash, and the great heights of helicopter lifts. Propeller wash can dislodge treetops, tree limbs, and other objects high above and endanger personnel below. Employees should not work under hovering aircraft except while hooking or unhooking loads. Communications and signals between helicopter crews and ground personnel must be clear, continuous, and unambiguous.

Figure 8-15. Construction Laborers Work to Secure Fabrics Around Large Wood Toe Placements on the Outside of a Meander Bend in a Shallow Channel

Note the spotter (orange hard hat) in visual contact with both the equipment operator and laborers. Source: Inter-Fluve.

8.6.7 Chainsaw Operation

Chainsaws are efficient, but extremely dangerous, tools. All types of power saws should be kept sharp and in good repair at all times. All exhaust parts on power chainsaws should be constructed and maintained so the operator is exposed to a minimum amount of fumes and noise. Chainsaws should not be operated from unstable water craft or floating plant or while standing in water. Guidelines for the safe use of chainsaws are widely available and include the following (USACE 2008):

- Chainsaws shall have an automatic chain brake or kickback device.
- The idle speed shall be adjusted so that the chain does not move when the engine is idling.
- Operators will wear proper PPE. Eye, ear, hand, foot (safety shoes), and leg protection are required as a minimum.

- Chainsaws will not be fueled while running, while hot, or near an open flame. Saws will not be started within 3 meters of a fuel container.
- The operator will hold the saw with both hands during all cutting operations.
- A chainsaw must never be used to cut above the operator's shoulder height.
- Chainsaws shall have sprockets and drive end of the bar adequately guarded. Idler ends, when used as two-man saw, shall also be guarded.
- Combustion engine-driven power saws shall be equipped with a clutch. Saws with faulty clutches shall not be used.
- Combustion engine-driven power saws shall be equipped with an automatic throttle, which will return the motor to idling speed upon release of the throttle.
- Power saw motors shall be stopped while being fueled.

8.7 Managing Environmental Impacts

Large wood projects are intended to rehabilitate environmental resources associated with stream corridors. It is therefore incumbent upon those who implement these projects to do so in ways that minimize collateral environmental damages. Sections above may be consulted for methods for procuring, transporting, and placing large wood in ways that reduce impacts. During construction, actions described below may be used to minimize impacts on water quality and ecological resources.

8.7.1 Water Quality

Construction in stream corridors require permits that specify erosion controls to limit sediment-related water quality impacts. Guidelines for construction best management practices are widely available (e.g., Fifield 2011), and a good basic summary from a European perspective is provided by Scottish EPA (2009).

> *CROSS-REFERENCE*
>
> Section 8.2, *Regulatory Compliance and Public Involvement*, provides more information on required water quality protection measures in large wood projects.

Permit regulations for most wood installations require special care be taken to prevent harmful chemical spills from occurring during construction. Common requirements include replacement of hydraulic fluids in heavy machinery with food-grade vegetable oil, pressure washing machinery prior to arriving on site to remove debris and chemicals, and maintaining spill kits kept onsite during construction. In addition, either the contractor or owner is often required to submit a spill prevention plan for approval by the regulatory agency prior to construction.

8.7.2 Fish Exclusion

Fish exclusion refers the removal of fish from the work area to allow for continued survival. Detailed guidelines are provided by the Washington Department of Transportation (2012). Some regulatory authorities require exclusion of live fish from work areas prior to instream large wood construction. This requirement is most common in streams with anadromous fishes in the Pacific Northwest, and fish exclusion is virtually unheard of in many other places. Excluded fish are typically relocated in reaches adjacent to the project area.

Fish exclusion is scheduled so that fish are removed prior to complete dewatering or initiation of construction below the water line.

Prior to removal of fish, block nets are placed around the construction area to keep removed fish from re-entering the work area. The basic idea for fish capture is to concentrate in areas where they can be easily seined and netted. Complex cover structures such as long culverts can present a challenge to fish exclusion operations. For example, it may be appropriate to place block nets at the ends of culverts. Once most or all of the fish have been removed from other parts of the work area, block nets may be removed to encourage volitional downstream movement of fish.

To be most effective and to minimize stress and risk of injury to fish (including stranding), in the Pacific Northwest, regulatory agency personnel coordinate fish exclusion operations with plans for dewatering or flow diversion. Plans for dewatering and/or flow diversion proceed at a measured pace (within constraints), to encourage the volitional downstream movement of fish, and reduce the risk of stranding. The directing biologist monitors the dewatering process to ensure that water is removed slowly to allow for fish capture and to preclude stranding. Dewatering or flow diversion should not proceed unless there are sufficient staff and materials on site to capture and safely remove fish in a timely manner. Generally this will require a minimum of two persons (three if electrofishing), but large or complicated sites may require higher levels of effort.

8.7.3 Cultural Resources

Because stream corridors have long attracted human use and activity, they are often rich in historical and archeologically significant resources. Assessing potential impacts on cultural resources and avoidance or mitigation should be similar to practices for any water resources project. Federal and state regulations govern these assessments.

GUIDANCE

Fish Capture for Exclusion

Seining–Most common method used. Large nets are swept across the bed by teams of people holding each end. Seines are pursed by drawing the ends together and then retained partially in the water while fish are removed with dip nets. Seines with a “bag” minimize handling stress and are preferred. Small mesh sizes are more effective across the full range of fish size (and age class), but also increase resistance and can make deployment/ retrieval more difficult in flowing waters. Seines with a small mesh size in the bag (or body) and a larger, less resistant mesh size in the wings offer a compromise.

Baited Minnow Traps—Typically used before seining. Traps should be inspected at least four times daily to remove captured fish and minimize predation within the trap. Predation risk to juvenile salmonids is greater at night from large sculpin.

Dip Netting—Commonly used in conjunction with seining; nets are particularly effective during gradual dewatering or flow diversion. Once netted, fish should remain in water until transferred to a bucket, cooler, or holding tank. Dip nets that retain a volume of water (“sanctuary nets”) are preferred method to transfer fish but may be ineffective unless flow velocity is low. When water depths are very shallow or fish are concentrated in very small receding pools or coarse substrate, “aquarium” nets may be a better, more effective choice. Use of dip nets in conjunction with snorkeling, flushing of the cover, or around the hours of dawn or dusk (i.e., during low-light conditions) can be effective for capturing fish sheltered below cover.

Connecting Rod Snakes—Connecting rod snakes are composed of wood sections approximately 1 meter (3.3 feet) in length. They may be used to flush fish out of stream crossing structures (i.e., culverts).

Electrofishing—Electrofishing or electroshocking is commonly performed only when other methods are impracticable or ineffective. In shallow (wadeable) water, electrofishing may be performed using hand crews and backpack-mounted equipment. In deeper water, boat-mounted electro-shock equipment is used, and boat crews remove fish with long-pole dip nets. Larger fish (i.e., adult and sub-adult fish with comparatively longer spine lengths) are more susceptible to electrofishing injury than smaller fish. As a general rule, electrofishing is not conducted under conditions that offer poor visibility (i.e., visibility of less than 0.5 meter) due to the potential for increased fish mortality.

Section 106 of the National Historic Preservation Act requires that federal agencies consult with state and local groups before non-renewable cultural resources, such as archaeological sites and historic structures, are affected. The Advisory Council on Historic Preservation (ACHP) is responsible for developing regulations to enforce Section 106 compliance (ACHP 2010). Basically, the law requires federal agencies to initiate a review of applicable actions, identify potential impacts on significant resources, and explore alternatives for avoiding or mitigating impacts. These alternatives include site preservation, monitoring, data recovery, and other actions. Approvals must be obtained from the State Historic Preservation Officer or native American tribe or ACHP, depending on resource details.

Archaeological sites may be directly affected by construction traffic and excavation or indirectly affected by soil compaction and erosion. Diversion of flows may erode banks containing artifacts, remains, or other resources. Routinely, a three-staged approach is followed to comply with Section 106:

1. Identification of the resources present in the project area through background research and a field survey.
2. If resources are present, evaluation of their significance.
3. Mitigation of impacts on the significant resources.

Mitigation means to alleviate any destructive impacts the project may have on the cultural resource. ACHP regulations describe mitigation as a consultative process that allows for leeway in the actual details. If the affected resource comprises standing structures, mitigation may consist in having them properly recorded to the Historic American Building Survey or Historic American Engineering Record standards (i.e., architectural drawings or large format photographs) or some other standard before moving or demolishing them. Mitigation for an archaeological site may involve long-term site protection, monitoring, or site excavation and data recovery.

It is important to note that these efforts are usually completed well before implementation, during the planning phase of the project. However, if significant cultural resources or any type of human remains are discovered during construction, federal and many state jurisdictions require immediate cessation of activities that affect the remains and notification of authorities.

8.7.4 Noise

Noise is any sound that has the potential to annoy or disturb humans, or cause an adverse psychological or physiological effect on humans. Sound becomes noise when it is too loud, unexpected, or perceived as uncontrollable. Most sounds that humans are capable of hearing have a decibel (dB) range of 0 to 140. A whisper is about 30 dB, conversational speech 60 dB, and 130 dB is the threshold of physical pain. Human exposure limits are based on duration, with 90 dB a typical upper limit for an 8-hour exposure. Construction activities involving heavy machinery generate noise that may adversely affect workers, nearby residents, or wildlife. Many states and federal agencies have promulgated guidelines and regulations for construction-related noise management. These policies and global guidance relevant to transportation construction projects are provided by the Federal Highway Administration (FHWA 2006).

Noise generation on most construction projects is the result of equipment operation, principally diesel engines. In assessing noise generation, construction equipment can be grouped into two categories, stationary and mobile. Equipment noise can also be categorized as being either continuous or impulse in nature. Stationary equipment is considered to operate in one location for one or more days at a time; pumps, generators, compressors, and screens are typical examples of stationary equipment. In addition, pile drivers are sometimes categorized as stationary equipment. Mobile equipment includes machinery that performs cyclic processes such as bulldozers, scrapers, loaders, and haul trucks. Newer equipment tends to be much quieter than older equipment due to design features to intentionally reduce noise. Noise mitigation measures include specifying the types of equipment that may be used, scheduling, limiting travel routes and work zones, and erecting noise barriers (FHWA 2006).

8.8 Maintenance and Adjustments

Ideally, instream and floodplain large wood projects create conditions that foster natural recruitment and retention of appropriate and desirable levels of large wood loading and channel dynamism, making them self-sustaining and maintenance-free over the long term. In reality, such ideal conditions rarely occur, and the effects of a large wood project will often be temporary without some level of adjustment, adaptive management, or maintenance. Wood that is alternatively wet and dry, especially in regions that are relatively warm and humid, decays rapidly (e.g., Shields et al. 2008).

> *CROSS-REFERENCE*
>
> Wood decay rates are discussed in Section 6.4, *Design Life of Placed Wood*, and in Chapter 3, *Ecological and Biological Considerations*, Chapter 4, *Geomorphic and Hydrologic Considerations*, Chapter 5, *Watershed-Scale and Long-Term Considerations,* and Chapter 7, *Risk Considerations*.

However, even in the Pacific Northwest wood becomes lighter and more brittle within 3 years of placement (e.g., Thorne et al. 2014). Dry density of large wood in riparian zones of the North Carolina Coastal Plain was observed to decrease by 65% as it aged (Rheinhardt et al. 2012). Dynamic fluvial systems exhibit a complex pattern of erosion, deposition, and avulsion in response to large wood addition, particularly during periods of higher flows.

It is important to note that maintenance requirements for large wood projects should be assessed differently than for more orthodox river works. Displacement of large wood, trapping additional wood and sediment, unanticipated scour, or even avulsion may not necessitate remediation and may, in fact, indicate that the large wood is functioning as intended by restoring natural fluvial and biotic processes. Maintenance needs should be assessed based on the functional performance of the large wood, not its appearance. Some features noted on inspection (e.g., loss of wood or ballast) may legitimately motivate maintenance even though the large wood remains functional because they indicate trends that will lead to project failure if not addressed (Thorne et al. 2014).

8.8.1 Three Types of Maintenance

Guidance for river restoration project planning and design identifies three types of maintenance (FISRWG 1998).

- Remedial maintenance is triggered by results of routine inspection. Inspections should identify and prioritize maintenance needs that are not emergencies but that are unlikely to be addressed through maintenance actions that are already planned or routine.
- Scheduled maintenance refers to activities that are planned during project planning or design and for which funds are budgeted. Scheduled maintenance is typically rare for large wood addition projects, but can include (for example) replenishment of smaller (“racked”) wood; control of exotic

vegetation; planting cuttings of pioneer species on recent sediment deposits; and reconfiguring wood, stone, or sediment to redirect impinging flows.

- Emergency maintenance requires immediate mobilization to repair, limit, or prevent damage. It may include measures such as replacement of plants that fail to establish, or repair or replacement of wood intended to provide bank protection or channel stabilization. Sources of funding, labor, and materials for emergency maintenance should be identified prior to project implementation as part of the contingency planning process. Plans should include a strategy for allowing rapid response to any emergency. Plans also should include a process for obtaining required permits, access routes for emergency construction, and coordination with agencies and utilities that are responsible for riparian roads, transmission lines, and utility crossings.

8.8.2 Maintenance Activities

Typical maintenance activities include removing or replacing large wood in constructed groupings or structures to maintain structural stability and habitat benefits or to avoid undesirable local scour of banks or bed. Natural large wood formations often experience cyclical replenishment of wood from upstream sources so that the appearance of the jam seems more or less static even as most individual members change. It may be necessary to adjust the frequency or volume of supplemental upstream wood inputs to achieve similar effects in regulated systems.

Restraining elements such as pilings, anchors, or ballast should be carefully inspected and replaced or adjusted as needed. Cables can become safety hazards and warrant special attention in reaches subject to recreational use. Some project plans call for periodic tightening of anchoring hardware such as cables to maintain tension as wood decays and shrinks.

Vegetative components often require intensive maintenance over the short- to intermediate term to replace dead plantings, provide irrigation during dry seasons, and combat damage due to herbivory or vandalism as noted in Section 8.5.6.2, *Revegetation*.

8.8.3 Adjustments Based on Monitoring and Adaptive Management

CROSS-REFERENCE

Detailed guidance for preparing large wood project monitoring and adaptive management plans is provided in Chapter 9, *Assessing Ecological Performance*.

Once environmental documentation is approved, permits are received, and construction is completed, the monitoring and adaptive management phase of the project begins. Although completion of the environmental documentation and permitting process may introduce new requirements that require modification of the monitoring and adaptive management plan, by this stage in the project, all of the key elements of the plan should be approved and in place. The monitoring and adaptive management plan will have clear criteria stating which elements will be monitored, the frequency of monitoring, and whether performance standards have been met.

Use of balloons (Russell and Holburn 2009) or drones to obtain images that may be analyzed using photogrammetric techniques may be efficient for physical monitoring. Additional guidance pertaining especially to projects in remote locations is provided by Davis et al. (2001). An example of a thorough post-project appraisal is provided by Thorne et al. (2014).

As the monitoring is implemented and reports are written, the stakeholders will use the approved adaptive management plan to determine any remedial work that must be performed. The transfer of "bottom line" type summaries from monitoring to those responsible for maintenance and adaptive management is a key link. Adaptive management actions should be based on monitoring information. Monitoring may also lead to modification of maintenance plans and schedules. Few large wood projects will trigger natural processes and plant succession rapidly enough to eliminate all maintenance requirements. The length of monitoring and adaptive management will vary between projects based on budget constraints, but the longer the monitoring periods, the greater the probability the project will achieve its objectives.

8.9 Acknowledgments

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8.10 Uncertainties and Research Needs

1. Development of approaches for inducing formation of large wood accumulations rather than constructing them.
2. Enhanced techniques for rapid revegetation of riparian zones and floodplains.
3. Equitable distribution of risk among project designers, constructors, sponsors, and other stakeholders.
4. Improved techniques for rapidly and economically driving or inserting piles in streambeds and banks.
5. Guidance for using drones and webcams to monitor implementation.
6. Development of general principles ("rules of thumb") for deciding what proportion of project resources should be reserved for adaptive management activities.

8.11 Key Points

1. Even the best planning and design can be entirely negated by shoddy construction work.
2. A variety of contractual arrangements are available for procuring implementation services. See descriptions applicable to federal agencies in Appendix A-1. Because construction contracts often result in litigation and distribution of risk varies with the type of contract, personnel involved in implementation should seek legal counsel and review of contracting arrangements.
3. Maintaining a daily log is an important part of implementation project management. The log should include photos from fixed points and notes regarding materials, equipment, personnel, and conversations with contractors.
4. A wood sourcing plan should be developed during project design to allow adequate lead time.

5. Water management is a key issue in implementation. Available approaches may be categorized as working in the dry conditions, working in wet but controlled conditions, and working in uncontrolled wet conditions. Working in the dry requires dewatering or diversion.
6. Substantial regional variations exist in requirements for mitigating project impacts on water quality (turbidity), aquatic habitat, and fish or other organisms. Temporary crossing structures are sometimes used to reduce heavy equipment impacts on streambeds.
7. Key construction steps include excavation, wood placement, and securing wood. Risks may be reduced by careful selection of appropriate equipment and methods for each step.
8. Large wood projects are complex from a safety management standpoint because they combine potential hazards incurred by logging, construction, amphibious operations, and non-ideal weather conditions. It is advisable to require Job Hazard Analyses for each phase of work and a site-specific safety plan.
9. The effects of a large wood project will often be temporary without some level of adjustment, adaptive management, or maintenance.

8.12 References

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Advisory Council on Historic Preservation (ACHP). 2010. *Protecting Historic Properties: A Citizen's Guide to Section 106 Review*. Advisory Council on Historic Preservation. Washington, D.C.

Bocchiola, D., M. C. Rulli, and R. Rosso. 2006. Transport of Large Woody Debris in the Presence of Obstacles. *Geomorphology* 76(1):166–178.

Braudrick, C. A., and G. E. Grant. 2000. When do Logs Move in Rivers? *Water Resources Research* 36(2):571–583.

Brown, S. A. and E. S. Clyde. 1989. Design of Riprap Revetment. Hydraulic Engineering Circular 11, Publication No. FHWA-IP-89-016, Federal Highway Administration, US Department of Transportation, Washington, DC.

Cramer, M. L. (ed.). 2012. *Stream Habitat Restoration Guidelines*. Copublished by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service. Olympia, WA.

Davis, J. C., G. Minshall, W. Robinson, T. Christopher, and P. Landres. 2001. *Monitoring Wilderness Stream Ecosystems.* Gen. Tech. Rep. RMRS-GTR-70. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Escarameia, M. (1998). *River and Channel Revetments: A Design Manual*. London: Thomas Telford.

Federal Highway Administration (FHWA). 2006. *Construction Noise Handbook*. Report numbers FHWA-HEP-06-015, DOT-VNTSC-FHWA-06-02, NTIS No. PB2006-109102. U.S. Department of

Transportation, Research and Innovative Technology Administration, Cambridge, MA. Available: http://www.fhwa.dot.gov/environment/noise/construction_noise/handbook/. Accessed: July 10, 2014.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Restoration Implementation, Monitoring, and Management. Chapter 9 in *Stream Corridor Restoration: Principles, Processes and Practices*. National Technical Information Service, U. S. Department of Commerce, Springfield, VA. Also published as NRCS, U.S. Department of Agriculture (1998) *National Engineering Handbook* (NEH), Part 653. Washington, D.C.

Fifield, J. S. 2011. *Designing and Reviewing Effective Sediment and Erosion Control Plans*. Third Edition, Santa Barbara, CA: Forester Press.

Fischenich, J. C. 2001. *Plant Material Selection and Acquisition.* EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-33), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Goldsmith, W., D. H. Gray, and J. McCullah. 2014. *Bioengineering Case Studies*. New York Springer.

Greer, E. S., S. R. Pezeshki, and F. D. Shields, Jr. 2006. Root Elongation of Black Willow Stakes in Response to Cutting Size and Soil Moisture Regime (Tennessee). *Ecological Restoration* 24(3):195–197.

Idaho Office of the Administrative Rules Coordinator. Undated. *Idaho Minimum Standards for Logging—Sections 17.08.01 through 17.08.16*. Available: http://adminrules.idaho.gov/rules/current/17/index.html. Accessed: July 10, 2014. Industrial Commission. Idaho Office of the Administrative Rules Coordinator, Boise, Idaho.

Li, S., L. T. Martin, S. R. Pezeshki, and F. D. Shields Jr. 2005. Responses of Black Willow (*Salix nigra*) Cuttings to Herbivory and Flooding. *Acta Oecologica* 28(2):173–180.

Martin, L. T., S. R. Pezeshki, and F. D. Shields Jr. 2004. High Oxygen Level in a Soaking Treatment Improves Early Root and Shoot Development of Black Willow Cuttings. *The Scientific World Journal* 4:899–907.

McMillan, LLC. 2014. *Fourth of July Creek Stream Restoration Draft Design Report*. Prepared for Pend Oreille County Public Utility District. February 14, 2014.

MTZ Associates. 2000. *River Corridor Recreation Safety Study: Sacramento River Bank Protection Project.* Prepared for the U.S. Army Corps of Engineers, Contract 42E, Sacramento, CA.

National Institute for Occupational Safety and Health. 2012. *Logging Safety.* Centers for Disease Control and Prevention. Atlanta, GA. Available: http://www.cdc.gov/niosh/topics/logging/. Accessed: July 10, 2014.

National Resources Conservation Service (NRCS). 2007c. Chapter 15—Project Implementation. In Part 654, *Stream Restoration Design National Engineering Handbook*. U.S. Department of Agriculture, Washington, D.C.

National Resources Conservation Service (NRCS). 2007d. Technical Supplement 14I—Streambank Soil Bioengineering. In Part 654, *Stream Restoration Design National Engineering Handbook*. U.S. Department of Agriculture, Washington, D.C.

Nichols, R. A. and S. G. Sprague. 2003. The Use of Long-Line Cabled Logs for stream Bank Rehabilitation. Pages 422–442 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press: Seattle.

Occupational Safety and Health Administration (OSHA). Undated a. *Logging eTool*. Occupational Safety and Health Administration. Washington, D.C. Available: https://www.osha.gov/SLTC/etools/logging/index.html. Accessed: July 10, 2014.

Occupational Safety and Health Administration (OSHA). Undated b. *Trenching and Excavation Safety*. Fact Sheet. Occupational Safety and Health Administration. Washington, D.C. Available: https://www.osha.gov/SLTC/trenchingexcavation/construction.html. Accessed: July 10, 2014.

Rheinhardt, R., M. Brinson, G. Meyer, and K. Miller. 2012. Integrating Forest Biomass and Distance from Channel to Develop an Indicator of Riparian Condition. *Ecological Indicators* 23:46–55.

Riley, A. L. 1998. *Restoring Streams in Cities: A Guide for Planners, Policymakers, and Citizens*. Washington, D.C. Island Press.

Roadway Safety Alliance. Undated. *Internal Traffic Control Plans*. Developed under a contract with the Centers for Disease Control and Prevention contract No. 212-2003-M-02677, Laborers' Health and Safety Fund of North America, Washington, D.C.

Russell, K., and E. Holburn. 2009. Field Evaluation of Engineered Large Woody Debris for Structure Performance and Habitat Value. Pages 3234–3243 in *World Environmental and Water Resources Congress 2009.* American Society of Civil Engineers.

Schaff, S. D., S. R. Pezeshki, and F. D. Shields Jr. 2002.The Effect of Pre-Planting Soaking on Growth and Survival of Black Willow (*Salix nigra*) Cuttings. *Restoration Ecology* 10(2):267–274.

Scottish Environment Protection Agency. 2009. *Engineering in Water Environment Good Practice Guide: Temporary Construction Methods.* First edition.

Shields, F. D., Jr., N. Morin, and C. M. Cooper. 2004. Large Woody Debris Structures for Sand-Bed Channels. *Journal of Hydraulic Engineering* 130(3):208–217.

Shields, F. D., Jr., S. R. Pezeshki, G. V. Wilson, W. Wu, and S. M. Dabney. 2008. Rehabilitation of an Incised Stream with Plant Materials: The Dominance of Geomorphic Processes. *Ecology and Society* 13 (2):54. Available: http://www.ecologyandsociety.org/vol13/iss2/art54/.

Southerland, B. S., and F. Reckendorf. 2010. Performance of Engineered Log Jams in Washington State—Post Project Appraisal. In *Joint Federal Interagency Conferences 2010: Book of Abstracts*, 446 pp., ISBN 097790027X, Joint Fed. Interagency Conf., 2010, Conference on Sedimentation and Hydrologic Modeling, June 27–July 1, Las Vegas, Nev., Government Printing Office, Washington, D. C.

Southwide Safety Committee. 2010. *Timber Harvesting Safety Manual*. Rockville, MD. National Timber Harvesting and Transportation Safety Foundation. Available: http://loggingsafety.com/content/timber-harvesting-safety-manual. Accessed: July 10, 2014.

Thorne, C., J. Townsend, and T. Ashley. 2014. *Geomorphic and Ecological Assessment and Evaluation of Grade Building Structures on the SRS Sediment Plain, North Fork Toutle River Final Report*. Performed for the U.S. Army Corps of Engineers, Portland District, OR.

U. S. Army Corps of Engineers. 1994. *Engineering and Design: Hydraulic Design of Flood Control Channels.* EM 1110-2-1601. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U.S. Army Corps of Engineers. 2008. *Safety and Health Requirements*. Engineer Manual 385-1-1. U.S. Army Corps of Engineers Headquarters, Washington, D.C.

Washington Department of Transportation. 2012. *WSDOT Fish Exclusion Protocols and Standards*. Available: http://www.wsdot.wa.gov/Environment/Biology/BA/BAtemplates.htm>. Washington DOT, Olympia.

Washington State Legislature. Undated. *Safety Standards—Logging Operations*. Chapter 296-54 WAC. Available: http://apps.leg.wa.gov/WAC/default.aspx?cite=296-54. Accessed: July 10, 2014. Washington State Legislature. Olympia, Washington.

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Chapter 9

ASSESSING ECOLOGICAL PERFORMANCE

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9.1 Introduction

The bulk of evidence presented in the previous chapters supports the notion that the addition of large wood and large wood structures in streams, as a restoration action, can enhance ecological functions, and generally results in greater abundance and/or biomass of fish and other aquatic species. However, a considerable amount of uncertainty remains associated with the use of large wood for restoring function in aquatic ecosystems.

> *CROSS-REFERENCE*
>
> See the *Uncertainties and Research Needs* sections of Chapters 3, *Ecological and Biological Considerations*, 4, *Geomorphology and Hydrology Considerations*, 5, *Watershed-Scale and Long-Term Considerations*, 6, *Engineering Considerations*, 7, *Risk Considerations*, and 8, *Regulatory Compliance, Public Involvement, and Implementation*, for detailed lists of uncertainties that remain for each area of concern.

The observed response of aquatic ecosystems to wood enhancement can reflect a suite of watershed-level conditions that can obscure the effects of site-specific wood restoration. Engineering solutions that do not account for species habitat needs, stream dynamics, disturbance regimes, and watershed characteristics are often unsuccessful (Beschta 1997). Nagayama and Nakamura (2010) found ample examples of restoration projects that failed, concluding that, "restoration projects should be aimed at restoring natural processes of wood recruitment and routing, which can
It is alarming, however, to note the rate at which evaluation approaches are left out of restoration projects. For 42% of 50 European large wood projects reviewed, no monitoring occurred (Kail et al. 2007). Those results were similar to the findings of Bash & Ryan (2002), who reported the lack of evaluation of 47% of restoration projects in the state of Washington. Most notable, however, were the findings by

provide fish and other organisms with sustainable wood habitats at the watershed scale over the long term." In other words, large wood enhancement should be viewed as an interim restoration measure until natural processes of wood recruitment recover to natural levels. Within this context, assessing the value of placing wood in a stream channel at a specific site while determining the performance of restoration actions at reestablishing natural ecosystem processes and functions will likely require different assessment perspectives.

As highlighted in the previous chapters, ecosystems are highly variable and have inherent uncertainties. As such, resource managers often need to accept the reality of uncertainty and address it through a structured evaluation process (e.g., adaptive management), while minimizing management risks associated with proposed activities (Keith et al. 2011). In other words, while measures can be put in place that help to reduce the uncertainty of management decisions, uncertainty and its associated risks will always be a component of ecological systems and restoration actions. Successful resource managers must be both flexible, to accommodate uncertainty in future events, and be able to respond to scientific paradigm shifts associated with new information. In this light, each large wood placement project should be viewed, to some degree, as experimental, with a minimum level of scientific effort dedicated to addressing uncertainties. That is, large wood placements that produce some ecological benefits but do not provide some level of learning for future efforts are not successful overall.

Bernhardt et al. (2005), who reported that only
It is alarming, however, to note the rate at which evaluation approaches are left out of restoration projects. For 42% of 50 European large wood projects reviewed, no monitoring occurred (Kail et al. 2007). Those results were similar to the findings of Bash & Ryan (2002), who reported the lack of evaluation of 47% of restoration projects in the state of Washington. Most

notable, however, were the findings by Bernhardt et al. (2005), who reported that only 10% of more than 37,000 projects evaluated incorporated any form of project monitoring, and little if any of this information was either appropriate or available for assessing the ecological effectiveness of restoration activities.

This chapter emphasizes the use of carefully designed approaches and/or experiments that address key uncertainties associated with large wood restoration actions, monitoring the effects of the restoration actions, and subsequently directing necessary adjustments. It provides the foundation for a discussion of monitoring and research activities necessary to answer questions associated with the placement of large wood in streams and provides practitioners with information needed to help guide them to make informed resource management decisions. The information includes:

1. Best Science Practices
2. Measurable Outcomes and Performance Indicators
3. Monitoring Approaches
4. Research Approaches
5. Decision Making and Choices

9.2 Incorporating Best Science Practices

Science plays an increasingly important role in contributing to how people perceive and respond to restoration of ecosystem processes. The current understanding of ecosystem processes is quite different from that of a few decades ago. Additionally, constant changes in population growth, land subsidence, catastrophic events, and climate change ensure that the future will be very different from today. As such, incorporating best science practices is an ever-changing and critical component of any restoration project.

9.2.1 Using Best Available Knowledge

Several federal and state mandates or directives offer insights to the application of best available science. A number of authors have addressed this issue (Doremus 2004; Murphy and Weiland 2010). For example, Murphy and Weiland (2010) reviewed the incorporation of best available science into the ESA compliance process. They noted that the ESA, along with the Marine Mammal Protection Act and the Magnuson-Stevens Fishery Conservation and Management Act, require federal agencies implementing actions to use the best available scientific and commercial data when making decisions. Under ESA, USFWS and NMFS must follow the best available scientific data mandate when making listing decisions, designating critical habitat, and completing the consultation process on proposed federal actions. USFWS and NMFS have not issued regulations that interpret the requirement to use the best scientific and commercial data available. However, they issued a policy statement on information standards under the ESA in 1994.

Two additional federal statutes provide guidance on the use of best available science. The Administrative Procedure Act of 1946 provides parties affected by final agency actions with a means to seek judicial review of those actions. In addition, it requires that a reviewing court set aside an agency action that is "arbitrary, capricious, an abuse of discretion, or otherwise not in accordance with law." Under the Information Quality Act of 2001, the Office of Management and Budget issued guidance to federal agencies to ensure the "quality, objectivity, utility, and integrity" of information disseminated by those agencies to the public. Additionally, the standards in these statutes emphasize the importance of transparent decision making to allow affected individuals and reviewing courts to determine that federal agencies have considered the full record before them and have made agency determinations based upon the data, analyses, and findings in that record.

While evaluating the use of large wood in 50 restoration projects, researchers came to similar conclusions (Kail et al. 2007). They emphasized: (1) that it is not possible to predict precisely the effect of restoration measures (Kail et al. 2007; Kondolf 1998), and, therefore, information from surrogate metrics such as monitoring stream morphology and biota should be used to obtain information to help make corrections (Bryant 1995; Kail et al. 2007); and (2) monitoring results may provide valuable information for the improvement of future project designs (Bryant 1995; Kondolf 1995, 1996, 1998; Bash and Ryan 2002; Downs and Kondolf 2002; Bisson et al. 2003; Reich et al. 2003; Kail et al. 2007). To this end, restoration projects can be successful in providing valuable information for the design of future projects, even if the projects fail to achieve some of the performance objectives (Kail et al. 2007: Kondolf 1995). It is also important to emphasize the importance of incorporating learning objectives into restoration projects in addition to performance objectives (Downs & Kondolf 2002; Kail et al. 2007).

9.2.2 Using Conceptual Models

Conceptual models describe our current understanding of a functioning ecosystem. They provide a framework for learning about a system and help formulate hypotheses about cause-and-effect relationships.

CROSS-REFERENCE

A detailed detailed discussion of the use of ecological models is included in Chapter 3, *Ecological and Biological Considerations.*

Conceptual models differ from quantitative models in that they do not posit any mathematical relationship between factors or processes. Instead, they illustrate a logic path that links ecosystem components to indicators of desired species and ecosystem conditions. They are useful for management because they can help identify which factors may be important in a system, which of these factors may be influenced by management, and hence which attribute (component or condition) of the system should be assessed.

Conceptual models can inform the research program in several important ways, by: providing a basis from which to test assumptions about the relative importance of certain processes, helping to identify threats or stressors, identifying species or other attributes that function as ecosystem indicators, and serving as a repository of our changing understanding of the system as more data become available. Conceptual models can also be used to communicate the understanding of the system to other scientists and the public and to facilitate review. For a multi-species, habitat-based conservation plan, these types of models provide a useful framework to help us understand how species react to management actions. These models must be complex enough to capture the relationships that drive the system and translate these relationships to covered species, but must be streamlined enough to be useful as management and monitoring tools.

As ecological conceptual models are refined with data from monitoring and research, the effects of conservation measures and associated management actions on ecological parameters (as identified in monitoring actions) can be more readily anticipated. The anticipated effects can ultimately be stated as hypotheses and tested with data from targeted studies and research. In this manner, effects can be systematically analyzed. From this approach we can increase our understanding of the system and potential effects of conservation measures.

GUIDANCE

Restoration actions, intended to offset the effects of anthropogenic activities, can affect species habitat through two major pathways:

1. Some habitat restoration approaches focus on restoring natural processes (e.g., road removal, riparian replanting) and thus affect ecosystem functions by influencing the underlying watershed processes (e.g., sediment supply, delivery of organic material).
2. Other techniques focus on manipulating or enhancing habitats for organisms at specific sites (e.g., wood placement for cover). Restoration actions should be at a scale commensurate with environmental problems. (Roni 2005)

9.2.3 Following Scientific Principles and Guidelines

Evaluation of restoration actions should be based on scientific principles that guide continual refinement of restoration efforts to effectively implement a restoration strategy. In this way, the adaptive management process is likely to lead to the development of alternative management strategies and ultimately the testing of the effectiveness of those strategies. Because of this, there is a continuum of management actions that incorporate scientific principles to varying degrees. The most basic monitoring involves simply assessing effects once a management action has occurred without any replication, controls, or comparison of management treatments. At the other end of the spectrum are directed studies that test a hypothesis in a manner that can be validated through statistical inference. Even simple experimental methods will yield important results to help guide and improve management.

In addition to these scientific guidelines, the following steps should precede experimental design.

1. **Define the question**. Research strategies should be designed to address specific hypotheses. Conceptual, statistical, or spatially explicit models will define those hypotheses.
2. **Determine what to measure.** Establish the attributes or variables that the research will measure to answer the question defined above.
3. **Develop data collection protocols**. Questions to be answered by the research program can be at the species, community, or landscape level. Research protocols will vary with scale and with the target of the question.
4. **Use indicator species, if appropriate**. In some cases groups of species or indicator species will streamline data collection. Indicators are selected because they are easy to survey and provide usable information on the species or system in question.
5. **Consider sampling design**. Sampling design needs to be a consideration prior to initiating the experiment. The experimental-management approach requires that questions of site selection, pseudo-replication, power, and significance be incorporated, as much as possible.

9.2.4 Existing Protocols and Indices

9.2.4.1 Protocols

When available, scientifically accepted monitoring protocols that are compatible with measuring the success of a restoration project should be adopted to facilitate data comparison with other studies. For example, in addition to others, the National Park Service's Inventory and Monitoring Program guidelines for monitoring protocols (Oakley et al. 2003) or the Bureau of Land Management's guidelines (Elzinga et al. 1998) can be used as references for developing research and monitoring protocols. To be successful, these protocols need to be appropriate to the task, implemented precisely, and as cost-effective as possible. Research and monitoring protocols should be standardized (implemented consistently) as much as possible across restoration projects. Ongoing training may be necessary to ensure there is consistency in protocol implementation.

GUIDANCE

- Monitoring and research activities should incorporate scientific principles of replication, control, and pre- and post-treatment monitoring when feasible.
- Monitoring and research actions should be linked to hypotheses about species' ecological relationships and responses to management actions, when possible.
- When feasible, research should include an experimental design with appropriate significance levels (alpha level) as well as sufficient power to detect effects (beta level).

Research and monitoring protocols can be at a landscape, community, or species scale. The level of detail of data collected will depend on the scale and also on the available opportunities for detecting monitored variables. For example, monitoring protocols will vary by covered species. For species that are difficult to detect in the project area, monitoring may be limited to determining whether the species persists from sample period to sample period, what features define its habitat, and what threats it faces. Surveys for species that are more readily detectible may indicate whether the species' occurrence locations are increasing or decreasing

9.2.4.2 Indices

The Index of Biotic Integrity (IBI) is an example of a well-known indexing procedure commonly used by academia, agencies, and resource managers to assess watershed condition. This index has been used throughout the United States and many countries internationally, and has proven to be a reliable means of assessing the effect of human disturbance on streams and watersheds. As such, it has application for assessing the ecological value of restoration activities.

IBI was first developed by Dr. James Karr to help resource managers' sample, evaluate, and describe the condition of small warm water streams in central Illinois and Indiana (Karr 1981). The original version had 12 metrics that reflected fish species' richness and composition, number and abundance of species, trophic organization and function, reproductive behavior, fish abundance, and condition of individual fish. In 1993, Karr developed a Benthic-Index of Biotic Integrity (B-IBI), modeled after the fish IBI. The B-IBI included 13 metrics based on benthic macroinvertebrate data collected from rivers in the Tennessee Valley (Kerans and Karr 1994).

The phrase "biological integrity" comes from the 1972 Clean Water Act, which established "restoration and maintenance of the chemical, physical, and biological integrity of the Nation's waters." Integrity implies an unimpaired condition or quality or state of being complete. "Biotic integrity" is based on the premise that the status of living organisms provides the most direct and effective measure of the "integrity of water." As such, IBI provides managers with a technique for evaluating the biological condition of the water resource management activities (Teels and Danielson 2001; Karr et al. 1986; Simon and Lyons. 1995).

9.3 Measurable Outcomes and Performance Indicators

A key component of a restoration action evaluation framework is defining measurable outcomes and associated performance metrics that are directly related to the project objectives.

Measurable outcomes can be predicted using quantitative models. Each outcome should have at least one associated performance indicator (e.g., Carignan and Villard 2002), a target for successful achievement of that outcome, a monitoring program designed to identify progress toward that target, and decision points for amending actions if acceptable progress is not being made. For the purposes of this manual, performance indicators are biotic and abiotic variables that are selected to facilitate monitoring of systems or species that are otherwise difficult to examine.

Ecological indicators can be used in many ways: to predict species richness (MacNally and Fleishman 2004), to estimate biodiversity (Kati et al. 2004), to assess levels of disturbance, or to provide targeted information on a system or species (Caro and O'Doherty 1999; Carignan and Villard 2004). In general, ecological indicators demonstrate changes or trends that are quantifiable. Indicators may include a variety of measures or a single indicator species. An indicator species is an organism whose characteristics are used as an index of attributes too difficult, inconvenient, or expensive to measure that relate to other species or environmental conditions of interest (Landres et al. 1988).

Ecological variables or structure-based characteristics, such as water inundation depth and duration are also used as indicators of performance Some examples of potential ecological indicators, in the riverine environment, include those discussed in the following sections.

9.3.1 Water Quality

Physiochemical water quality characteristics affect the ability of species to persist in a given lotic (flowing water) habitat. Water quality data are collected to determine the acid-base status, trophic condition (nutrient enrichment), and chemical stressors. Physical parameters include light penetration (e.g., turbidity, suspended solids), temperature, and ionic strength (e.g., conductivity). Chemical parameters include the concentrations of dissolved gases, major cations, anions, and nutrients (i.e., nitrogen, phosphorus).

GUIDANCE

Characteristics of Effective Performance Indicators

- Relevant to project goals and objectives and can be used to assess the project performance at the appropriate spatial and temporal levels.
- Sensitive to changes in the ecosystem, providing early warning of response to environmental or management impacts.
- Indicate the cause of change, not just the existence of change.
- Provide a continuum of responses to a range of stressors such that the indicator will not quickly reach a minimum or maximum threshold.
- Have known statistical properties, with baseline data, references, or benchmarks available.
- Are technically feasible, easily understood, and cost effective to measure by all personnel involved in the monitoring.
- Can be measured with an adequate level of precision and accuracy. (Carignan and Villard 2002).

Information from these analyses is used to evaluate a stream's condition with respect to stressors such as acidic deposition, nutrient enrichment, and other inorganic contaminants. In addition, streams can be classified with respect to water chemistry type, water clarity, mass balance budgets of constituents, temperature regime, and the presence of anoxic conditions. Examples of relationships between stream chemistry and watershed-level land use data are described in Herlihy et al. (1998).

9.3.2 Periphyton

Periphyton are algae, fungi, bacteria, protozoa, and organic matter associated with channel substrates. They are useful indicators of environmental conditions because they respond rapidly and are sensitive to a number of anthropogenic disturbances, including habitat degradation, and contamination by nutrients, metals, herbicides, hydrocarbons, and acidification (Banta et al. 2000).

Periphyton exhibit high diversity and are a major component in energy flow and nutrient cycling in aquatic ecosystems. Many characteristics of periphyton community structure and function can be used to develop indicators of ecological conditions in streams. Periphyton are sensitive to many environmental conditions, which can be detected by changes in species composition, cell density, ash free dry mass (AFDM), chlorophyll, and enzyme activity (e.g., alkaline and acid phosphatase). Each of these characteristics may be used, singly or in concert, to assess condition with respect to societal values such as biological integrity and trophic condition.

A hierarchical framework can be used in the development of the periphyton indices of stream condition. The framework involves the calculation of composite indices for biotic integrity, ecological sustainability, and trophic condition. The composite indices will be calculated from measured or derived first-order and second-order indices. The first-order indices include species composition (richness, diversity), cell density, AFDM, chlorophyll, and enzyme activity, which individually are indicators of ecological condition in streams. Second-order indices will be calculated from periphyton characteristics, such as the autotrophic index (Lakowicz and Weber 1973), community similarity compared to reference sites, and autecological indices (e.g., Lowe 1974; Lange-Bertalot 1979; Dixit et al. 1992). Banta et al. (2000) describe the development of a multimetric index based on periphyton assemblages in wadable streams.

9.3.3 Aquatic Macroinvertebrates

Aquatic macroinvertebrates play important functional roles in lotic ecosystems and are good indicators of stream quality. Aquatic macroinvertebrates represent a fundamental link in the food web between organic matter resources (e.g., leaf litter, periphyton, detritus) and fishes. Within specific biogeographical regions, aquatic macroinvertebrate assemblages respond in predictable ways to changes in stream environmental variables. Because many aquatic macroinvertebrates have limited migration patterns or a sessile mode of life, they are particularly well suited for assessing site-specific effects.

Benthic macroinvertebrates inhabit the sediment or live on the bottom substrates of streams. Macroinvertebrate assemblages in streams reflect the overall biological integrity of the benthic community, and monitoring these assemblages is useful in assessing the status of the water body and discerning trends. Benthic communities respond differently to a wide array of stressors. As a result of this, it is often possible to determine the type of stress that has affected a benthic macroinvertebrate community (Barbour et al. 1999; Kerans and Karr 1994). Additionally, macroinvertebrate community structure can sometimes be used as an indicator of past conditions.

There are generally two different approaches being used for developing ecological indicators based on benthic invertebrate assemblages. The first is a multimetric approach, where different structural and functional attributes of the assemblage are characterized as "metrics." Individual metrics that respond to different types of stressors are scored against expectations under conditions of minimal human disturbance. The individual metric scores are then summed into an overall index value that is used to judge the overall level of impairment of an individual stream reach. Examples of multimetric indices based on benthic invertebrate assemblages include Fore et al. (1996), Barbour et al. (1996), and Resh et al. (1995).

The second approach is to develop indicators of conditions based on multivariate analysis of benthic assemblages and associated abiotic variables. Examples of this type of approach as applied to benthic invertebrate assemblages include the IBI discussed above (Kerans and Karr 1994), the River Invertebrate Prediction and Classification System (RIVPACS; Wright 1995), and the Benthic Assessment of Sediment (BEAST; Reynoldson et al. 1995). Rosenberg and Resh (1993) present several approaches to biological monitoring using benthic invertebrates, and Norris (1995) briefly summarizes approaches to analyzing benthic macroinvertebrate community data.

9.3.4 Fish and Aquatic Vertebrate Assemblage

Fish and other aquatic vertebrates can indicate stream and riparian quality. Extensive life history information is available for many species, and because many are high order consumers, they often reflect the responses of the entire trophic structure to environmental stress. Also, fish provide a more publicly understandable indicator of environmental degradation. Fish generally have long life histories and integrate pollution effects over longer time periods and large spatial scales.

The fish assemblage represents a critical component of biological integrity from both an ecosystem function and a public interest perspective. Historically, fish assemblages have been used for biological monitoring in streams more often than in lakes (e.g., Karr and Kerans 1991). Fish assemblages can serve as good indicators of ecological conditions because they are long-lived and mobile, forage at different trophic levels, integrate effects of lower trophic levels, and reasonably easy to identify.

Amphibians also comprise a substantial portion of vertebrate biomass in streams throughout the United States (Hairston 1987; Bury and Corn 1991). Reports of dramatic declines in amphibian biodiversity (e.g., Blaustein and Wake 1990) have increased the level of interest in monitoring these assemblages. Amphibians may also provide more information about ecosystem conditions in headwater or intermittent streams in certain areas of the country than other biological response indicators (Hughes 1993).

Overall, field sampling is used to collect a representative sample of the aquatic vertebrate assemblage by methods designed to (1) collect all except very rare species in the assemblage and (2) provide a measure of the abundance of species in the assemblages (McCormick 1993).

9.4 Monitoring

Roni et al. (2003) emphasize the importance of monitoring activities associated with ecosystem restoration projects while providing excellent guidelines on developing and implementing monitoring programs. A well-designed monitoring plan includes well-developed testable hypotheses, data collection and data management to answer questions, and clear communication of the results and conclusions.

9.4.1 Compliance Monitoring

The purpose of compliance monitoring is to (1) track progress of project implementation in accordance with established timetables, and (2) ensure compliance with terms and conditions of the project permits. Compliance monitoring is required to ensure that avoidance and minimization measures are properly carried out where specific sensitive occurrences of covered species (e.g., an active nesting site for a covered bird species or a population of a highly restricted covered plant species) or other risks (e.g., sedimentation of a wetland) have been identified at or adjacent to a construction site.

GUIDANCE

Monitoring Types

Compliance Monitoring

Required by permits; focuses on whether the restoration activities are being implemented as designed.

Effectiveness Monitoring, including

- *Performance monitoring*. Identifies whether conservation measures are achieving the expected outcomes or targets.
- *Mechanistic monitoring*. Demonstrates whether the mechanisms thought to link a restoration action to the desired outcomes are working as predicted.
- *System-level monitoring*. Identifies the degree of the program's success relative to the desired outcome. This requires a sustained, long-term commitment to monitoring critical features of the system.

Long-Term Status and Trend Monitoring

Used to determine the status and trends of ecosystems, natural communities, and species.

9.4.2 Effectiveness Monitoring

Effectiveness monitoring assesses ecosystem-, natural community–, and covered species–scale responses to the implementation of restoration actions and monitors progress made toward achieving biological goals and objectives. Effectiveness monitoring will be closely coordinated with research actions to support adaptive management. Evaluating clearly discernible change in environmental conditions is often difficult, due to the multitude of interacting factors. For example, it is often not clear which environmental component will be affected by a stressor manipulation and what type of change will occur. A changing environment is natural, and variation due to natural effects may be great. To account for this, monitoring designs should be based on where and when effects are expected to occur (both spatially and temporally), what organisms are expected to be affected (fish, wildlife, plants, aquatic invertebrates, etc.), what the expected benefits are (magnitude, duration), potential mitigating factors (including distribution and exposure), and how various factors may alter exposure and effect.

It is anticipated that the extent to which effectiveness monitoring would occur can be reduced over time as causal relationships between the implementation of restoration actions and the responses of species and ecosystems to those measures are better understood (as a result of knowledge gained under the monitoring and research activities). For example, if relationships between the placement of a large wood structure and macro invertebrate production are established through monitoring and research on initially restored channels, then effectiveness monitoring for assessing the production of macro invertebrates associated with subsequent restoration of a stream channel may be reduced or no longer required. Effectiveness monitoring can also be spatially stratified and occur long enough to establish the effectiveness of the restoration activities in ecologically relevant portions of the planning area.

As described above, research and monitoring plans associated with specific restoration actions should be considered as part of the implementation process. These plans should be reviewed on a regular basis and adjustments made in response to new information and/or identified research needs. Plan implementation, monitoring, analysis, and research are all part of an overall adaptive management process. This is not intended to be a stand-alone process, but rather one that integrates information and learning to facilitate decision making, including decisions to adjust the design and implementation of restoration actions, and the type and extent of monitoring associated with those activities.

9.4.3 Long-Term Status and Trend Monitoring

Long-term monitoring is used to determine the status and trends of ecosystems, natural communities, and species. Long-term monitoring should use the framework developed during the baseline studies to carry out effectiveness monitoring and to implement adaptive management.

GUIDANCE

Tasks During Long-Term Monitoring

- Assess status and trends at the landscape and natural community levels.
- Monitor species response to enhancement, restoration, and habitat creation.
- Monitor restoration sites for success.

9.4.4 Collect, Analyze, Synthesize, and Evaluate Data

Collection, analysis, synthesis, and evaluation of project actions and follow up monitoring are crucial to improve our current understanding of the use of large wood. Analysis and synthesis should incorporate how conditions have changed, expectedly and unexpectedly, because of project actions. Evaluation should address whether the objectives have been met and why. In addition to ecological information, the right data can provide valuable information about non-ecological factors such as project costs and compliance, and efficiency

Proper data management, analysis, and reporting are critical to the success of an adaptive management program. All data and metadata related to monitoring methods, results, and analysis must be managed, stored, and made available to Implementation Office staff, decision-makers, scientific advisors, and other involved persons. A database and a clear reporting procedure is also required for permit compliance.

GUIDANCE

Issues to Consider During Data Analysis

- Availability of sites on which treatments can be applied.
- Availability of reference sites.
- The site-selection process (i.e., is it random, stratified random, non-random).
- Systematic versus opportunistic sampling.
- Detection probability of the protocol.
- Replication versus pseudo-replication (Hurlbert 1984).
- The clarity of hypotheses.
- Sufficient statistical power (1-≤≥) or significance level (≤≥).(Scheiner and Gurevitch 2001)

9.5 Research and Experimentation

Adjustments to natural resource management actions might entail more than minor corrective actions. This may require the need for a commitment, most often driven by quantitative models, for identifying and experimentally evaluating alternative hypotheses about responses to resource management actions (Briceño-Linares et al. 2011; Kingsford et al. 2011; Van Wilgen and Biggs 2011; Walters 2002).

Management programs associated with ecological restoration have an experimental component aimed at improving the performance of restoration actions (Keith et al. 2011). Well-defined experiments, supplemented by expert knowledge, are often applied to evaluate the assumptions underlying resource management strategies (Rumpff et al. 2011). Simple experimental designs can go a long way toward separating resource management action effects from other causes of ecological change (Mackenzie and Keith 2009). In some cases, low numbers, small areas, and urgent time frames place severe constraints on experimental design.

GUIDANCE

For species that are sufficiently detectable to obtain estimates of population size or probability of detection, monitoring a randomly selected subset of the population to make statistical inference to the whole population can be achieved through the principles listed below:

- Develop and state the assumptions in the hypotheses and models before collecting monitoring data or conducting manipulations such as experiments and adaptive management.
- When designing an experiment or using adaptive management, select the number and location of sampling units so as to apply sufficient scientific rigor for evaluating the hypothesis being advanced (although flexibility is needed because the number of units required to arrive at a statistically valid result may depend on the variability of the characteristic being measured).
- Use spatial and temporal survey site replicates for population estimates and/or those receiving a management action/treatment. Use controls when appropriate.
- Measure the sensitivity of variables to reflect true changes in the resource being sampled. When appropriate, adjust counts, measures of species richness, and determinations of patch occupancy (i.e., presence/absence) with an estimate of detection probability as described by Yoccoz et al. (2001) and Pollock et al. (2002).

In these situations, a succession of trial-and-error evaluations may offer the only practical insights into how to adjust management strategies (Briceño-Lenares et al. 2011). The design of targeted studies that address key uncertainties should be driven by hypotheses about key factors for the landscape, natural community, and/or species for which the restoration action is applied. Adaptive management actions and monitoring should be directed toward confirming or disproving those hypotheses. In this light, targeted studies should be conducted using an experimental design that will yield statistically valid results to address critical uncertainties (see Section 9.4, *Monitoring*).

9.5.1 Research

Research may be conducted to resolve specific questions related to the following.

- Key ecological processes.
- Technologies and methods for effectively implementing and measuring the outcome of conservation measures.
- Development of new and more sensitive indicators and metrics.
- Increasing understanding of the ecological requirements of covered species for effective implementation of conservation measures.
- Modeling and assessing responses of covered species to conservation measures.
- Determining causal relationships between ecological stressors and drivers and changes in natural communities and covered species.
- Identifying and evaluating trade-offs among restoration options.

Research results should be sufficient to help direct and prioritize subsequent implementation of restoration projects though the adaptive management process. Ideally, directed research can detect both false negatives and false positives, yielding statistically valid results. This type of research should answer specific restoration-related questions that arise from monitoring results and should address data gaps and provide information necessary to successfully implement restoration actions. The design of experimental research should be driven by hypotheses about key factors in the natural community in which management is applied. Management actions and monitoring should be directed towards confirming or disproving those hypotheses. For key management questions, directed research should be tested on a small scale using an experimental design that will yield statistically valid results.

9.5.2 Before-and-After Studies

Studies intended to evaluate restoration projects often have failed to include the collection of baseline data prior to the restoration (Anderson and Dugger 1998; Wissmar and Beschta 1998). Without pre-restoration data as a benchmark for comparison with post-restoration data, however, it is not possible to document what changes have occurred. Conclusions about achievement of the restoration project's goals, and the success or failure of the project, are enhanced by an ability to prove quantitatively and statistically that the restored system has changed. Change detection relative to a baseline condition is therefore an important aspect of restoration evaluation.

Baseline conditions need to be defined to serve as a comparison point for future monitoring actions. Accordingly, resources of interest that occur on a site need to be documented, mapped, and inventoried.

Before-and-after studies involve measurement of a variable prior to and following a perturbation both at a location that will be affected by the perturbation (impact) and in an area that will not be affected (control) (Stewart-Oaten et al. 1992). This approach is analogous to an experimental design in which some subjects receive a treatment and others do not, although true replication in the experimental sense may not be possible. One classic approach to analysis proposed by Stewart-Oaten et al. (1992) is to compare the mean difference between the control and impact area in the before period with the mean control-impact difference in the after period. A significant difference suggests that an effect of the perturbation has been detected.

GUIDANCE

Tasks for Documenting Baseline Conditions

- Inventory and document resources and improve mapping.
- Use the results of land acquisition assessments as the first source of baseline data.
- Standardize data-collection methodologies and nomenclature to facilitate information sharing.
- Conduct baseline surveys for plants in areas where covered activities may impact plant occurrences.
- Research and document historical data and trends, as appropriate.
- Use baseline data to validate and refine species-habitat models as lands are surveyed and acquired (species models will be updated annually as new, relevant information becomes available).
- Conduct post-acquisition biological inventories. Additional surveys will be needed to supplement data gathered in pre-acquisition assessments.
- Conduct post-construction surveys for covered plants in areas where covered activities may have impacted occurrences of covered plants.
- Use aerial photos and ground surveys, as needed, to assess quality and location of local and regional landscape linkages between unprotected natural areas and adjacent protected lands.
- Collect additional baseline data needed to refine conceptual models.

9.5.3 Pilot Projects

Pilot projects can be used to ascertain which management actions may ultimately yield the desired restoration gains prior to initiating a long-term project. Pilot projects are also a cost-effective way to test restoration actions that can and should be used during the early phases of project implementation to field-test different management actions. Pilot projects are designed to evaluate alternative monitoring protocols and sampling designs and to select the best technique for obtaining information. For example, if the objective is to quantify wildlife use of a corridor crossing, a pilot project may test the effectiveness of different tracking methodologies (i.e., comparisons between using tracking plates, bait stations, and trail cameras). The results of the projects would then be used to develop long-term monitoring protocols.

Different management techniques should be implemented and evaluated experimentally. In some cases, restoration, enhancement, and monitoring methods are not known or have not been successfully reproduced on a large scale by land managers or the scientific community. Before restoration or enhancement through management can occur successfully, these methodologies need to be tested on a smaller scale.

Pilot projects designed to test the effectiveness of restoration and enhancement can be long-term (i.e., 5- to 15-year) endeavors. They can inform long-term management and can be included as part of a long-term restoration program. Results from these types of projects can guide future restoration efforts. This feedback can increase the efficiency with which restoration projects can be managed and the overall success rate of the actions. Similar pilot projects can be developed as research studies when multiple techniques are intended to achieve a desired outcome and are appropriate for monitoring habitat function within a broader study area. Testing the use of indicators for ecosystem function or covered species; refining monitoring protocols; establishing control plots for long-term management; and reviewing the literature for guidance on sampling, experimental design, and management will all be a part of research.

Pilot projects may also be short-term experiments or observations that give information on long-term effects. For example, Opperman and Merenlander (2004) evaluated the effectiveness of methods to restore riparian vegetation along stream corridors. The study examined the long-term effects of grazing within the riparian corridor by comparing historically grazed stream reaches to ungrazed reaches. Although the study was short-term (<1 year), it provided information on long-term effects of grazing and led to recommendations on riparian corridor management.

9.6 Making Decisions and Choices

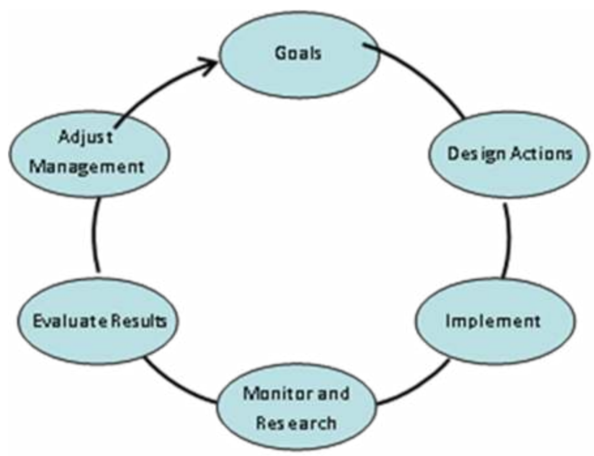
As described in Chapter 2, *Large Wood and the Fluvial Ecosystem Restoration Process*, this manual recommends that practitioners adopt a structured process to design, implement, and evaluate restoration projects. As such, practitioners should consider integrating adaptive management into their restoration projects. Adaptive management is systematic and designed to address uncertainty predicated on principles of experimental design. Adequate data are gathered and statistically analyzed to identify effective alterations to a restoration program or project. Even if quantitative data acquisition is limited, a record of qualitative observations can produce information valuable for advancing the state of the art.

Adaptive management is a structured approach to addressing uncertainty about the potential environmental and biological response to management actions. The process promotes flexible decision making that can be adjusted based on outcomes of management actions and changes in ecological processes (Holling 1978; Walters 2002). It requires well-articulated management objectives and explicit assumptions about expected outcomes to compare against actual outcomes (Williams et al. 2009). Importantly, adaptive management requires explicit recognition of uncertainties and how these may affect achievement of management goals. Also, applying adaptive management principles requires scientific rigor, including using models to develop hypotheses about potential resource responses to management actions, maintain flexibility in management, and committing to carry out monitoring and re-evaluating management goals over time. With these qualities, adaptive management programs can reduce uncertainty and associated management risks by improving our understanding through monitoring and researching the outcomes of restoration actions. The challenge in using an adaptive management approach lies in finding the correct balance between gaining knowledge to improve management in the future and achieving the best short-term outcome based on current knowledge (Allan and Stankey 2009).

One of the earliest applications of the adaptive management concept for use with natural resource decisions involved management of commercial fishing in 1957 (Beverton and Holt 1957). However, it took until the 1970s for the traditional concept and application of adaptive management as a natural resource management tool to be improved and evolve (Holling 1978; Walters 2002; Pahl-Wostl 1995; Lee 1999; Oglethorpe 2002). Since that time, it has been applied to a wide range of resource management approaches (Walters 2002; Christensen et al. 1996; Stanford and Poole 1996; Oglethorpe 2002; Habron 2003; Kaplan 2008; Lyons et al. 2008; Williams et al. 2009). Many of these involve water supply management and ecosystem restoration activities (Poff et al. 2003), such as the Glen Canyon Dam and the Colorado River ecosystem (National Research Council 1999); the Missouri River ecosystem (Prato 2003); USACE water resource project planning (National Research Council 2004); Columbia River system (Vail and Skaggs 2002; Volkman and McConnaha 1993); and the Everglades ecosystem (Gunderson and Light 2006). Lessons learned from these applications, as well as advances in other scientific disciplines, have greatly improved the utility and application of adaptive management to aquatic ecosystem restoration.

Adaptive management relies on existing information to develop and implement ecosystem restoration actions in such a manner that new information can be gained and utilized in the process. The process is designed to use new information to inform a systematic and integrated critical review at regular intervals. As restoration actions are implemented, the knowledge base is expanded, biological assumptions are revised, and changes may be made to the restoration project objectives and associated hypotheses, metrics, targets, and monitoring metrics (Figure 9-1).

Figure 9-1. Key Components of an Adaptive Management Framework



Modified from USFWS 2014.

Decision-makers should reexamine the steps of the adaptive management framework and make revisions when needed. This may include modifying the goals and objectives, modifying the metrics, applying new and modified analytical tools and models, modifying conservation measures, and implementing new or modified monitoring. As described above, the targets and criteria used to define a restoration project should reflect judgments based on the best available science. As the project is implemented, however, new information may indicate that some of these targets or criteria are less effective at producing desired outcomes. To allow for flexible and responsive implementation of the project, it is important that the plan identify decision points that establish the parameters that will be used to improve the effectiveness of the project, respond to changing biological conditions, and/or respond to social and economic directives.

Communicating the current understanding of the results of the restoration action is an important step for informing and equipping policy makers, managers, stakeholders, and the public. The information communicated should be technically sound, well synthesized, and translated into formats conducive to informing nontechnical audiences. If necessary, the communication should include any potential adjustments that need to be implemented, such as refining the objectives, models, and conservation measures, and potentially selecting an alternative action.

Fir an adaptive management plan to succeed, technical staff and decision-makers must be regularly involved in the exchange of information as data are analyzed and synthesized. The information should be provided to those directly involved in the adaptive management process as well as all those interested in the outcome. The communication should be ongoing and occur at appropriate decision points.

Guidance

Important Considerations

- Does the project meet the expected benefits?
- Is the project consistent with and contribute to fulfilling the restoration plan and objectives?
- Is the project compliant with federal and state law?
- Is the project being implemented within a reasonable timeframe?
- Do the restoration activities have clear, measurable, and achievable end points?
- Does the monitoring plan enable evaluation of the project's progress and ultimate success?
- Is the cost to carry out and monitor the project reasonable relative to benefits and available funds?
- Are the project's potential harmful effects on natural resources and ecological services deemed acceptable?
- Is the project resulting in a net benefit or improvement for the environment?
- Have any adverse impacts resulting from the project been fully mitigated by restoring, replacing, rehabilitating, or acquiring the equivalent of the same or similar resources harmed by the project?
- Has the project benefited multiple species or resources?
- Has the project contributed to an ecologically balanced and integrated approach to restoration?
- Has the project benefited any of the following economic sectors: tourism, fisheries, maritime, and recreation?
- Has the project built community resiliency and benefited communities vulnerable to disasters?
- Has the project addressed underlying sources of environmental stress and provided a long-term approach and/or solution to restoring natural processes rather than addressing the symptoms of environmental degradation through short-term fixes?
- Has the project provided long-term ecological benefits commensurate with the investment?
- Has the project enhanced resilience and adaptation of river and stream environments and species with respect to climate change impacts?
- Does the project represent a restoration approach for which the public has expressed support or would likely provide support based on previous public comment or input?
- Does the project contain a public education component such as onsite interpretation, signage. or some other means to inform the public about the project's importance and results.

9.7 References

Allan, C., and G. H. Stankey. 2009. *Adaptive Environmental Management*. Volume 351. Springer.

Anderson, D. H., and B. D. Dugger. 1998. A Conceptual Basis for Evaluating Restoration Success. *Transactions of the North American Wildlife and Natural Resources Conference* Volume 63. Wildlife Management Institute.

Banta, E. R., M. C. Hill, and M. G. McDonald. 2000. MODFLOW-2000, the US Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process. Reston, VA, USA: US Geological Survey.

Barbour, M. T., J. Gerritsen, G. E. Griffith, R. Frydenborg, E. McCarron, J. S. White, and M. L. Bastian. 1996. A Framework for Biological Criteria for Florida Streams Using Benthic Macroinvertebrates. *Journal of the North American Benthological Society* (1996):185–211. Available: http://www.jstor.org/discover/10.2307/1467948?uid=3739936&uid=2&uid=4&uid=3739256&sid=21104863995063.

Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. Rapid Bioassessment Protocols for use in Streams and Wadeable Rivers. USEPA, Washington. Available: http://zoology.okstate.edu/zoo_lrc/biol1114/study_guides/labs/lab12/gen_usepa_barbouretal_1999_rba.pdf.

Bash, J. S. and C. M. Ryan. 2002. Stream Restoration and Enhancement Projects: Is Anyone Monitoring? *Environmental Management* 29(6):877¬885.

Bernhardt, E. S., and 24 others. 2005. Synthesizing U.S. River Restoration Efforts. *Science*. 308(5722):636–637

Beschta, R. L. 1997. Restoration of Riparian and Aquatic Systems for Improved Aquatic Habitats in the Upper Columbia River Bbasin. Pages 475-491 in D. J. Stouder and P. A. Bisson (eds.). *Pacific Salmon and Their Ecosystems: Status and Future Options*. New York: Chapman Hall.

Beverton, R. J. H., and S. J. Holt. 1957. On the Dynamics of Exploited Fish Populations. Fisheries Investigation Series 2 (19). *Fisheries and Food.* London: Ministry of Agriculture.

Bisson, P. A., B. E. Rieman, C. Luce, P. F. Hessburg, D. C. Lee, J. L. Kershner, G. H. Reeves, and R. E. Gresswell. 2003. Fire and Aquatic Ecosystems of the Western USA: Current Knowledge and Key Questions. *Forest Ecology and Management* 178:213–229.

Blaustein, A. R., and D. B. Wake. 1990. Declining Amphibian Populations: A Global Phenomenon? *Trends in Ecology & Evolution* 5 (7):203–204.

Briceño-Linares, J. M., J. P. Rodríguez, K. M. Rodríguez-Clark, F. Rojas-Suárez, P. A. Millán, E. G. Vitton, and M. Carrasco-Muñoz. 2011. Adapting to changing poaching intensity of yellow-shouldered parrot (*Amazona barbadensis*) nestlings in Margarita Island, Venezuela. *Biological Conservation* 144 (4):1188–1193.

Bury, R. B., and P. S. Corn. 1991. *Sampling Methods for Amphibians in Streams in the Pacific Northwest.* Available: http://www.treesearch.fs.fed.us/pubs/3069.

Carignan, V., and M.-A. Villard. 2002. Selecting Indicator Species to Monitor Ecological Integrity: A Review. *Environmental Monitoring and Assessment* 78(1):45–61.

Carignan, V., and M. A. Villard. 2004. Biological Indicators in Environmental Monitoring Programs: Can We Increase Their Effectiveness. *Environmental Monitoring*:567–582.

Caro, T. Mi, and G. O'Doherty. 1999. On the Use of Surrogate Species in Conservation Biology. *Conservation Biology* 13(4):805–814.

Christensen, N. L., and 12 others. 1996. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications* 6(3):665–691.

Dixit, S. S., J. P. Smol, J. C. Kingston, and D. F. Charles. 1992. Diatoms: Powerful Indicators of Environmental Change. *Environmental Science & Technology* 26 (1):22–33.

Doremus, H. 2001. Adaptive Management, the Endangered Species Act, and the Institutional Challenges of “New Age” Environmental Protection. *Washburn Law Journal* 41:50–89.

Doremus, H. 2004. The Purposes, Effects, and Future of the Endangered Species Act's Best Available Science Mandate. *Environmental Law* 34:397.

Downs, P. W., and G. M. Kondolf. 2002. Post-project Appraisals in Adaptive Management of River Channel Restoration. *Environmental Management* 29(4):477–496.

Elzinga, C. L., D. W. Salzer, and J. W. Willoughby. 1998. Measuring & Monitoring Plant Populations. Denver, CO: Bureau of Land Management Technical Reference 1730-1.

Fore, L. S., J. R. Karr, and R. W. Wisseman. 1996. Assessing Invertebrate Responses to Human Activities: Evaluating Alternative Approaches. *Journal of the North American Benthological Society* 15(2):212–231.

Gunderson, L., and S. S. Light. 2006. Adaptive Management and Adaptive Governance in the Everglades Ecosystem. *Policy Sciences* 39(4):323–334.

Habron, G. 2003. Role of Adaptive Management for Watershed Councils. *Environmental Management* 31(1):0029–0041.

Hairston, N. G. 1987. *Community Ecology and Salamander Guilds*. Cambridge University Press, 1987

Herlihy, A. T., J. L. Stoddard, and C. Burch Johnson. 1998. The Relationship between Stream Chemistry and Watershed Land Cover Data in the Mid-Atlantic Region, U.S. Pages 377–386 in *Biogeochemical Investigations at Watershed, Landscape, and Regional Scales*. Springer Netherlands.

Holling, C. S. 1978. *Adaptive Environmental Assessment and Management*. Chichester, UK: Wiley Interscience.

Hudson, P. L., R. W. Griffiths, and T. J. Wheaton. 1992. Review of Habitat Classification Schemes Appropriate to Streams, Rivers, and Connecting Channels in the Great Lakes Drainage Basin. Pages 73–107 in W. D. N. Busch and P. G. Sly (eds.), *The Development of an Aquatic Habitat Classification System for Lakes.* Ann Arbor, MI: CRC Press.

Hughes, R. M. (ed.). 1993. *Stream Indicators and Design Workshop.* EPA/600/R-93/138. U.S. Environmental Protection Agency, Corvallis, OR.

Hurlbert, S. H. 1984. Pseudoreplication and the Design of Ecological Field Experiments. *Ecological Monographs* 54 (2:187–211.

Kail, J., D. Hering, S. Muhar, J. Gerhard, and S. Preis. 2007. The Use of Large Wood in Stream Restoration: Experiences from 50 Projects in Germany and Austria. *Journal of Applied Ecology* 44:1145–1155.

Kaplan, R. S. 2008. Conceptual Foundations of the Balanced Scorecard. *Handbook of Management Accounting Research* 3:1253–1269.

Karr, J. R. 1981. Assessment of Biotic Integrity Using Fish Communities. *Fisheries* 6(6):21–27.

Karr, J. R., and B. L. Kerans. 1991. *Components of Biological Integrity: Their Definition and Use in Development of an Invertebrate IBI*. Midwest Pollution Control Biologists Meeting, Chicago, Ill., 1991, Proceedings: US Environmental Protection Agency, Region V, EPA-905/R-92-003.

Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. *Assessing Biological Integrity in Running Waters: A Method and its Rationale.* Illinois Natural History Survey Special Publication 5, Urbana, IL.

Kati, V., P. Devillers, M. Dufrene, A. Legakis, D. Vokou, and P. Lebrun. 2004. Testing the Value of Six Taxonomic Groups as Biodiversity Indicators at a Local Scale. Conservation Biology 18(3):667–675.

Kaufmann, P. R., P. Levine, E. G. Robison, C. Seeliger, and D. V. Peck. 1999. *Quantifying Physical Habitat in Streams*. U.S. Environmental Protection Agency, Washington, D.C. Available: http://www.epa.gov/emap2/html/pubs/docs/groupdocs/surfwatr/field/phyhab.pdf.

Keith, D. A., T. G. Martin, E. McDonald-Madden, and C. Walters. 2011. Uncertainty and Adaptive Management for Biodiversity Conservation. *Biological Conservation* 144(4):1175–1178.

Kerans, B. L., and J. R. Karr. 1994. A Benthic Index of Biotic Integrity (B-IBI) for Rivers of the Tennessee Valley. *Ecological Applications*. 4(4):768–785.

Kingsford, R. T., K. F. Walker, R. E. Lester, W. J. Young, P. G. Fairweather, J. Sammut, and M. C. Geddes. 2011. A Ramsar Wetland in Crisis—The Coorong, Lower Lakes and Murray Mouth, Australia. *Marine and Freshwater Research* 62(3):255–265.

Kondolf, G. M. 1995. Five Elements for Effective Stream Restoration. *Restoration Ecology* 3:133–136.

Kondolf, G. M. 1996. A Cross Section of Stream Channel Restoration. *Journal of Soil and Water Conservation* 51(2):119–125.

Kondolf, G. M. 1998. Lessons Learned from River Restoration Projects in California. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8(1):39–52.

Lakowicz, J. R., and G. Weber. 1973. Quenching of Fluorescence by Oxygen. Probe for Structural Fluctuations in Macromolecules. *Biochemistry* 12(21): 4161–4170.

Landres, P. B., J. Verner, and J. W. Thomas. 1988. Ecological Uses of Vertebrate Indicator Species: A Critique. *Conservation Biology* 2(4):316–328.

Lange-Bertalot, H. 1979. Pollution Tolerance of Diatoms as a Criterion for Water Quality Estimation. *Nova Hedwigia, Beih.* 64:285–304.

Lee, K. N. 1999. Appraising Adaptive Management. *Conservation Ecology* 3(2):3.

Lowe, R. L. 1974. *Environmental Requirements and Pollution Tolerance of Freshwater Diatoms.* National Environmental Research Center, Office of Research and Development, U.S. Environmental Protection Agency.

Lyons, J. E., M. C. Runge, H. P. Laskowski, and W. L. Kendall. 2008. Monitoring in the Context of Structured Decision-Making and Adaptive Management. *The Journal of Wildlife Management* 72(8):1683–1692.

Mackenzie, B. D. E, and D. A. Keith. 2009. Adaptive Management in Practice: Conservation of a Threatened Plant Population. *Ecological Management & Restoration* 10(s1):S129–S135.

MacNally, R., and E, Fleishman. 2004. A Successful Predictive Model of Species Richness Based on Indicator Species. *Conservation Biology* 18(3):646–654.

McCormick, F. H. 1993. Fish Communities as Indicators of Stream Condition. In R. M. Hughes (ed.), *EMAP Streams Bioassessment Workshop.* Report of the Proceedings. EPA/600/R-93/138. U.S. Environmental Protection Agency, Corvallis, OR.

Murphy, D. D., and P. S. Weiland. 2010. The Route to Best Science in Implementation of the Endangered Species Act's Consultation Mandate: The Benefits of Structured Effects Analysis. *Environmental Management* 47(2):161–172.

Nagayama, S., and F. Nakamura. 2010. Fish Habitat Rehabilitation Using Wood in the World. *Landscape and Ecological Engineering* 6(2):289–305.

National Research Council (US). 1999. Committee on Health Risks of Exposure to Radon*. Health Effects of Exposure to Radon*. Vol. 6. National Academies Press.

National Research Council. 2004. *Adaptive Management for Water Resources Planning*, The National Academies Press. Washington, D.C.

Norris, R. H. 1995. Biological Monitoring: The Dilemma of Data Analysis." *Journal of the North American Benthological Society*:440–450.

Oakley, K. L., L. P. Thomas, and S. G. Fancy. 2003. Guidelines for Long-Term Monitoring Protocols. *Wildlife Society Bulletin* 31(4):1000–1003.

Oglethorpe, J. 2002. *Adaptive Management: From Theory to Practice*. The World Conservation Union (IUCN).

Opperman, J. J., and A. M. Merenlender. 2004. The Effectiveness of Riparian Restoration for Improving Instream Fish Habitat in Four Hardwood-Dominated California Streams. *North American Journal of Fisheries Management* 24(3):822–834.

Pahl-Wostl, C. 1995. The Dynamic Nature of Ecosystems: Chaos and Order Entwined. Chichester: Wiley.

Pastorok, R. A., A. MacDonald, J. R. Sampson, P. Wilber, D. J Yozzo, and J. P Titre. 1997. An Ecological Decision Framework for Environmental Restoration Projects. *Ecological Engineering* 9 (1–2):89–107.

Poff, N. L., J. D. Allan, M. A. Palmer, D. D. Hart, B. D. Richter, A. H. Arthington, K. H. Rogers, J. L. Meyer, and J. A. Stanford. 2003. River Flows and Water Wars: Emerging Science for Environmental Decision Making. *Frontiers in Ecology and the Environment* 1:298–306.

Pollock, K. H., J. D. Nichols, T. R. Simons, G. L. Farnsworth, L. L. Bailey, and J. R. Sauer. 2002. Large Scale Wildlife Monitoring Studies: Statistical Methods for Design and Analysis. *Environmetrics* 13:105–119.

Prato, T. 2003. Adaptive Management of Large Rivers with Special Reference to the Missouri River. *Journal of the American Water Resources Association* 39(4):935–946.

Reich, P. B., I. Wright, J. Cavender-Bares, J. Craine, J. Oleksyn, M. Westoby, and M. B. Walters. 2003. The Evolution of Plant Functional Variation: Traits, Spectra, and Strategies. *International Journal of Plant Sciences* 164:s143–s164.

Resh, V. H., R. H. Norris, and M. T. Barbour. 1995. Design and Implementation of Rapid Assessment Approaches for Water Resource Monitoring Using Benthic Macroinvertebrates. *Australian Journal of Ecology* 20(1):108–121.

Reynoldson, T. B., R. C. Bailey, K. E. Day, and R. J. Norris. 1995. Biological Guidelines for Freshwater Sediment Based on BEnthic Assessment of SedimenT (the BEAST) Using a Multivariate Approach for Predicting Biological State. *Australian Journal of Ecology* 20(1):198–219.

Roni, P. (ed.). 2005. *Monitoring Stream and Watershed Restoration*. American Fisheries Society, Bethesda, MD.

Roni, P., M. Liermann, and A. Steel. 2003. Monitoring and Evaluating Fish Response to Instream Restoration. In D. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies. University of Washington Press: Seattle.

Rosenberg, D. M., and V. H. Resh (eds.). 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrate*s. Springer.

Rumpff, L., Duncan, D. H., P. A. Vesk, D. A. Keith, and B. A. Wintle. 2011. State-and-Transition Modelling for Adaptive Management of Native Woodlands. *Biological Conservation* 144(4):1224–1236.

Scheiner S. M., and J. Gurevitch (eds.). 2001. *Design and Analysis of Ecological Experiments.* Oxford University Press.

Simon, T.P., and J. Lyons. 1995. Application of the Index of Biotic Integrity to Evaluate Water Resource Integrity in Freshwater Ecosystems. Chapter 16 in W. S. Davis and T. P. Simon. *Bioassessment and Criteria: Tools for Water Resources Planning and Decision Making*. CRC Press.

Stanford, J. A., and G. C. Poole. 1996. A Protocol for Ecosystem Management. *Ecological Applications*:741–744.

Stewart-Oaten, A., J. R. Bence, and C. W. Osenberg. 1992. Assessing Effects of Unreplicated Perturbations: No Simple Solutions. *Ecology*:1396–1404.

Teels, B. M., and T. Danielson. 2001. Using a Regional IBI to Characterize Condition of Northern Virginia Streams, with Emphasis on the Occoquan Watershed. USDANRCS. Technical Note 190-13-1. December 2001

U.S. Environmental Protection Agency (EPA). 1995. *A Decision-Making Guide for Restoration in Ecological Restoration*. EPA 841-F-95-007 (November)

Vail, L. W., and R. L. Skaggs. 2002. *Adaptive Management Platform for Natural Resources in the Columbia River Basin*. Pacific Northwest National Laboratory. Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13875.pdf.

Van Wilgen, B. W., and H. C. Biggs. 2011. A Critical Assessment of Adaptive Ecosystem Management in a Large Savanna Protected Area in South Africa. *Biological Conservation* 144(4):1179–1187.

Volkman, J. M., and W. E. McConnaha. 1993. Through a Glass, Darkly: Columbia River Salmon, the Endangered Species Act, and Adaptive Management. *Environmental Law* 23:1249–1272.

Walters, C. 2002. Adaptive Management of Renewable Resources. The Blackburn Press.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2009. *Adaptive Management: The U.S. Department of the Interior Technical Guide*. Adaptive Management Working Group, U.S. Department of the Interior, Washington, D.C.

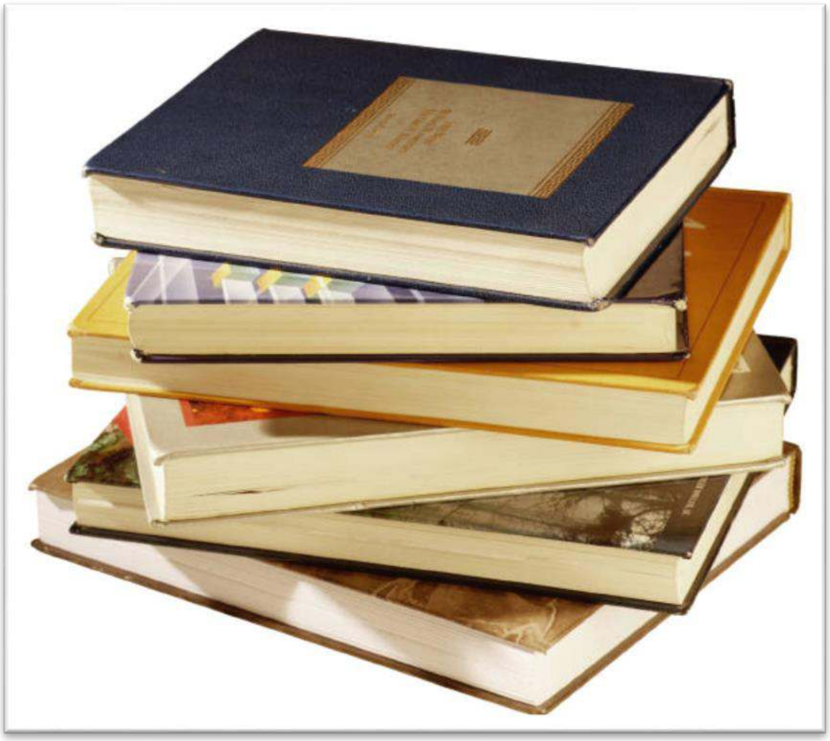
Wissmar, R. C., and R. L. Beschta. 1998. Restoration and Management of Riparian Ecosystems: A Catchment Perspective. *Freshwater Biology* 40(3):571–585.

Wright, L. D. (ed.). 1995. Morphodynamics of Inner Continental Shelves. CRC Press.

Yoccoz, N. G., J. D. Nichols, and T. Boulinier. 2001. Monitoring of Biological Diversity in Space and Time. *Trends in Ecology & Evolution* 16(8):446–453.

Chapter 10

LARGE WOOD BIBLIOGRAPHY



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Abbe, T. B. 2000. *Patterns, Mechanics, and Geomorphic Effects of Wood Debris Accumulations in a Forest River System*. Ph.D. dissertation. University of Washington, Seattle, WA.

Abbe, T. 2008. *Alluvial Landscape Response to Climate Change in Glacial Rivers and the Implications to River Restoration.* Presentation at River Restoration Northwest. Available: http://archive.rrnw.org/docs/2008/zSession%202/4-Abbe%20RRNW%202008%20final.pdf.

Abbe, T. B., and A. P. Brooks. 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration. Pages 419–451 in A. Simon, S. J. Bennett, and J. M. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Geophysical Monograph Series 194. Washington, D.C.: American Geophysical Union.

Abbe, T. B., and D. R. Montgomery. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. *Regulated Rivers: Research and Management* 12:201–221.

Abbe, T. B., and D. R. Montgomery. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. *Geomorphology* 51:81–107.

Abbe, T. B., D. R. Montgomery, K. Fetherston, and E. M. McClure. 1993. A Process-Based Classification of Woody Debris in a Fluvial Network: Preliminary Analysis of the Queets River, Washington. *EOS*, *American Geophysical Union Transactions* 73(43):296.

Abbe, T. B., D. R. Montgomery, and C. Petroff. 1997. Design of Stable In-Channel Wood Debris Structures for Bank Protection and Habitat Restoration: An Example from the Cowlitz River, WA. Pages 809–816 in S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, F.D. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi, Oxford, MS.

Abbe, T. B., J. Carrasquero, M. McBride, A. Ritchie, M. McHenry, and K. Dublanica. 2003a. *Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington*. Proceedings of the Georgia Basin/Puget Sound 2003 Research Conference, Vancouver, B.C., March 31–April 1, 2003, T. Droscher (ed.). Puget Sound Action Team, Olympia, WA.

Abbe, T. B, A. P. Brooks, and D. R. Montgomery. 2003b. Wood in River Rehabilitation and Management. Pages 367–389 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003c. Integrating Engineered Log Jam Technology into River Rehabilitation. In D. R. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies, University of Washington, Seattle.

Abbe, T. B., C. Miller, and A. Michael. 2009. *Self-Mitigating Protection for Pipeline Crossings in Degraded Streams: A Case Study from Woodward Creek, Washington.* 9th International Right of Way Symposium. 2009. Portland, OR.

Abbe. T., J. Bjork, A. Zehni, T. Nelson, and J. Park. 2011. New Innovative, Habitat-Creating Bank Protection Method. Pages 2011–2021 in *Proceedings of ASCE World Environmental and Water Resources Congress*.

Abbe. T., M. Ericsson, and L. Embertson, L. 2013. *Geomorphic Assessment of the Larson Reach of the South Fork Nooksack River, NW Washington*. Report submitted to Lummi Indian Nation.

Abt, S. R., R. J. Wittler, A. Taylor, and D. J. Love. 1989. Human Stability in a High Flood Hazard Zone. *American Water Resources Association. Water Resources Bulletin* 25(4):881–889.

Advisory Council on Historic Preservation (ACHP). 2010. *Protecting Historic Properties: A Citizen's Guide to Section 106 Review*. Advisory Council on Historic Preservation. Washington, D.C.

Agee, J. K. 1990. The Historical Role of Fire in Pacific Northwest Forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1992. The Historical Role of Fire in Pacific Northwest Forests. Pages 25–38 in J. Walstad, S. R. Radosevich, and D. V. Sandberg (eds.), *Natural and Prescribed Fire in Pacific Northwest Forests*. Corvallis: Oregon State University Press.

Agee, J. K. 1993. *Fire Ecology of Pacific Northwest Forests*. Washington, DC: Island Press.

Agrawal, A., M. A. Khan, and Z. Yi. 2007. *Handbook of Scour Countermeasures and Design*. FHWA-NJ-2005-027. New Jersey Department of Transportation and Federal Highway Administration, Washington, DC.

Ahmad, M. 1951. Spacing and Projection of Spurs for Bank Protection. *Civil Engineering and Public Works Review.* March:172–174; April:256–258.

Allan, C., and G. H. Stankey. 2009. *Adaptive Environmental Management*. Volume 351. Springer.

Allan, J. D. 1995. *Stream Ecology: Structure and Function of Running Waters.* Boston, MA: Kluwer Academic Publishers.

Allan, J. D., M. S. Wipfli, J. P. Caouette, A. Prussian, and J. Rodgers. 2003. Influence of Streamside Vegetation on Inputs of Terrestrial Invertebrates to salmonid Food Webs. *Canadian Journal of Fisheries and Aquatic Sciences* 60(3):309–320.

Allen, H. H., and J. R. Leech. 1997. *Bioengineering for Streambank Erosion Control*. Technical Report E 97-8, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Ambrose, H. E., M. A. Wilzbach, and K. W. Cummins. 2004. Periphyton Response to Increased Light and Salmon Carcass Introduction in Northern California Streams. *Journal of the North American Benthologocial Society* 23(4):701–712.

American Fisheries Society. 1983. *Stream Obstruction Removal Guidelines. Stream Renovation Guidelines Committee*. The Wildlife Society and American Fisheries Society. Published by AFS, Washington D.C.

American Society of Landscape Architects (ASLA). 2013. *American Society of Landscape Architects (ASLA)*. Available: http://www.asla.org. Accessed: August 27, 2013.

American Whitewater Association. 2012. *Integrating Recreational Boating Considerations into Stream Channel Modificatin & Design Projects*. Written by Kevin Colburn, National Stewardship Director. Illustrations by Chad Lewis. Figure 8.4, page 13. Available: http://www.americanwhitewater.org/content/Document/fetch/documentid/1006/.raw.

Anderson, B. 2005. *Will Replanting Vegetation along River Banks Make Floods Worse*? 8th International River Symposium, Brisbane, Australia.

Anderson, D. B. 2006. *Quantifying the Interaction between Riparian Vegetation and Flooding: from Cross-Section to Catchment Scale*. University of Melbourne.

Anderson, D. H., and B. D. Dugger. 1998. A Conceptual Basis for Evaluating Restoration Success. *Transactions of the North American Wildlife and Natural Resources Conference* Volume 63. Wildlife Management Institute.

Anderson, N. H., R. J. Steedman, and T. Dudley. 1984. Patterns of Exploitation by Stream Invertebrates of Wood Debris (Xylophagy). *Verhandlungen der Internationalen Vereinigung für theoretische und angewandte Limnologie* 22:1847-1852.

Anderson, P. D., D. J. Larson, and S. S. Chan. 2007. Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon. *Forest Science* 53(2):254–269.

Andrus, B., and J. Gessford. 2007. *Understanding the Legal Risks Associated with the Design and Construction of Engineered Logjams*. Skellenger Bender Attorneys, Seattle, WA.

Andrus, C. W., B. A. Long, and H. A. Froehlich. 1988. Woody Debris and its Contribution to Pool Formation in a Coastal Stream 50 Years after Logging: *Canadian Journal of Fish and Aquatic Science* 45:2080–2086.

Angradi, T. R., E. W. Schweiger, D. W. Bolgrien, P. Ismert, and T. Selle. 2004. Bank Stabilization, Riparian Land Use and the Distribution of Large Woody Debris in a Regulated Reach of the Upper Missouri River, North Dakota, USA. *River Research and Applications* 20:829–846.

Armstrong J. D., and K. H. Nislow. 2006. Critical Habitat During the Transition from Maternal Provisioning in Freshwater Fish, with Emphasis on Atlantic Salmon (*Salmo salar*) and Brown Trout (*Salmo trutta*). *Journal of Zoology* 269,403–413.

Arnáez, J., V. Larrea, and L. Ortigosa. 2004. Surface Runoff and Soil Erosion on Unpaved Forest Roads from Rainfall Simulation Tests in Northeastern Spain. *Catena* 57:1–14.

Arneson, L. A., L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper. 2012. *Evaluating Scour at Bridges*. Hydraulic Engineering Circular 18, FHWA-HIF-12-003, National Highway Institute, Federal Highway Administration, Arlington, VA.

Arno, S. F., and R. J. Hoff. 1989. Silvics of Whitebark Pine (*Pinus albicaulis*). USDA For. Serv. Gen Tech. Rep. INT-253.

Babakaiff, S., D. Hay, and C. Fromuth. 1997. Rehabilitating Stream Banks. In P. A. Slaney and D. Zaldokas (eds.), *Fish Habitat Rehabilitation Procedures, Watershed Restoration Program*. Ministry of Environment, Lands and Parks, Vancouver, BC.

Bailey, R. G. 1995. *Description of Ecoregions of the United States*, 2nd Edition, USDA, US Forest Service. Washington, D.C. Miscellaneous Publication No. 1391.

Bailey, R. G. 2009. *Ecosystem Geography – From Ecoregions to Sites*. New York, NY: Springer Science and Business Media.

Baillie, B. R., and T. R. Davies. 2002. Influence of Large Woody Debris On Channel Morphology in Native Forest and Pine Plantation Streams in the Nelson Region, New Zealand. *New Zealand Journal of Marine and Freshwater Research*. 36:763–774.

Baillie, B. R., L. G. Garret, and A. W. Evanson. 2008. Spatial Distribution Influence of LWD in an Old-growth Forest River System, New Zealand. *Forest Ecology and Management* 256:20–27.

Bain, M. B., and N. J. Stevenson (eds.). 1999. *Aquatic Habitat Assessment: Common Methods*. Bethesda, MD: American Fisheries Society.

Baker, C. O. 1979. *The Impacts of Logjam Removal on Fish Populations and Stream Habitat in Western Oregon.* M.S. Thesis, Oregon State University, Corvallis, OR.

Banta, E. R., M. C. Hill, and M. G. McDonald. 2000. *MODFLOW-2000, the US Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process*. Reston, VA, USA: US Geological Survey.

Barbour, M. T., J. Gerritsen, G. E. Griffith, R. Frydenborg, E. McCarron, J. S. White, and M. L. Bastian. 1996. A Framework for Biological Criteria for Florida Streams Using Benthic Macroinvertebrates. *Journal of the North American Benthological Society* (1996):185–211. Available: http://www.jstor.org/discover/10.2307/1467948?uid=3739936&uid=2&uid=4&uid=3739256&sid=21104863995063.

Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. *Rapid Bioassessment Protocols for use in Streams and Wadeable Rivers*. USEPA, Washington. Available: http://zoology.okstate.edu/zoo_lrc/biol1114/study_guides/labs/lab12/gen_usepa_barbouretal_1999_rba.pdf.

Bardini, L., F. Boano, M. B. Cardenas, A. H. Sawyer, R. Revelli and L. Ridolfi. 2013. Small-Scale Permeability Heterogeneity has Negligible Effects on Nutrient Cycling in Streambeds. *Geophysical Research Letters* 40:1118–1122.

Barker, B. L., R. D. Nelson, and M. S. Wigmosta. 1991. Performance of Detention Ponds Designed According to Current Standards. *Puget Sound Water Quality Authority, Puget Sound Research '91: Conference Proceedings*. Seattle, Washington.

Barrett, M. L. 1996. Environmental Reconstruction of a 19th Century Red River Raft Lake: Caddo Lake, Louisiana and Texas. *Gulf Coast Association of Geological Societies Transactions* 46:471–471.

Bartholow, J. 1988. Stream Segment Shade Model (SSSHADE) Version 1.4. *Temperature Model Technical Note #3*. U.S. Fish and Wildlife Service, Fort Collins, CO.

Bartz, K. K., K. M. Lagueux, M. D. Scheuerell, T. Beechie, A. D. Haas, and M. H. Ruckelshaus. 2006. Translating Restoration Scenarios into Habitat Conditions: An Initial Step in Evaluating Recovery Strategies for Chinook Salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Science*s 63(7):1578–1595.

Bash, J. S. and C. M. Ryan. 2002. Stream Restoration and Enhancement Projects: Is Anyone Monitoring? *Environmental Management* 29(6):877¬885.

Baxter, C. V., K. D. Fausch, and W. Carl Saunders. 2005. Tangled Webs: Reciprocal Flows of Invertebrate Prey Link Streams and Riparian Zones. *Freshwater Biology* 50(2):201–220.

Beckman, N. D., and E. Wohl. 2014. Carbon Storage in Mountainous Headwater Streams: The Role of Old-Growth Forest and Logjams. *Water Resources Research* 50:2376–2393.

Beamer, E. M., and R. A. Henderson. 1998. *Juvenile Salmonid use of Natural and Hydromodified Stream Bank Habitat in the Mainstem Skagit River, Northwest Washington*. Miscellaneous Report. Skagit System Cooperative. La Connor, WA.

Beecher, H. A., B. A. Caldwell, S. B. DeMond, D. Seiler, D., and S. N. Boessow. 2010. An Empirical Assessment of PHABSIM Using Long-Term Monitoring of Coho Salmon Smolt Production in Bingham Creek, Washington. *North American Journal of Fisheries Management* 30(6):1529–1543. doi:10.1577/M10.

Beechie, T. J., and S. Bolton. 1999. An Approach to Restoring Salmonid Habitat-Forming Processes in Pacific Northwest Watersheds. *Fisheries* 24:6–15.

Beechie, T. J., and K. Wyman. 1992. *Stream Habitat Conditions, Unstable Slopes and Status of Roads in Four Small Watersheds of the Skagit River.* Skagit System Cooperative, Fisheries services for the Swinomish Tribal Community, Upper Skagit and Sauk-Suiattle Indian Tribes.

Beechie, T. J., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling Recovery Rates and Pathways for Woody Debris Recruitment in Northwestern Washington Streams. *North American Journal of Fisheries Management* 20:436–452.

Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, P. Roni, and M. M. Pollock. 2010. Process-Based Principles for Restoring River Ecosystems. *Bioscience* 60:209–222.

Beechie, T. J., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N Mantua. 2012. Restoring Salmon Habitat for a Changing Climate. *River Research and Applications* 29:939–960.

Beesley, L. 1996. *The Ecological Importance of Large Woody Debris in the Sandy River Systems of the Swan Coastal Plain (Perth, Western Australia).* Honors thesis, University of Western Australia, Perth.

Beets, P. N., I. A. Hood, M. O. Kimberley, G. R. Oliver, S. H. Pearce, and J. F. Gardner. 2008. Coarse Woody Debris Decay Rates for Seven Indigenous Tree Species in the Central North Island of New Zealand. *Forest Ecology and Management* 256:548–557.

Begon, M., J. L. Harper, and C. R. Townsend. 1990. *Ecology: Individuals, Populations, Communities,* 2nd Edition. Blackwell Scientific Publications: Boston.

Beltaos, S. 1983. River Ice Jams: Theory, Case Studies, and Applications. *Journal of Hydraulic Engineering* 109(10):1338–1359.

Bencala, K. E. 2005. Hyporheic Exchange Flows. *Encyclopedia of Hydrological Sciences*, M. G. Anderson and J. J. McDonnell (eds.). Wiley-Blackwell.

Bencala, K. E., M. N. Gooseff, and B. A. Kimball. 2011. Rethinking Hyporheic Flow and Transient Storage to Advance Understanding of Stream-Catchment Connections. *Water Resources Research* 47(3):W00h03.

Benda, L. and T. W. Cundy. 1990. Predicting Deposition of Debris Flow in Mountain Channels. *Canadian Geotechnical Journal* 27:409–417.

Benda, L. E., and J. C. Sias. 2003. A Quantitative Framework for Evaluating the Mass Balance of In-Stream Organic Debris. *Forest Ecology and Management* 172:1–16.

Benda, L., Miller, D., Bigelow, P., Andras, K. 2003a. Effects of Post-Wildfire Erosion on Channel Environments, Boise River, Idaho. *Forest Ecology and Management* 178:105–119.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003b. Wood Recruitment Processes and Wood Budgeting. *American Fisheries Society Symposium* 37:49–73.

Benda, L. E., D. Miller, K. Andras, P. E. Bigelow, G. H. Reeves, and D. Michael. 2007. NetMap: A New Tool in Support of Watershed Science and Resource Management. *Forest Science* 53(2):206–219.

Bender, L. C., G. J. Roloff, and J. B. Haufler. 1996. Evaluating Confidence Intervals for Habitat Suitability Models. *Wildlife Society Bulletin* 24(2):347–352.

Benke, A. C. 2001. Importance of Flood Regime to Invertebrate Habitat in an Unregulated River-Floodplain Ecosystem. *Journal of the North American Benthological Society* 20:225–240.

Benke, A. C., and J. B. Wallace. 1990. Wood Dynamics in Coastal Plain Blackwater Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 47:92–99.

Benke, A. C., and J. B. Wallace. 2010. Influence of Wood on Invertebrate Communities in Streams and Rivers. *American Fisheries Society Symposium* 37:149–177.

Benke, A. C., R. L. Henry III, D. M. Gillespie, and R. J. Hunter. 1985. Importance of Snag Habitat for Animal Production in Southeastern Streams. *Fisheries* 10:8–12.

Bentz, B. J., J. Régnière, C. J. Fettig, M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negrón, and S. J. SeyboLd. 2010. Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience* 60:602–613.

Berg, N. A., A. Carlson, and D. Azuma. 1998. Function and Dynamics of Woody Debris in Stream Reaches in the Central Sierra Nevada, California. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1807–1820.

Bernhardt, E. S., and 24 others. 2005. Synthesizing U.S. River Restoration Efforts. *Science*. 308(5722):636–637

Bernhardt, E. S., E. B. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, J. Follastad-Shah, B. A. Hassett, R. Jenkinson, R. Lave, J. Rumps, and L. Pagano. 2007. Restoring Rivers One Reach at a Time: Results from a Survey of U.S. River Restoration Practitioners. *Restoration Ecology* 15(3):482–493.

Bertoldi, W., A. M. Gurnell, and M. Welber 2013. Wood Recruitment and Retention: The Fate of Eroded Trees on a Braided River Explored Using a Combination of Field and Remotely-Sensed Data Sources. *Geomorphology* 180–181(0):146–155.

Beschta, R. L. 1997. Restoration of Riparian and Aquatic Systems for Improved Aquatic Habitats in the Upper Columbia River Bbasin. Pages 475-491 in D. J. Stouder and P. A. Bisson (eds.). *Pacific Salmon and Their Ecosystems: Status and Future Options*. New York: Chapman Hall.

Beschta, R. L., R. E. Bilby, L. B. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions. Pages 191-232 in E. O. Salo and

T. W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Seattle, WA. 471p.

Beverton, R. J. H., and S. J. Holt. 1957. On the Dynamics of Exploited Fish Populations. *U.K. Ministry of Agriculture, Fisheries Investigation Service* 2(19):553.

Bilby, R. E. 1981. Role of Organic Debris Dams in Regulating the Export of Dissolved and Particulate Matter from a Forested Watershed. *Ecology* 62(5):1234–1243.

Bilby, R. E. 1984. Removal of Woody Debris May Affect Stream Channel Stability. *Journal of Forestry*, 609–613. October.

Bilby, R. E. 2003. Decomposition and Nutrient Dynamics of Wood in Streams and Rivers. *The Ecology and Management of Wood in World Rivers, American Fisheries Society Symposium* 37:135–147.

Bilby, R. E., and P. A. Bisson. 1998. Function and Distribution of Large Woody Debris. Pages 324–346 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coast Ecoregion*. New York, NY: Springer-Verlag.

Bilby, R. E., and G. E. Likens. 1980. Importance of Debris Dams in the Structure and Function of Stream Ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E. and J. W. Ward. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48:2499–2508.

Bilby, R. E., and J. W. Ward. 1989. Changes in Characteristics and Function of Woody Debris With Increasing Size of Streams in Western Washington. *Transactions of the American Fisheries Society* 118:368–378.

Bilby, R. E., and L. J. Wasserman. 1989. Forest Practices and Riparian Management in Washington State: Data Based Regulation Development. In R. E. Gresswell, B. A. Barton, and J. L. Kershner (eds.), *Practical Approaches to Riparian Management.* U.S. Bureau of Land Management, BLM MT PT 89 001 4351, Billings, Montana.

Bilby, R. E., B. R. Fransen, P. A. Bisson, and J. K. Walter. 1998. Response of Juvenile Coho Salmon (*Oncorhynchus kisutch*) and Steelhead (*Oncorhynchus mykiss*) to the Addition of Salmon Carcasses to Two Streams in Southwestern Washington, U.S.A. *Canadian Journal of Fisheries and Aquatic Science* 55:1909–1918.

Bilby, R. E., J. T. Heffner, B. R. Fransen, F. W. Ward, and P. A. Bisson. 1999. Effects of Immersion in Water on Deterioration of Wood from Five Species of Trees Used for Habitat Enhancement Projects. *North American Journal of Fisheries Management* 19(3):687–695.

Binns, N. A., and F. M. Eiserman. 1979. Quantification of Fluvial Trout Habitat in Wyoming. *Transactions of the American Fisheries Society* 109(3):215–228.

Bisson, P. A., J. L. Nielsen, and R. A. Palmason. 1982. A System of Naming Habitat Types in Small Steams, with Examples of Habitat Utilization by Salmonids during Low Steamflow. Pages 62–73 in N. B. Armantrout (ed.), *Acquisition and Utilization of Aquatic Habitat Inventory Information*. Bethesda, MD: American Fisheries Society.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future. Pages 143–190, in E. O. Salo and T. W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Seattle, Washington.

Bisson, P. A., B. E. Rieman, C. Luce, P. F. Hessburg, D. C. Lee, J. L. Kershner, G. H. Reeves, and R. E. Gresswell. 2003. Fire and Aquatic Ecosystems of the Western USA: Current Knowledge and Key Questions. *Forest Ecology and Management* 178:213–229.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat Requirements of Salmonids in Streams. Pages 83-138 in W. R. Meehan (ed.), *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats.* Bethesda, MD: American Fisheries Society.

Blair, G. R., L. C. Lestelle, and L. E. Mobrand. 2009. The Ecosystem Diagnosis and treatment Model: A Tool for Assessing Salmonid Performance Potential Based on Habitat Conditions. Pages 289–309 in E. E. Knudsen and J. J. Michael, Jr., *Pacific Salmon Environment and Life History Models: Advancing Science for Sustainable Salmon in the Future.* Bethesda, MD: American Fisheries Society.

Blanckaert, K. A. Duarte, and A. J. Schleiss. 2010. Influence of Shallowness, Bank Inclination and Bank Roughness on the Variability of Flow Patterns and Boundary Shear Stress due to Secondary Currents in Straight Open-Channels. *Advances in Water Resources* 33(9):1062–1074.

Blaustein, Andrew R., and David B. Wake. 1990. Declining Amphibian Populations: A Global Phenomenon? *Trends in Ecology & Evolution* 5 (7):203–204.

Boano, F., A. Demaria, R. Revelli, and L. Ridolfi. 2010. Biogeochemical Zonation due to Meander Hyporheic Flow. *Water Resources Research* 46:W20511.

Bocchiola, D., M. C. Rulli, and R. Rosso. 2006. Transport of Large Woody Debris in the Presence of Obstacles. *Geomorphology* 76(1):166–178.

Bocchiola, D., M. C. Rulli, and R. Rosso. 2008. A Flume Experiment on the Formation of Wood Jams in Rivers. *Water Resources Research* 44: W02408, doi:10.1029/2006WR005846.

Boisclair, D. 2001. Fish Habitat Modeling: From Conceptual Framework to Functional Tools. Canadian *Journal of Fisheries and Aquatic Sciences* 58:1–9.

Bolton, S., A. Watts, T. Sibley, and J. Dooley. 1998. A Pilot Study Examining the Effectiveness of Engineered Large Woody Debris (ELWD™) as an Interim Solution to Lack of LWD in Streams. *EOS, Transactions of the American Geophysical Union* 79(45):F346.

Boose, E. R., K. E. Chamberlin, and D. R. Foster. 2001. Landscape and Regional Impacts of Hurricanes in New England. *Ecological Monographs* 71:27–48.

Booth, D. B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. *Water Resources Bulletin* 26:407–417.

Booth, D. 1991. Urbanization and the Natural Drainage System: Impacts, Solutions, and Prognoses. *The Northwest Environmental Journal* 7, 93-118.

Booth, D., and L. E. Reinelt. 1993. *Consequences of Urbanization on Aquatic Systems—Measured Effects, Degradation Thresholds, and Corrective Strategies.* Watershed '93, American Water Resources Association, pages 545–550.

Borg, D., I. Rutherford, and M. Stewardson. 2007. The Geomorphic and Ecological Effectiveness of Habitat Rehabilitation Works: Continuous Measurement of Scour and Fill around Large Logs in Sand-Bed Streams. *Geomorphology* 89(1/2):205–216.

Boulton, A. J. 1989. Over-Summering Refuges of Aquatic Macroinvertebrates in Two Intermittent Streams in Central Victoria. *Transactions of the Royal Society of South Australia* 113:23–34.

Boulton, A. J., T. Datry, T. Kasahara, M. Mutz, and J.A. Stanford. 2010. Ecology and Management of the Hyporheic Zone – Groundwater Interactions of Running Waters and Their Floodplains. *Journal of the North American Benthological Society* 29:26–40.

Bouwes, N., J. Moberg, N. Weber, B. Bouwes, S. Bennett, C. Beasley, C. E. Jordan, P. Nelle, M. Polino, S. Rentmeester, B. Semmens, C. Volk, M. B. Ward, and J. White. 2011. *Scientific Protocol for Salmonid Habitat Surveys within the Columbia Habitat Monitoring Program.* Prepared by Terraqua, Inc., Wauconda, WA, for Integrated Status and Effectiveness Monitoring Program,

Bovee, K. D., T. J. Newcomb, and T. G. Coon. 1994. *Relations Between Habitat Variability and Population Dynamics of Bass in the Huron River, Michigan.* Biological Report 21. National Biological Survey, U.S. Department of the Interior. Washington D.C.

Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor, and J. Henriksen. 1998. *Stream Habitat Analysis using the Instream Flow Incremental Methodology*. Washington, DC: U.S. Geological Survey.

Boyce, M. S., and L. L. McDonald. 1999. Relating Populations to Habitats Using Resource Selection Functions. *Trends in Ecology and Evolution* 14(7):268–272.

Bradford, M. J., J. Korman, and P. S. Higgins. 2005. Using Confidence Intervals to Estimate the Response of Salmon Populations (*Oncorhynchus spp*.) to Experimental Habitat Alterations. *Canadian Journal of Fisheries and Aquatic Sciences* 62(12):2716–2726.

Bradley, J., D. Richards, and C. Bahner 2005. *Debris Control Structures – Evaluation and Countermeasures.* Hydraulic Engineering Circular No. 9. FHWA-IF-04-016. U.S. Department of Transportation, Federal Highway Administration., Salem, OR.

Bragg, D. C. 2000. Simulating Catastrophic and Individualistic Large Woody Debris Recruitment for a Small Riparian Ecosystem. *Ecology* 81:1383–1394.

Braudrick, C. A., and G. E. Grant. 2000. When do Logs Move in Rivers? *Water Resources Research* 36(2):571–583.

Braudrick, C. A., and G. E. Grant. 2001. Transport and Deposition of Large Woody Debris in Streams: A Flume Experiment. *Geomorphology* 41:263–283.

Braudrick, C. A., G. E. Grant, Y. Ishikawa, and H. Ikeda. 1997. Dynamics of Wood Transport in Streams: A Flume Experiment. *Earth Surface Processes and Landforms* 22:669–683.

Braun, A., K. Auerswald, and J. Geist. 2012. Drivers and Spatio-Temporal Extent of Hyporheic Patch Variation: Implications for Sampling. *PLOS One* 7:e42046.

Brenkman, S., J. Duda, C. E. Torgersen, E. Welty, G. R. Pess, R. Peters, and M. L. McHenry. 2012. A Riverscape Perspective of Pacific Salmonids and Aquatic Habitats Prior to Large-Scale Dam Removal in the Elwha River, Washington, USA. *Fisheries Management and Ecology* 19:36–53.

Bretherton, W. D., J. S. Kominoski, D. G. Fischer, and C. J. LeRoy. 2011. Salmon Carcasses Alter Leaf Litter Species Diversity Effects on In-stream Decomposition. *Canadian Journal of Fisheries and Aquatic Sciences* 68(8):1495–1506.

Briceño-Linares, J. M., J. P. Rodríguez, K. M. Rodríguez-Clark, F. Rojas-Suárez, P. A. Millán, E. G. Vitton, and M. Carrasco-Muñoz. 2011. Adapting to changing poaching intensity of yellow-shouldered parrot (*Amazona barbadensis*) nestlings in Margarita Island, Venezuela. *Biological Conservation* 144 (4):1188–1193.

Brigham, M. E., D. A. Wentz, G. R. Aiken, and D. P. Krabbenhoft. 2009. Mercury Cycling in Stream Ecosystems. 1. Water Column Chemistry and Transport. *Environmental Science and Technology* 43:2720–2725.

Brooks, A. P. 2006. *Design Guidelines for the Reintroduction of Wood into Australian Streams*. Land & Water Australia, Canberra.

Brooks, A. P., and G. J. Brierly. 2002. Mediated Equilibrium: The Influence of Riparian Vegetation and Wood on the Long-Term Evolution and Behavior of a Near-Pristine River. *Earth Surface Processes and Landforms* 27:343–367.

Brooks, A., and G. J. Brierly. 2004. Framing Realistic River Rehabilitation Targets in Light of Altered Sediment Supply and Transport Relationships: Lessons from East Gippsland, Australia. *Geomorphology* 58:107–123.

Brooks, A. P., G. J. Brierly, and R. G. Millar. 2003. The Long-Term Control of Vegetation and Woody Debris on Channel and Flood-Plain Evolution: Insights from a Paired Catchment Study in Southeastern Australia. *Geomorphology* 51:7–30.

Brooks, A. P., P. Gehrke, J. D. Jansen, and T. B. Abbe. 2004. Experimental Reintroduction of Woody Debris on the Williams River, NSW: Geomorphic and Ecological Responses. *River Research and Applications* 20:513–536.

Brooks, A. P., T. Howell, T. B. Abbe, and A. H. Arthington. 2006a. Confronting Hysteresis: Wood Basin River Rehabilitation in Highly Altered Riverine Landscapes of South-Eastern Australia. *Geomorphology* 79(3/4):395–422.

Brooks, A. P., T. Abbe, T. Cohen, N. Marsh, S. Mika, A. Boulton, T. Broderick, D. Borg, and I. Rutherfurd 2006b. *Design Guidelines for the Reintroduction of Wood into Australian Streams*. Land & Water Australia, Canberra, Australia.

Brosofske, K. D., J. Chen, R. J. Naiman, and J. F. Franklin. 1997. Harvesting Effects on Microclimatic Gradients from Small Streams to Uplands in Western Washington. *Ecological Applications* 7(4):1188–1200.

Brown, S. A. and E. S. Clyde. (1989). *Design of Riprap Revetment*. Hydraulic Engineering Circular 11, Publication No. FHWA-IP-89-016, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Brummer, C., T. B. Abbe, J. R. Sampson, and D. R. Montgomery. 2006. Influence of Vertical Channel Change Associated with Wood Accumulations on Delineating Channel Migration Zones, Washington State, USA. *Geomorphology* 80:295–309.

Bryant, M. D. 1980. Evolution of large, Organic Debris after Timber Harvest: Maybeso Creek, 1949 to 1978. USDA Forest Service, General Technical Report, PNW-101.

Bryant, M. D. 1983. The Role and Management of Woody Debris in West Coast Salmonid Nursery Stream. *North American Journal of Fisheries Management* 3(3):322–330.

Bryant, M. D., and J. R. Sedell. 1995. Riparian Forests, Wood in the Water, and Fish Habitat Complexity. Pages 202–224 in N. B. Armantrout and R. J. Wolotira, Jr. (eds.), *Conditions of the World's Aquatic Habitats. Proceedings of the World Fisheries Congress Theme 1.* Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Buckley B. M., and F. J. Triska 1978. Presence and Ecological Role of Nitrogen-Fixing Bacteria Associated with Wood Decay in Streams. *Internationale Vereinigung für Theoretische und Angewandte Limnologie Verhandlungen* 20:1333–1339.

Buffington, J. M., and D. R. Montgomery. 1999a. A Procedure for Classifying Textural Facies in Gravel-bed Rivers. *Water Resources Research* 35(6):1903-1914.

Buffington, J. M., and D. R. Montgomery. 1999b. Effects of Hydraulic Roughness on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3507–3521.

Buffington, J. M., and D. R. Montgomery. 1999c. Effects of Sediment Supply on Surface Textures of Gravel-Bed Rivers. *Water Resources Research* 35(11):3523–3530.

Buffington, J. M. and D. Tonina. 2009. Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange. *Geography Compass* 3:1038–1062.

Buffington, J. M., T. E. Lisle, R. D. Woodsmith, and S. Hilton. 2002. Controls on the Size and Occurrence of Pools in Coarse-Grained Forest Rivers. *River Research and Applications* 18:507–531.

Burchsted, D., M. Daniels, R. Thorson, and J. Vokoun. 2010. The River Discontinuum: Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. *BioScience* 60(11):908–922.

Burkholder, B. K., G. E. Grant, R. Haggerty, T. Khangaonkar, and P. J. Wampler. 2008. Influence of Hyporheic Flow and Geomorphology on Temperature of a Large, Gravel-Bed River, Clackamas River, Oregon, USA. *Hydrological Processes* 22:941–953.

Bury, R. B., and P. Stephen Corn. 1991. *Sampling Methods for Amphibians in Streams in the Pacific Northwest.* Available: http://www.treesearch.fs.fed.us/pubs/3069.

Cafferata, P., T. Spittler, M. Wopat, G. Bundros, and S. Flanagan. 2004. Designing Watercourse Crossings for Passage of 100-Year Flood Flows, Wood, and Sediment. California Forestry Report No.1. California Department of Forestry and Fire Protection. Available: http://www.fire.ca.gov/php/rsrc-mgt_forestpractice_pubsmemo.php.

Camp, A., C. Oliver, P. Hessburg, and R. Everett. 1996. Predicting Late-Successional Fire Refugia Pre-Dating European Settlement in the Wenatchee Mountains. USDA PNW, Wenatchee For. Sci.

Lab., Univ. of Washington, Seattle. Elsevier Science Publishers B.V. *Forest Ecology and Management* 95:63–77.

Cannon, S. H., and J. DeGraff. 2009. The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change. Pages 177–190 in K. Sassa and P. Canuti (eds.), *Landslides—Disaster Risk Reduction*. Berlin Heidelberg: Springer-Verlag. Available: http://landslides.usgs.gov/docs/cannon/Cannon_Degraff_2008_Springer.pdf.

Cannon, S. H., J. E. Gartner, M. G. Rupert, J. A. Michael, A. H. Rea, and C. Parrett. 2010. Predicting the Probability and Volume of Postwildfire Debris Flows in the Intermountain Western United States. *Geological Society of America Bulletin* 122(1-2):127–144. doi:10.1130/B26459.1.

Carignan, V., and M.-A. Villard. 2002. Selecting Indicator Species to Monitor Ecological Integrity: A Review. *Environmental Monitoring and Assessment* 78(1):45–61.

Carignan, V., and M. A. Villard. 2004. Biological Indicators in Environmental Monitoring Programs: Can We Increase Their Effectiveness. *Environmental Monitoring*:567–582.

Carlson, J. Y., C. W. Andrus, and H. A. Froehlich. 1990. Woody Debris, Channel Features, and Macroinvertebrates of Streams with Logged and Undisturbed Riparian Timber in Northeastern Oregon, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 47:1103–1111.

Caro, T. Mi, and G. O'Doherty. 1999. On the Use of Surrogate Species in Conservation Biology. *Conservation Biology* 13(4):805–814.

Castelle, A. J., A. W. Johnson, and C. Conolly. 1994. Wetland and Stream Buffer Size Requirements—A Review. *Journal of Environmental Quality* 23(5):878–882.

Castro, J., and R. Sampson. 2001. *Incorporation of Large Wood into Engineering Structures.* Natural Resource Conservation Service Engineering Technical Note Number 15. U.S. Department of Agriculture. Boise, ID.

Cederholm, C. J., W. J. Scarlett, N. P. and Peterson. 1988. Low-Cost Enhancement Technique for Winter Habitat of Juvenile Coho Salmon. *North American Journal of Fisheries Management* 8:438–441.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B .R. Fransen, W. J. Scarlett, and J. W. Ward. 1997a. Response of Juvenile Coho Salmon and Steelhead to Placement of Large Woody Debris in a Coastal Washington Stream. *North American Journal of Fisheries Management* 17:947–963.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997b. Response of Juvenile Coho Salmon and Steelhead to the Placement of Large Woody Debris in a Coastal Washington Stream. *Transactions of the American Fisheries Society*. 118:368–378.

Cederholm, C. J., L. G. Dominguez, and T. W. Bumstead. 1997c. Rehabilitating Stream Channels and Fish Habitat Using Large Woody Debris. In P. A. Slaney and D. Zaldokas (eds.), *Fish Habitat Procedures*. Watershed Restoration Program, Ministry of Environment, Lands and Parks, Vancouver, British Columbia.

Cederholm, C. J., M. D. Kunze, T. Murota, and A. Sibatani. 1999. Pacific salmon Carcasses: Essential Contributions of Nutrients and Energy for Aquatic and Terrestrial Ecosystems. *Fisheries* 24(10):6–15.

Chambers, J. Q., J. I. Fisher, H. Zeng, E. L. Chapman, D. B. Baker, and G. C. Hurtt. 2007. Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. *Science* 318 (5853):1107.

Chapman, D. W. 1966. Food and Space as Regulators of Salmonid Populations in Streams. *American Naturalist* 100:345–357.

Chen, J., J. F. Franklin, and T. A. Spies. 1995. Growing-Season Microclimatic Gradients from Clearcut Edges into Old-Growth Douglas-Fir Forests. *Ecological Applications* 5(1):74–86.

Chesney, C. 2000. *Functions of Wood in Small, Steep Streams in Eastern Washington: Summary of Results for Project Activity in the Ahtanum, Cowiche, and Tieton Basins*. Washington Department of Natural Resources. Prepared for the Timber/Fish/Wildlife Monitoring Advisory Group and the Northwest Indian Fisheries Commission. TFW Effectiveness Monitoring Report: TFW-MAGl-00-002.

Chin, A., M. D. Daniels, M. A. Urban, H. Piegay, K. J. Gregory, W. Bigler, A. Z. Butt, J. L. Grable, S. V. Gregory, M. Lafrenz, L. R. Laurencio, and E. Wohl. 2008. Perceptions of Wood in Rivers and Challenges for Stream Restoration in the United States. *Environmental Management* 41:893–903.

Christensen, N. L., and 12 others. 1996. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications* 6(3):665–691.

Claussens, L., C. L. Tague, P. M. Groffman, and J. M. Melack. 2010. Longitudinal and Seasonal Variation of N Uptake in an Urbanizing Watershed: Effect of organic Matter, Stream Size, Transient Storage and Debris Dams. *Biogeochemistry* 98:45–62.

Clay, C. 1949. The Colorado River Raft. *The Southwestern Historical Quarterly* 102 (4):400–426.

Clemen, R. T., and T. Reilly. 2001. *Making Hard Decisions with Decision Tools.* South-Western Cengage Learning.

Coe, H. J., P. M. Kiffney, G. R. Press, K. K. Kloehn, and M. L. McHenry. 2009. Periphyton and Invertebrate Response to Wood Placement in Large Pacific Coastal Rivers. *River Research and Applications* 25(8):1025–1035.

Coho, C., and S. J. Burges. 1993. Dam-Break Floods in Low Order Mountain Channels of the PNW. *Water Resources Series Tech Rep no. 138*. Dept. Civil Engineering, Univ. of Washington, Seattle.

Coho, C., and S. J. Burges. 1994. *Dam Break Floods in Low Order Mountain Channels of the Pacific Northwest*. TFW SH9 93 001. Timber Fish and Wildlife, Department of Natural Resources, Olympia.

Colburn, K. 2011. Integrating Recreational Boating Considerations into Stream Channel Modification and Design Projects. *American Whitewater* (2011).

Collins, B. D., and A. J. Sheikh. 2005. *Historical Reconstruction, Classification, and Change Analysis of Puget Sound Tidal Marshes*. University of Washington (Seattle, WA) and the Nearshore Habitat Program, Washington State Dept. of Natural Resources, Olympia, WA. See more at: http://www.eopugetsound.org/science-review/3-tidal-wetlands#sthash. T4OyhfFd.dpuf

Collins, B. D., and D. R. Montgomery. 2002. Forest Development, Wood Jams, and Restoration of Floodplain Rivers in the Puget Lowland, Washington. *Restoration Ecology* 10:237–247.

Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical Changes in the Distribution and Functions of Large Wood in Puget Lowland Rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59:66–76.

Collins, B. D., D. R. Montgomery, and A. J. Sheikh. 2003. Reconstructing the Historical Riverine Landscape of the Puget Lowland. Pages 79–128 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press, Seattle.

Collins, B. D., D. R. Montgomery, K. L. Fetherston, and T. B. Abbe. 2012. The Floodplain Large-Wood Cycle Hypothesis: A Mechanism for the Physical and Biotic Structuring of Temperate Forested Alluvial Valleys in the North Pacific Coastal Ecoregion. *Geomorphology* 139/140:460–470.

Comiti, F. and Mao, L. 2012. *Recent Advances in the Dynamics of Steep Channels. Gravel-bed Rivers: Processes, Tools, Environments*, pages 351–377.

Comiti, F., A. Andreoli, M. A. Lenzi, and L. Mao. 2006. Spatial Density and Characteristics of Woody Debris in Five Mountain Rivers of the Dolomites (Italian Alps). *Geomorphology* 78:44–63.

Comiti, F., A. Andreoli, L. Mao, and M. A. Lenzi. 2008. Wood Storage in Three Mountain Streams of the Southern Andes and its Hydro-Morphological Effects. *Earth Surface Processes and Landforms* 33:244–262.

Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett. 2003. Nitrogen Export from Forested Watersheds in the Oregon Coast Range: The Role of N_2-Fixing Red Alder. *Ecosystems* 6(8):773–785.

Conquest, L. L., and S. C. Ralph. 1998. Statistical Design and Analysis Considerations for Monitoring and Assessment. Pages 455-475 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. New York: Springer.

Convertino, M., K. M. Baker, J. T. Vogel, C. Lu, B. Suedel, and I. Linkov. 2013. *Multi-Criteria Decision Analysis to Select Metrics for Design and Monitoring of Sustainable Ecosystem Restorations*. U.S. Army Research. Paper 190. Available: http://digitalcommons.unl.edu/usarmyresearch/1905.

Cook, W. J. 2014. *Bridge Failure Rates, Consequences, and Predictive Trends*. PhD Dissertation. Utah State University, Logan, UT.

Copeland, R. R. 1983. *Bank Protection Techniques Using Spur Dikes*. Paper No. HL-83-1. Hydraulics Laboratory. U.S. Army Waterways Experiment Station. Vicksburg, MS.

Cordova, J. M., E. J. Marshall-Rosi, A. M. Yamamoto, and G. A. Lamberti. 2007. Quantity, Controls, and Functions of Large Woody Debris in Midwestern USA Streams. *River Research and Applications* 23(1):21–33.

Costa, J. E. 1984. Physical Geometry of Debris Flows. Pages 268–317 in J. E. Costa and P. J. Fleisher (eds.), *Developments and Applications of Geomorphology*. Springer-Verlag, Berlin.

Cramer, M. L. (ed). 2012. *Stream Habitat Restoration Guidelines*. Copublished by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service. Olympia, WA.

Cramer, S. P., and N. K. Ackerman. 2009. Prediction of Stream Carrying Capacity for Steelhead; The Unit Characterization Method. Pages 255–288 in *Pacific Salmon Environment and Life History Models*. Bethesda, MD: American Fisheries Society.

Cramer, M., K. Bates, D. Miller, K. Boyd, L. Fotherby, P. Skidmore, T. Hoitsma, B. Heiner, K. Buchanan, P. Powers, G. Birkeland, M. Rotar, and D. White. 2002. *Integrated Streambank Protection Guidelines*. Washington State Aquatic Habitat Guidelines Program, Washington State Department of Fish and Wildlife. Olympia, WA.

Creamean, J. M., K. J. Suski, D. Rosenfeld, A. Cazorla, P. J. DeMott, R. C. Sullivan, A. B. White, F. M. Ralph, P. Minnis, J. M. Comstock, J. M. Tomlinson, and K. A. Prather. 2013. Dust and Biological Aerosols from the Sahara and Asia Influence Precipitation in the Western U.S. *Science* 339: 1572–1578, doi:10.1126/ science.1227279.

Crispell, J. K., and T. A. Endreny. 2009. Hyporheic Exchange Flow around Constructed In-Channel Structures and Implications for Restoration Design. *Hydrological Processes* 23:1158–1168.

Crook, D., and A. Robertson. 1999. Relationships between Riverine Fish and Woody Debris: Implications for Lowland Rivers*. Marine and Freshwater Research* 50:941–953.

Cummins, K. W. 1974. Structure and Function of Stream Ecosystems. *BioScience* 24(11):631–641.

Cummins, K. W., G. W. Minshall, J. R. Sedell, C. E. Cushing, and R. C. Petersen. 1984. Stream Ecosystem Theory. *Internationale Vereinigung fur theoretische und angewandte Limnologie, Verhandlungen* 22:1818–1827.

Curran, J. C. 2010. Mobility of Large Woody Debris (LWD) Jams in a Low Gradient Channel. *Geomorphology* 116:320–329.

Curran, J. H., and E. E. Wohl 2003. Large Woody Debris and Flow Resistance in Step-Pool Channels, Cascade Range, Washington. *Geomorphology* 51:141–157.

Cushman, M. J. 1981. *The Influence of Recurrent Snow Avalanches on Vegetation Patterns in the Washington Cascades*. Ph.D. dissertation. University of Washington, Seattle, Washington.

D'Aoust, S. G. and R. G. Millar. 2000. Stability of Ballasted Woody Debris Habitat Structures*. Journal of Hydraulic Engineering* 126(11):810–817.

Dacy, G. H. 1921. Pulling the Mississippi's Teeth. *Scientific American* 75(4):60, 70.

Daley, J. S. 2012. *Taming the Hungry Beast: The Effectiveness of Engineered Log Jams in an Incising Gravel Bedded River*. B.S. Honors Thesis, School of Earth and Environmental Science, University of Wollongong, Australia. Available: http://ro.uow.edu.au/thsci/38.

Danehy, R. J., and B. J. Kirpes. 2000. Relative Humidity Gradients across Riparian Areas in Eastern Oregon and Washington Forests. *Northwest Science* 74(3):224–233.

Daniels, M. D., and Rhoads, B. L. 2004. Effect of Large Woody Debris Configuration on Three-Dimensional Flow Structure in Two Low-Energy Meander Bends at Varying Stages. *Water Resources Research* (40):W11302.

Daniels, M. D., and B. L. Rhoads. 2004. Spatial Pattern of Turbulence Kinetic Energy and Shear Stress in a Meander Bend with Large Woody Debris. Pages 87–97 in S. J. Bennett and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*. American Geophysical Union, Washington D.C.

Daniels, M. D., and B. Rhoads. 2007. Influence of Experimental Removal of Large Woody Debris on Spatial Patterns of Three-Dimensional Flow in a Meander Bend. *Earth Surface Processes and Landforms* 32:460–474.

Davis, J. C., G. Minshall, W. Robinson, T. Christopher, and P. Landres. 2001. *Monitoring Wilderness Stream Ecosystems.* Gen. Tech. Rep. RMRS-GTR-70. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Davis, J. M., C. V. Baxter, E. J. Rosi-Marshall, J. L. Pierce, and B. T. Crosby. 2013. Anticipating Stream Ecosystem Responses to Climate Change: Toward Predictions that Incorporate Effects via Land–Water Linkages. *Ecosystems* 16:909–922. DOI:10.1007/s10021-013-9653-4.

Davis, W. M. 1901. *Physical Geography*. Boston, MA: Ginn and Company.

Dean, D. J., M. L. Scott, P. B. Shafroth, and J. C. Schmidt. 2011. Stratigraphic, Sedimentologic, and Dendrogeomorphic Analyses of Rapid Floodplain Formation Along the Rio Grande in Big Bend National Park, Texas. *Geological Society of America Bulletin* 123:1908–1925.

DeBano, L. F., S. J. DeBano, D. E. Wooster, and M. B. Baker, Jr. 2004. Linkages between Riparian Corridors and Surrounding Watersheds. Pages 77–97 in M. B. Baker, Jr., P. E. Ffolliott, L. F. DeBano, and D. G. Neary (eds.), *Riparian Areas of the Southwestern United States*. Lewis Publishers.

Derrick, D. L. 1997. Twelve low-Cost, Innovative, Landowner Financed, Streambank Protection Demonstration Projects. Pages 446–451 in *Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, and Restoration*. Center for Computational Hydroscience and Engineering, University of Mississippi.

Dickman, A., and S. Cook. 1989. Fire and Fungus in a Mountain Hemlock Forest. *Canadian Journal of Botany* 67:2005–2016.

Diehl, T. H. 1997. *Potential Drift Accumulation at Bridges*. Publication FHWA-RD-97-028. U.S. Department of Transportation, McLean, VA.

Dixit, S. S., J. P. Smol, J. C. Kingston, and D. F. Charles. 1992. Diatoms: Powerful Indicators of Environmental Change. *Environmental Science & Technology* 26 (1):22–33.

Doloff, C. A., and M. L. Warren, Jr. 2003. Fish Relationships With Large Wood in Small Streams. *American Fisheries Symposium* 37:179–193.

Dominguez, L. G., and C. J. Cederholm. 2000. Rehabilitating Stream Channels Using Large Woody Debris with Considerations for Salmonid Life History and Fluvial Geomorphic Processes. Pages 545–563 in E. E. Knudsen. C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser (eds.), *Sustainable Fisheries Management: Pacific Salmon*. Lewis Publishers, New York.

Doremus, H. 2001. Adaptive Management, the Endangered Species Act, and the Institutional Challenges of “New Age” Environmental Protection. *Washburn Law Journal* 41:50–89.

Doremus, H. 2004. The Purposes, Effects, and Future of the Endangered Species Act's Best Available Science Mandate. *Environmental Law* 34:397.

Downs, P. W., and G. M. Kondolf. 2002. Post-project Appraisals in Adaptive Management of River Channel Restoration. *Environmental Management* 29(4):477–496.

Doyle, M. W., and F. D. Shields, Jr. 2000. Incorporation of Bed Texture into a Channel Evolution Model. *Geomorphology* 34:291–309.

Doyle, M. W., E. H. Stanley, J. M. Harbor, and G. S. Grant, G.S. 2003. Dam Removal in the United States: Emerging Needs for Science and Policy. *Eos, Transactions American Geophysical Union* 84:29.

Draut, A. E., J. B. Logan, and M. C. Mastin, M.C. 2011. Channel Evolution on the Dammed Elwha River, Washington, USA. *Geomorphology* 127:71–87.

Drury, T. A. 1999. *Stability and Pool Scour of Engineered Log Jams in the North Fork Stillaguamish River, Washington*. Thesis, Master of Science in Civil Engineering. University of Washington, Seattle.

Drury, T. A., C. Petroff, T. B. Abbe, D. R. Montgomery, and G. R. Pess. 1999. *Evaluation of Engineered Log Jams as a Soft Bank Stabilization Technique: North Fork Stillaguamish River, Washington*. Proceedings of Annual Conference, Water Resources Engineering. American Society of Civil Engineers. Reston, VA.

Dunkerley, D. 2014. Nature and Hydro-Geomorphic Roles of Trees and Woody Debris in a Dryland Ephemeral Stream: Fowlers Creek, Arid Western New South Wales, Australia. *Journal of Arid Environments* 102:40-49.

Dunne, T., and L. B. Leopold. 1978. *Water in Environmental Planning*. New York, NY: W.H. Freeman & Co.

Dwire, K. A., and J. B. Kauffman. 2003. Fire and Riparian Ecosystems in Landscapes of the Western USA. *Forest Ecology and Management* 178:61–74.

East, A. E., G. R. Pess, J. A. Bountry, C. S. Magirl, A. C. Ritchie, J. B. Logan, T. J. Randle, M. C. Mastin, J. T. Minear, J. J. Duda, M. C. Liermann, M. L. McHenry, T. J. Beechie, and P. B. Shafroth. 2014. Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change. *Geomorphology* 228:765–786.

Eaton, B. C. 2006. Bank Stability Analysis for Regime Models of Vegetated Gravel Bed Rivers. *Earth Surface Processes and Landforms* 31:1438–1444.

Eaton, B. C., M. Chuch, and R. G. Millar. 2004. Rational Regime Model of Alluvial Channel Morphology and Response. *Earth Surface Processes and Landforms* 29:511–529.

Eaton, B.C., R. C. Millar, and S. Davidson. 2010. Channel Patterns: Braided, Anabranching and Single Thread. *Geomorphology* 120:353–364.

Eaton, J. M., and D. Lawrence. 2006. Woody Debris Stocks and Fluxes During Succession. *Forest 7Ecology and Management* 232(1-3):46–55.

Eaton, B. C., M. A. Hassan, and S. L. Davidson. 2012. Modeling Wood Dynamics, Jam Formation, and Sediment Storage in a Gravel-Bed Stream. *Journal of Geophysical Research* 117:F00A05, doi:10.1029/2012JF002385.

Edmonds, R. L., T. B. Thomas, and K. P. Maybury. 1993. Tree Population Dynamics, Growth, and Mortality in old-Growth Forests in the Western Olympic Mountains, Washington. *Canadian Journal of Forest Research* 23:512–519.

Eggert, S. L., and J. B. Wallace. 2007. Wood Biofilm as a Food Resource for Stream Detritivores. *Limnology and Oceanography* 52(3):1239–1245.

Ehrman, T. P., and G. A. Lamberti. 1992. Hydraulic and Particulate Matter Retention in a 3rd-Order Indiana Stream. *Journal of the North American Benthological Society*. 11:341–349.

Elliot, R., D. Froehlich, and R. MacArthur. 2012. *Calculating the Potential Effects of Large Woody Debris Accumulations on Backwater, Scour, and Hydrodynamic Loads*. Pages 1213–1222 in Proceedings of the World Environmental and Water Resources Congress 2012. Reston, VA: American Society of Civil Engineers.

Elmore, W., and R. L. Beschta. 1988. The Fallacy of Structures and the Fortitude of Vegetation. *Proceedings of California Riparian Systems Conference*. Davis, Calif.

Elosegi, A., J. Diez, and J. Pozo. 2007. Contribution of Dead Wood to the Carbon Flux in Forested Streams. *Earth Surface Processes & Landforms* 32(8):1219–1228.

Elzinga, C. L., D. W. Salzer, and J. W. Willoughby. 1998. Measuring & Monitoring Plant Populations. Denver, CO: Bureau of Land Management Technical Reference 1730-1.

Embertson, L, and J. Monahan. 2011. *Public Safety Assessment of Habitat Enhancement Projects Fobes and Skookum Reach Restoration Projects South Fork Nooksack River*. GeoEngineers, Bellingham Washinghton. March 1, 2011.

Endreny, T., L. Lautz, and D. I. Siegel. 2011. Hyporheic Flow Path Response to Hydraulic Jumps at River Steps: Flume and Hydrodynamic Models. *Water Resources Research* 47:W02517.

Ensign, S. H., and M. W. Doyle. 2005. In-channel Transient Storage and Associated Nutrient Retention: Evidence from Experimental Manipulations. *Limnology and Oceanography* 50(6):1740–1751.

Environmental Agency. 2009. *The Hyporheic Handbook. a Handbook of the Groundwater-Surface Water Interface and Hyporheic Zone for Environmental Managers.* Science Report SC050070. Available: http://www.hyporheic.net/SCHO1009BRDX-e-e.pdf. Accessed: June 13, 2014.

Erskine, W. D., and A. A. Webb (2003). Desnagging to Resnagging: New Directions in River Rehabilitation in Southeastern Australia. *River Research and Applications*. 19:233–249.

Erskine, W. D., M. J. Saynor, A. C. Chalmers, and S. J. Riley. J. 2012. Water, Wind, Wood, and Trees: Interactions, Spatial Variations, Temporal Dynamics, and their Potential Role in River Rehabilitation. *Journal of Geographical Research* 50(1):60–74.

Eslamian, S. 2014. *Handbook of Engineering Hydrology.* Boca Raton, FL: CRC Press.

Evergreen Funding Consultants (EFC). 2003. A Primer on Habitat Project Costs. Available: http://www.evergreenfc.com/section_services/resources/primer.pdf.

Fahnestock, G. R. 1976. Fires, Fuel, and Flora as Factors in Wilderness Management: The Pasayten Case. *Tall Timbers Fire Ecology Conf*. 15:33–70.

Fahnestock, G. R., and J. K. Agee. 1983. Biomass Consumption and Smoke Production by Prehistoric and Modern Forest Fires in Western Washington. *Journal of Forestry* 81:653–657.

Falke, J. A., K. D. Fausch, R. Magelky, A. Aldred, D. S. Durnford, L. K. Riley, and R. Oad. 2011. The Role of Groundwater Pumping and Drought in Shaping Ecological Futures for Stream Fishes in a Dryland River Basin of the Western Great Plains, USA. *Ecohydrology* 4L682–697. doi:10.1002/eco.158. Available: http://onlinelibrary.wiley.com/doi/10.1002/eco.158/pdf.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to Riverscapes: Bridging the Gap Between Research and Conservation of Stream Fishes. *BioScience* 52(6):483–498.

Faustini, J. M., and J. A. Jones. 2003. Influence of Large Woody Debris on Channel Morphology and Dynamics in Steep, Boulder-Rich Mountain Streams, Western Cascades, Oregon. *Geomorphology* 51:187–205.

Federal Emergency Management Agency (FEMA). 1999. *Riverine Erosion Hazard Areas; Mapping Feasibility Study*. FEMA Technical Services Division, Hazard Study Branch.

Federal Emergency Management Agency (FEMA). 2009. *NFIP Floodplain Management Guidebook: A Local Administrator's Guide to Floodplain Management and the National Flood Insurance Program.* Fifth Edition, Federal Emergency Management Agency Region 10. Bothell, WA.

Federal Highway Administration (FHWA). 1985a. *Design of Spur-Type Streambank Stabilization Structures*. Federal Highway Administration Report No. FHWA/RD-84/101. U.S. Department of Transportation. Washington D.C.

Federal Highway Administration (FHWA) 1985b. *Hydraulic Design of Highway Culverts*. FHWA-IP-58-15. Available: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf.

Federal Highway Administration (FHWA). 2001. *Evaluating Scour at Bridges*, Fourth Edition. Hydraulic Engineering Circular No. 18. Publication No. FHWA NHI 01-001. Available: http://www.stream.fs.fed.us/fishxing/fplibrary/FHWA_2001_Evaluating_Scour_at_Bridges.pdf.

Federal Highway Administration (FHWA). 2005. *Debris Control Structures Evaluation and Countermeasures*. Hydraulic Engineering Circular No. 9. Publication No. FHWA-IF-04-016. Available: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/.

Federal Highway Administration (FHWA). 2006. *Construction Noise Handbook*. Report numbers FHWA-HEP-06-015, DOT-VNTSC-FHWA-06-02, NTIS No. PB2006-109102. U.S. Department of Transportation, Research and Innovative Technology Administration, Cambridge, MA. Available: http://www.fhwa.dot.gov/environment/noise/construction_noise/handbook/. Accessed: July 10, 2014.

Federal Highway Administration (FHWA). 2012a. *Climate Change & Extreme Weather Vulnerability Assessment Framework*. FHWA Publication No: FHWA-HEP-13-005.

Federal Highway Administration (FHWA). 2012b. *Stream Stability at Highway Structures.* Hydraulic Engineering Circular No. 20. Publication No. FHWA-HIF-12-004. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Restoration Implementation, Monitoring, and Management. Chapter 9 in *Stream Corridor Restoration: Principles, Processes and Practices*. National Technical Information Service, U. S. Department of

Commerce, Springfield, VA. Also published as NRCS, U.S. Department of Agriculture (1998) *National Engineering Handbook* (NEH), Part 653. Washington, D.C.

Federal Writers' Project. 1952. *West Virginia A Guide to the Mountain State.* U.S. History Publishers.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large Woody Debris, Physical Process, and Riparian Forest Development in Montane River Networks of the Pacific Northwest. *Geomorphology* 13:133–144. Elsevier Science B.V.

Fifield, J. S. 2011. *Designing and Reviewing Effective Sediment and Erosion Control Plans*. Third Edition., Santa Barbara, CA: Forester Press.

Findlay, S., J. Tank, S. Dye, H. M. Valett, P. J. Mulholland, W. H. McDowell, S. L. Johnson, S. K. Hamilton, J. Edmonds, W. K. Dodds, and W. B. Bowden. 2002. A Cross System Comparison of Bacterial and Fungal Biomass in Detritus Pools of Headwater Streams. *Microbial Ecology* 43(1):55–66.

Findlay, S. E. G., R. L. Sinsabaugh, W. V. Sobczak, and M. Hoostal. 2003. Metabolic and Structural Response of Hyporheic Microbial Communities to Variations In Supply of Dissolved Organic Matter. *Limnology and Oceanography* 48:1608–1617.

Fischenich, C. 2001. *Stability Thresholds for Stream Restoration Materials*, Publication No. ERDC TNEMRRP-SR-29. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fischenich, C., and J.V. Morrow, Jr. 2000. *Streambank Habitat Enhancement with Large Woody Debris.* Publication No. ERDC TN-EMRRP-SR-13. U.S. Army Engineer Research and Development Center.

Fischenich, J. C. 2001. *Plant Material Selection and Acquisition.* EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-33), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fisher, G. B., F. J. Magilligan, J. M. Kaste, and K. H. Nislow. 2010. Constraining the Timescales of Sediment Sequestration Associated with Large Woody Debris using Cosmogenic 7Be. *Journal of Geophysical Research* 115 (F3), DOI: 10.1029/2009JF001352.

Flanagan, S. A. 2004. *Woody Debris Transport Through Low-Order Stream Channels of Northwest California – Implications for Road-Stream Crossing Failure*. M.S. Thesis. Humboldt State University, Arcata, CA. Available: http://www.bof.fire.ca.gov/board/msg_supportedreports.html.

Flanagan, S. A. 2005. *Woody Debris Transport at Road-Stream Crossings. Stream Notes*. Rocky Mountain Research Station. U.S. Forest Service. Fort Collins, CO. October 2005. Available: http://www.stream.fs.fed.us/news/streamnt/pdf/SNOct_05.pdf.

Flebbe, P. A. 1999. Trout Use of Wood Debris and Habitat in Wine Spring Creek, North Carolina. *Forest Ecology and Management* 114:367–376.

Flores, L., A. Larranaga, J. Diez, and A. Elosegi. 2011. Experimental Wood Addition in Streams: Effects on Organic Matter Storage and Breakdown. *Freshwater Biology* 56(10):2156–2167.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins (eds.). 1998. *California Salmonid Stream Habitat Restoration Manual*. 3rd ed. California: California Department of Fish and Game, Inland Fisheries Division, Sacramento.

Flynn, K.M., Kirby, W.H., and Hummel, P.R. 2006. *User's Manual for Program PeakFQ Annual Flood-Frequency Analysis Using Bulletin 17B Guidelines*: *U.S. Geological Survey, Techniques and Methods*. Book 4, Chapter B4.

Fore, L. S., J. R. Karr, and R. W. Wisseman. 1996. Assessing Invertebrate Responses to Human Activities: Evaluating Alternative Approaches. *Journal of the North American Benthological Society* 15(2):212–231.

Forest Ecosystem Management Assessment Team (FEMAT). 1993. *Forest Ecosystem Management: An Ecological, Economic, and Social Assessmen*t. Report of the Forest Ecosystem Management Assessment Team. July.

Forest Products Laboratory. 2010. *Wood Handbook—Wood as an Engineering Material*. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI.

Foster, D. R., and E. R. Boose. 1992. Patterns of Forest Damage Resulting from Catastrophic Wind in Central New England, USA. *Journal of Ecology* 80:79–98.

Fox, M. J. 2001. *A New Look at the Quantities and Volumes of Instream Wood in Forested Basins within Washington State. Master of Science thesis.* College of Forest Resources, University of Washington.

Fox, M. J. 2003. *Spatial Organization, Position, and Source Characteristics of Large Woody Debris in Natural Systems*. Ph.D. dissertation. College of Forest Resources, University of Washington. Seattle, Washington.

Fox, M. J. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of Fisheries Management* 27:342–359.

Frangi, J. L., and A. E. Lugo. 1991. Hurricane Damage to a Flood Plain Forest in the Luquillo Mountains of Puerto Rico. *Biotropica* 23(4a):324–335.

Franklin, J. F., and C. T. Dyrness. 1973. *Natural Vegetation of Oregon and Washington*. USDA Forest Service. Gen. Tech. Rep. PNW-8.

Fremier, A. K., J. I. Seo, and F. Nakamura. 2010. Watershed Controls on the Export of Large Wood from Stream Corridors. *Geomorphology* 117:33–43.

Freschet, G. T., J. T. Weedon, R. Aerts, J. R. van Hal, and J. H. Cornelissen. 2012. Interspecific Differences in Wood Decay Rates: Insights from a New Short-Term Method to Study Long-Term Wood Decomposition. *Journal of Ecology* 100:161–170. doi: 10.1111/j.1365-2745.2011.01896.x.

Friedman, J. M., G. T. Auble, P. B. Shafroth, M. L. Scott, M. F. Merigliano, M. D. Preehling, and E. K.Griffin. 2005. Dominance of Non-Native Riparian Trees in Western USA. *Biological Invasions* 7:747–751.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. *North American Journal of Fisheries Management* 12 182–197.

Frissell, W. J., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A Hierarchical Framework for Stream Habitat Classification: Viewing Streams in a Watershed Context. *Environmental Management* 10(2):199–214.

Furniss, M., T. Ledwith, M. Love, B. McFadin, and S. Flanagan 1998. *Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California*. USDA-Forest Service, Technology & Development Program, Corvallis OR.

Gandy, C. J., and A. P. Jarvis. 2006. *Attenuation of Nine Pollutants in the Hyporheic Zone.* Environment Agency, Bristol, England, June.

Gandy, C. J., J. W. N. Smith, and A. P. Jarvis. 2007. Attenuation of Mining-Derived Pollutants in the Hyporheic Zone: A Review. *Science of the Total Environment* 373:435–446.

Garshelis, D. L. 2000. Delusions in Habitat Evaluation: Measuring Use, Selection, and Importance. Pages 11–165 in L. Boitani and T. K. Fuller (eds.), *Research Techniques in Animal* Ecology. New York: Columbia University Press.

Gastaldo, R. A., and C. W. Degges. 2007. Sedimentology and Paleontology of a Carboniferous Log Jam. *International Journal of Coal Geology* 69:103–113.

Gastaldo, R. A., and T. M. Demko. 2011. The Relationship Between Continental Landscape Evolution and the plant-Fossil Record: Long Term Hydrologic Controls on Preservation. Pages 249–285 in P. A. Allison and D. J. Bottjer (eds.)*, Taphonomy: Process and Bias Through Time*. *Aims & Scope Topics in Geobiology Voume 32*. Springer Netherlands.

Gerecht, K. E., M. B. Cardenas, A. J Guswa, A. H. Sawyer, J. D. Nowinski, and T. E. Swanson. 2011. Dynamic Hyporheic Flow and Heat Transport across a Bed-to-Bank Continuum in a Large Regulated River. *Water Resources Research* 47:W03524.

Ghosn, M., F. Moses, and J. Wang. 2003. *Design of Highway Bridges for Extreme Events*. NCHRP (National Cooperative Highway Research Program) Report 489. National Transportation Board. Washington D.C. Available: http://www.national-academies.org/trb/bookstore.

Gibling, M. R., and N. S. Davies. 2012. Palaeozoic Landscapes Shaped by Plant Evolution. *Nature Geoscience* 5(2):99–105.

Gibling, M. R., A. R. Bashforth, H. J. Falcon-Lang, J. P. Allen, and C. R. Fielding. 2010. Log Jams and Flood Sediment Buildup Caused Channel Abandonment and Avulsion in the Pennsylvanian of Atlantic Canada. *Journal of Sedimentary Research* 80:268–287.

Gillespie, Major G. L. 1881. Report of the Chief of Engineers, U.S. Army. Appendix OO 10, 2603–2605.

Gillespie, N., A. Unthank, L. Campbell, P. Anderson, R. Gubernick, M. Weinhold, D. Cenderelli, B. Austin, D. McKinley, S. Wells, J. Rowan, C. Orvis, M. Hudy, A. Bowden, A. Singler, E. Fretz, J. Levine, and R. Kirn 2014. Flood Effects on Road-Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs. *Fisheries* 39(2):62–76.

Gippel, C. J. 1995. Environmental Hydraulics of Large Woody Debris in Streams and Rivers. *Journal of Environmental Engineering* 121:388–395.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1992. *The Hydraulic Basis of Snag Management*. Center for Environmental Applied Hydrology, University of Melbourne, Melbourne, Victoria, Australia.

Gippel, C. J., I. C. O'Neill, B. L. Finlayson, and I. Schnatz, I. 1994. *Hydraulic Guidelines for Reintroduction and Management of Large Woody Debris in Degraded Lowland Rivers*. Pages 225–239 in Proceedings of the Conference on Habitat Hydraulics. International Association for Hydraulic Research.

Gippel, C. J., I. C. O'Neill, and B. L. Finlayson. 1996. Distribution and Hydraulic Significance of Large Woody Debris in a Lowland Australian River. *Hydrobiologia* 318:179–194.

Goldsmith, W., D. H. Gray, and J. McCullah. 2014. *Bioengineering Case Studies*. New York Springer.

Goode, J. R., C. H. Luce, and J. M. Buffington. 2012. Enhanced Sediment Delivery in a Changing Climate in Semi-Arid Mountain Basins: Implications for Water Resource Management and Aquatic Habitat in the Northern Rocky Mountains. *Geomorphology* 139-140:1–15.

Gordon, R. P., L. K. Lautz, and T. L. Daniluk. 2013. Spatial Patterns of Hyporheic Exchange and Biogeochemical Cycling around Cross-Vane Restoration Structures: Implications for Stream Restoration Design. *Water Resources Research* 49:20185.

Gosnell, H., and E. Kelly. 2010. Peace on the River? Social-Ecological Restoration and Large Dam Removal in the Klamath basin, USA. *Water Alternatives* 3:362–383.

Gotvald, A. J., N. A. Barth, A. G. Veilleux, and C. Parrett. 2012. *Methods for Determining Magnitude and Frequency of Floods in California, Based on Data Through Water Year 2006.* U.S. Geological Survey Scientific Investigations Report 2012–5113. Available: http://pubs.usgs.gov/sir/2012/5113/.

Gowan, C., and K. D. Fausch. 1996. Long-Term Demographic Responses of Trout Populations to Habitat Manipulation in Six Colorado Streams. *Ecological Applications* 6(3):931–946.

Graf, W. L. 1975. The impact of Suburbanization on Fluvial Morphology. *Water Resources Research* 11:690–692.

Graf, W. L. 1999. Dam Nation: A Geographic Census of American Dams and Their Large-Scale Hydrologic Impacts. *Water Resources Research* 35:1305–1311.

Graham, R., and K. Cromack. 1982. Mass, Nutrient Content, and Decay Rate of Dead Boles in Rain Forests of Olympic National Park. *Canadian Journal of Forest Research* 12(3):511–521.

Grant, G. E., and F. J. Swanson. 1995. Morphology and Processes of Valley Floors in Mountain Streams, western Cascades, Oregon. Pages 83–101 in J. D. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock (eds.). *Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph 89*. American Geophysical Union, Washington DC.

Grant, G. E., M. J. Crozier, and F. J. Swanson. 1984. An Approach to Evaluating Off-Site Effects of Timber Harvest Activities on Channel Morphology. *Proceedings of the Symposium on the Effects of Forest and Land Use on Erosion and Slope Stability. Environment and Policy Institute, E-West Center, University of Hawaii, Honolulu* 177–186.

Grant, G., J. Schmidt, J., and S. Lewis. 2003. A Geological Framework for Interpreting Downstream Effects of Dams on Rivers. Page 209–226 in *A Unique River, Water Science Application, Volume 7*. American Geophysical Union.

Gray, D. H. 1974. Reinforcement and Stabilization of Soil by Vegetation. *Journal of Geotechnical Engineering*, 100(GT6):695–699.

Gray, D. H. and D. Barker. 2004. Root-soil Mechanics and Interactions. Pages 113–123 in S. J. Bennett and A. Simon (eds.). *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*, American Geophysical Union, Washington D.C.

Greer, E. S., S. R. Pezeshki, and F. D. Shields, Jr. 2006. Root Elongation of Black Willow Stakes in Response to Cutting Size and Soil Moisture Regime (Tennessee). *Ecological Restoration* 24(3):195–197.

Gregory, K. J., R. J. Davis, and S. Tooth. 1993. Spatial Distribution of Coarse Woody Debris Dams in the Lymington Basin, Hampshire, UK. *Geomorphology* 6:207–224.

Gregory, R., L. Failing, M. Harstone, G. Long, T. MacDaniels, and D. Ohlson. 2012. *Structured Decision Making A Practical Guide to Environmental Choices.* Wiley-Blackwell.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An Ecosystem Perspective of Riparian Zones. *BioScience* 41(8):540–551.

Gregory, S. V., K. L. Boyer, and A. M. Gurnell (eds.). 2003a. *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Gregory, S.V., M.A. Meleason, and D.J. Sobota. 2003b. Modeling the Dynamics of Wood in Streams and Rivers. *American Fisheries Society Symposium* 37:315–335.

Grette, G. B. 1985. The role of Large Organic Debris in Juvenile Salmonid Rearing Habitat in Small Streams. MS thesis, University of Washington, Seattle, WA.

Grimm, W. C. 1967. *Familiar Trees of America*. New York: Harper & Row.

Grizzel, J. D., and N. Wolff. 1998. Occurrence of Windthrow in Forest Buffer Strips and its Effect on Small Streams in Northwest Washington. *Northwest Science* 72:214–223.

Grizzel, J., M. McGowan, D. Smith, and T. Beechie. 2000. Streamside Buffers and Large Woody Debris Recruitment: Evaluating the Effectiveness of Watershed Analysis Prescriptions in the North Cascades Region. TFW-MAGI-00-003. Washington State Timber, Fish & Wildlife.

Groffman, P. M., and eight others. 2009. Challenges to Incorporating Spatially and Temporally Explicit Phenomena (Hotspots and Hot Moments) in Denitrification Models. *Biogeochemistry* DOI 10.1007/s10533-008-9277-5.

Groot, C., and L. Margulis (eds.). 1991. *Pacific Salmon Life Histories*. Vancouver, BC: University of British Columbia Press.

Guardia, J. E. 1933. Some Results of the Log Jams in the Red River. *The Bulletin of the Geographical Society of Philadelphia* 31(3):103–114.

Gunderson, L., and S. S. Light. 2006. Adaptive Management and Adaptive Governance in the Everglades Ecosystem. *Policy Sciences* 39(4):323–334.

Gurnell, A. M., G. E. Petts, N. Harris, J. V. Ward, K. Tockner, P. J. Edwards, and J. Kollman. 2000. Large Wood Retention in River Channels: The Case of the Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms* 25:255–275.

Gurnell, A. M., H. Piegay, F. J. Swanson, and S. V. Gregory. 2002. Large Wood and Fluvial Processes. *Freshwater Biology* 47(4):601–619.

Gurnell, A. J., W. Bertoldi, and D. Corenblit. 2012. Changing River Channels: The Roles of Hydrological Processes, Plants and Pioneer Fluvial Landforms in Humid Temperate, Mixed Load, Gravel Bed Rivers. *Earth-Science Reviews* 111:129–141.

Guyette, R. P., and M. Stambaugh. 2003. The Age and Density of Ancient and Modern Oak Wood in Streams and Sediments. *The International Association of Wood Anatomists (IAWA) Journal* 24:345–353.

Guyette, R. P., D. C. Dey, and M. C. Stambaugh 2008. The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits. *Ecosystems* 11:643–653.

Habron, G. 2003. Role of Adaptive Management for Watershed Councils. *Environmental Management* 31(1):0029–0041.

Hafs, A. W., L. R. Harrison, R. M. Utz, and T. Dunne. 2014. Quantifying the Role of Woody Debris in Providing Bioenergetically Favorable Habitats for Juvenile Salmon. *Ecological Modelling* 285: 30–38.

Haga, H., T. Kumagai, K. Otsuki, and S. Ogawa. 2002. Transport and Retention of Coarse Woody Debris in Mountain Streams: An In Situ Field Experiment of Log Transport and a Field Survey of Coarse Woody Debris Distribution. *Water Resources Research* 38:1126, doi:10.1029/2001WR001123.

Hairston, N. G. 1987. *Community Ecology and Salamander Guilds*. Cambridge University Press, 1987.

Hall, L. S., P. R. Krausman, and M. L. Morrison. 1997. The Habitat Concept and a Plea for Standard Terminology. *Wildlife Society Bulletin* 25(1):173–182.

Hall, R. O., and J. L. Meyer. 1998. The Trophic Significance of Bacteria in a Detritus-Based Stream Food Web. *Ecology* 79:1995–2012.

Hall, R. O., J. B. Wallace, and S. L. Eggert. 2000. Organic Matter Flow in Stream Food Webs with Reduced Detrital Resource Base. *Ecology* 81(12):3445–3463.

Hamill, L. 1999. *Bridge Hydraulics.* New York, NY: Routledge.

Hamlet, A. F., M. M. Elsner, G. S. Mauger, S.-Y. Lee, I. Tohver, and R. A. Norheim. 2013. An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. *Atmosphere-Ocean*, 51(4):392–415.

Hammer, T. R. 1972. Stream Channel Enlargement due to Urbanization. *Water Resources Research* 8:1530–1540.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological Research* 15:133–302.

Harrod, R. 2000. Ecologist with the Wenatchee National Forest Service, Wenatchee, WA. Personal Communication.

Hart, E. A. 2002. Effects of Woody Debris on Channel Morphology and Sediment Storage in Headwater Streams in the Great Smoky Mountains, Tennessee-North Carolina. *Physical Geography* 23:492–510.

Hartopo, 1991. The *Effect of Raft Removal and Dam Construction on the Lower Colorado River, Texas*. Unpublished M.S. Thesis, Texas A & M University.

Harvey, J. W., and ten others. 2012. Hydrogeomorphology of the Hyporheic Zone: Stream Solute and Fine Particle Interactions with a Dynamic Streambed. *Journal of Geophysical Research* 117:G00N11.

Harvey, M. D, D. S. Biedenharn, and P. Combs. 1988. Adjustments of Red River Following Removal of the Great Raft in 1873 [abs.]. *Eos, Transactions of the American Geophysical Union* 69(18):567.

Harwood, K., and A. G. Brown. 1993. Fluvial Processes in a Forested Anastomosing River: Flood Partitioning and Changing Flow Patterns. *Earth Surface Processes and Landforms* 18:741–748.

Hauer, F. R. 1989. Organic Matter Transport and Retention in a Blackwater Stream Recovering from Flow Augmentation and Thermal Discharge. *Regulated Rivers: Research and Management* 4:371–380.

Hawkins, C. P., J. L. Kershner, P. A. Bisson, M. D. Bryant, L. M. Decker, S. V. Gregory, D. A. McCullough, C. K. Overton, G. H. Reeves, R. J. Steedman, and M. K. Young. 1993. A Hierarchical Approach to Classifying Stream Habitat Features. *Fisheries* 18(6):3–12.

Hax, C. L., and S. W. Golladay. 1993. Macroinvertebrate Colonization and Biofilm Development on Leaves and Wood in a Boreal River. *Freshwater Biology* 29(1):79–87.

Hayes, D. B., C. P. Ferreri, and W. W. Taylor. 1996. Linking Fish Habitat to Their Population Dynamics. *Canadian Journal of Fisheries and Aquatic Sciences* 53(S1):383–390.

Hazard, J. T. 1948. *Our Living Forests, the Story of Their Preservation and Multiple Use*. Seattle, WA: Superior Publishing.

He, Z., W. Wu, and F. D. Shields, Jr. 2009. Numerical Analysis of Effects of Large Wood Structures on Channel Morphology and Fish Habitat Suitability in a Southern U.S. Sandy Creek. *Ecohydrology* 2 (3):370–380. doi: 10.1002/eco.60.

Hedman, C. W., D. H. Van Lear, and W. T. Swank. 1996. In-Stream Large Woody Debris Loading and Riparian Forest Seral Stage Associations in the Southern Appalachian Mountains. *Canadian Journal of Forest Research* 26:1218–1227.

Heede, B. H. 1972. Influences of a Forest on the Hydraulic Geometry of Two Mountain Streams. *Water Resources Bulletin* 8:523–530.

Heede, B. H. and J. N. Rinne, 1990. Hydrodynamic and Fluvial Morphological Processes: Implications for Fisheries Management and Research. *North American Journal of Fisheries Management*, 10:249–268.

Helmus, M. R. and G. G. Sass. 2008. The Rapid Effects of a Whole-Lake Reduction of Coarse Woody Debris on Fish and Benthic Macroinvertebrates. *Freshwater Biology* 53:1423–1433.

Helton, A. M., and 22 others. 2011. Thinking outside the Channel: Modeling Nitrogen Cycling in Networked River Ecosystems. *Frontiers in Ecology and the Environment* 9:229–238.

Henderson, J. 1996. Unpublished Data Regarding Tree Height vs. Age for Two Common Plant Association Groups. USDA Forest Service, Pacific Northwest Region, Mount Lake Terrace, WA.

Henderson, J. A., R. D. Lesher, D. H. Peter and D. C. Shaw. 1992. *Field Guide to the Forested Plant Associations of the Mt. Baker-Snoqualmie National Forest*. USDA Forest Service, Pacific Northwest Region. Tech paper R6 ECOL TP 028-91.

Herlihy, A. T., J. L. Stoddard, and C. Burch Johnson. 1998. The Relationship between Stream Chemistry and Watershed Land Cover Data in the Mid-Atlantic Region, U.S. Pages 377–386 in *Biogeochemical Investigations at Watershed, Landscape, and Regional Scales*. Springer Netherlands.

Herrera Environmental Consultants, Inc. 2006. *Conceptual Design Guidelines: Application of Engineered Logjams.* Prepared for Scottish Environmental Protection Agency, Galashiels, United Kingdom.

Hershey, K. 1995. *Characteristics of Forests at Spotted Owl Nest Sites in the Pacific Northwest.* M.S. thesis, Oregon State University, Corvallis.

Hertzberg, R. 1954. Wave-Wash Control on Mississippi River Levees. *Transactions of the ASCE* 119(2688):628–638.

Hester, E. T., and M. W. Doyle. 2008. In-Stream Geomorphic Structures as Drivers of Hyporheic Change. *Water Resources Research* 44:W03427.

Hester, E. T., and M. N. Gooseff. 2010. Moving Beyond the Banks: Hyporheic Restoration is Fundamental to Restoring Ecological Services and Functions of Streams. *Environmental Science and Technology* 44:1521–1525.

Hester, E. T., M. W. Doyle, and G. C. Poole. 2009. The Influence of in-Stream Structures on Summer Water Temperatures via Induced Hyporheic Exchange. *Limnology and Oceanography* 54:355–367.

Hewitt, E. R. 1934. *Hewitt's Handbook of Stream Improvement.* New York: The Marchbanks Press.

Hickin E. J. 1984. Vegetation and River Channel Dynamics. *Canadian Geographer* 28(2):111–126.

Hilborn, R., and M. Mangel. 1997. *The Ecological Detective*. Princeton, NJ: Princeton University Press.

Hilborn, R., and C. J. Walters. 1992. *Quantitative Fish Stock Assessment*. London: Chapman and Hall.

Hilderbrand, R. H., A. D. Lemly, C. A. Dollof, and K. L. Harpster. 1997. Effects of Large Woody Debris Placement on Stream Channels and Benthic Macroinvertebrates. *Canadian Journal of Fisheries and Aquatic Sciences* 54:931–939.

Hilderbrand, R. H., A. D. Lemly, C. A. Dolloff, and K. L. Harpster. 1998. Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects. *North American Journal of Fisheries Management* 18:161–167.

Hinkle, S. R., J. H. Duff, F. J. Triska, A. Laenen, E. B. Gates, K. E. Bencala, D. A. Wentz, and S. R. Silva. 2001. Linking Hyporheic Flow and Nitrogen Cycling near the Willamette River – A Large River in Oregon, USA. *Journal of Hydrology* 244:157–180.

Hinkle, S. R., D. S. Morgan, L. L. Orzol, and D. J. Polette. 2007. *Ground Water Redox Zonation near La Pine, Oregon: Relation to River Position within the Aquifer-Riparian Zone Continuum.* U.S. Geological Survey Scientific Investigations Report 2007–5239.

Hinkle, S. R., K. E. Bencala, D. A. Wentz, and D. P. Krabbenhoft. 2013. Mercury and Methylmercury Dynamics in the Hyporheic Zone of an Oregon Stream. *Water Air and Soil Pollution* 225, article 1694.

Hoellein, T. J., J. L. Tank, E. J. Rosi-Marshall, S. A. Entrekin, and G. A. Lamberti. 2007. Controls on Spatial and Temporal Variation of Nutrient Uptake in Three Michigan Headwater Streams. *Limnol. Oceanogr*.52:1964–1977.

Hogan, D. L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. Pages 343–353 in R. L. Beschta, T. Blinn, G. E. Grant, F. J. Swanson, and G. G. Ice (eds.), *Erosion and Sedimentation in the Pacific Rim*. IAHS Publication No.165.

Holling, C. S. 1978. *Adaptive Environmental Assessment and Management*. Chichester, UK: Wiley Interscience.

Hollis, G. E. 1975. The Effects of Urbanization on Floods of Different Recurrence Intervals. *Water Resources Research* 11:431–435.

Holstine, C. 1992. *An Historical Overview of the Wenatchee National Forest, Washington*. Rep. 100-80. Archaeological and historical Services. Eastern Washington University, Cheney.

Homer, C. C., L. Huang, B. W. Yang, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* 70(7):829–840.

Hough-Snee, N., A. Kasprak, B. B. Roper, and C. S. Meredith. 2014. Direct and Indirect Drivers of Instream Wood in the Interior Pacific Northwest, USA: Decoupling Climate, Vegetation, Disturbance, and Geomorphic Setting. *Riparian Ecology and Conservation* 2:14–34.

House, R. A., and P. L. Boehne. 1985. Evaluation of Instream Enhancement Structures for Salmonid Spawning and Rearing in a Coastal Oregon Stream. *North American Journal of Fish Management* 5:283–295.

House, R. A., and P. L. Boehne. 1986. Effects of Instream Structures on Salmonid Habitat and Populations in Tobe Creek, Oregon. *North American Journal of Fisheries Management* 6:283–295.

Howey, C. A. F., and S. A. Dinkelacker. 2009. Habitat Selection of the Alligator Snapping Turtle (*Macrochelys temminckii*) in Arkansas. *Journal of Herpetology* 43(4):589–596.

Hudson, P. L., R. W. Griffiths, and T. J. Wheaton. 1992. Review of Habitat Classification Schemes Appropriate to Streams, Rivers, and Connecting Channels in the Great Lakes Drainage Basin. Pages 73–107 in W. D. N. Busch and P. G. Sly (eds.), *The Development of an Aquatic Habitat Classification System for Lakes.* Ann Arbor, MI: CRC Press.

Hughes, R. M. (ed.). 1993. *Stream Indicators and Design Workshop.* EPA/600/R-93/138. U.S. Environmental Protection Agency, Corvallis, OR.

Hughes, T. J. R., G. R. Feijoo, L. Mazzei, and J.-B. Quincy. 1998. The Variational Multiscale Method—A Paradigm for Computational Mechanics. *Computer Methods in Applied Mechanics and Engineering* 166 (1-2):3–24.

Hurlbert, S. H. 1984. Pseudoreplication and the Design of Ecological Field Experiments. *Ecological Monographs* 54 (2:187–211.

Huryn, A. D., and J. B. Wallace. 1987. Local Geomorphology as a Determinant of Macrofaunal Production in a Mountain Stream. *Ecology* 68:1932–1942.

Hutchens, J. J., E. F. Benfield, and J. R. Webster. 1997. Diet and Growth of a Leaf-Shredding Caddisfly in Southern Appalachian Streams of Contrasting Disturbance History. *Hydrobiologia* 346:193–201.

Hutchinson, G. E. 1957. Concluding Remarks. *Cold Springs Harbor Symposium on Quantitative Biology* 22:415–427.

Hyatt, T. L., and R. J. Naiman. 2001. The Residence Time of Large Woody Debris in the Queets River, Washington, USA. *Ecological Applications* 11(1):191–202.

Hygelund, B., and M. Manga. 2003. Field Measurements of Drag Coefficients for Model Large Woody Debris. *Geomorphology* 51:175–185.

Ibrahim, T. D. Lerner, and S. Thornton. 2011. Accounting for the Groundwater-Surface Water Interface in Contaminated Land Assessments. *CL:AIRE Technical Bulletin* 15.

ICF International. 2010. *Instream Woody Material Installation and Monitoring Guidance Manual.* Sacramento Area Flood Control Agency, Sacramento, California.

Idaho Office of the Administrative Rules Coordinator. Undated. *Idaho Minimum Standards for Logging—Sections 17.08.01 through 17.08.16*. Available: http://adminrules.idaho.gov/rules/current/17/index.html. Accessed: July 10, 2014. Industrial Commission. Idaho Office of the Administrative Rules Coordinator, Boise, Idaho.

Ikeya, H. 1981. A Method for Designation Forested Areas in Danger of Debris Flows. In E*rosion and Sediment Transport in Pacific Rim Steeplands.* Edited by T. R. H. Davies and A. J. Pearce. *International Association of Hydrological Sciences, Publication* 132:576–588.

Interagency Advisory Committee on Water Data (IACWD). 1982. *Guidelines for Determining Flood Flow Frequency*. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia. 183 p.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds.). Cambridge, UK, and New York, NY: Cambridge University Press.

International Union for Conservation of Nature (IUCN). 2014. I*UCN Releases an Economic Framework for Analyzing Forest Landscape Restoration Decisions*. Available: http://cmsdata.iucn.org/downloads/flr_economic_analysis_tutorial___july_2014_1.pdf.

Jackson, T. R., R. Haggerty, and S. V. Apte. 2013. A Fluid-Mechanic Classification Scheme for Surface Transient Storage in Riverine Sediments: Quantitatively Separating Surface from Hyporheic Storage. *Hydrology and Earth System Sciences* 17:2747–2779.

Jacobson, P. J., K. M. Jacobson, P. L. Angermeier, and D. S. Cherry. 1999. Transport, Retention, and Ecological Significance of Woody Debris within a Large Ephemeral River. *Journal of the North American Benthological Society* 18:429–444.

James, L. D. 1965. Using a Digital Computer to Estimate the Effects of Urban Development on flood Peaks. *Water Resources Research* 1:223–234.

Jeffries, R., S. E. Darby, and D. A. Sear. 2003. The Influence of Vegetation and Organic Debris on Flood-Plain Sediment Dynamics: Case Study of a Low-Order Stream in the New Forest, England. *Geomorphology* 51:61–80.

Jenkins, M. J., and E. G. Hebertson. 1998. *Using Vegetative Analysis to Determine the Extent and Frequency of Avalanches in Little Cottonwood Canyon, Utah.* Department of Forest Resources, Utah State University. WestWide Avalanche Network, UT.

Jia, Y., S. Scott, Y. Xu, and S. S. Y. Wang. 2009. Numerical Study of Flow Affected by Bendway Weirs in Victoria Bendway, the Mississippi River. *Journal of Hydraulic Engineering* 135(11):902–916.

Johnson, A. W., and J. M. Stypula (eds.). 1993. *Guidelines for Bank Stabilization Projects in the Riverine Environments of King County*. King County Department of Public Works, Surface Water Management Division. Seattle, WA.

Johnson, L. B., D. H. Breneman, and C. Richards. 2003. Macroinvertebrate Community Structure and Function Associated with Large Wood in Low Gradient Streams. *River Research and Applications* 19:199–218.

Johnson, P. A., R. D. Hey, M. Tessier, and D. L. Rosgen. 2001. Use of Vanes for Control of Scour at Vertical Wall Abutments. *Journal of Hydraulic Engineering* 127(9):772–778.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian Forest Disturbances by a Mountain Flood—The Influence of Floated Wood. *Hydrological Processes* 14:3031–3050.

Johnston, N. T., E. A. MacIsaac, P. J. Tschaplinski, and K. J. Hall. 2004. Effects of the Abundance of Spawning Sockeye Salmon (*Oncorhynchus nerka*) on Nutrients and Algal Biomass in Forested Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 61:384–403.

Johnston, N. T., S. A. Bird, D. L. Hogan, and E. A. MacIsaac. 2011. Mechanisms and Source Distances for the Input of Large Woody Debris to Forested Streams in British Columbia, *Canada Canadian Journal of Forest Research*. 41(11):2231–2246.

Jones, C. and P. Johnson. 2015. Risk Assessment for Stream Modification Projects in Urban Settings. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*, Part A: Civil Engineering. 10.1061/AJRUA6.0000815, 04015001.

Jonsson, B., and N. Jonsson. 2003. Migratory Atlantic Salmon as Vectors for the Transfer of Energy and Nutrients Between Freshwater and Marine Environments. *Freshwater Biology* 48:21–27.

Jowett, I. G., J. W. Hayes, and M. J. Duncan. 2008. *A Guide to Instream Habitat Survey Methods and Analysis.* NIWA Science and Technology Series No. 54. Available: http://www.niwa.co.nz/sites/niwa.co.nz/files/a_guide_to_instream_habitat_survey_methods_and_analysis.pdf.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The Flood Pulse Concept in River Floodplain Systems. Pages 110-127 in D. P. Dodge (ed.), *Proceedings of the International Large River Symposium.*

Kail, J., D. Hering, S. Muhar, J. Gerhard, and S. Preis. 2007. The Use of Large Wood in Stream Restoration: Experiences from 50 Projects in Germany and Austria. *Journal of Applied Ecology* 44:1145–1155.

Kanes, W. H. 1970. Facies and Development of the Colorado River Delta in Texas. Pages 78–106 in J. P. Morgan and R. H. Shaver (eds.), *Deltaic Sedimentation Modern and Ancient*. Special Publication No.15. Society of Economic Paleontologists and Mineralogists. Tulsa, Oklahoma.

Kaplan, R. S. 2008. Conceptual Foundations of the Balanced Scorecard. *Handbook of Management Accounting Research* 3:1253–1269.

Karr, J. R. 1981. Assessment of Biotic Integrity Using Fish Communities. *Fisheries* 6(6):21–27.

Karr, J. R., and B. L. Kerans. 1991. *Components of Biological Integrity: Their Definition and Use in Development of an Invertebrate IBI*. Midwest Pollution Control Biologists Meeting, Chicago, IL, 1991, Proceedings: US Environmental Protection Agency, Region V, EPA-905/R-92-003.

Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. *Assessing Biological Integrity in Running Waters: A Method and its Rationale.* Illinois Natural History Survey Special Publication 5, Urbana, IL.

Kasprak, A., F. J. Magilligan, K. H. Nislow, and N. P. Snyder, N.P. 2012. A Lidar-Derived Evaluation of Watershed-Scale Large Woody Debris Sources and Recruitment Mechanisms: Coastal Maine, USA. *River Research Applications* 28:1462–1476.

Kati, V., P. Devillers, M. Dufrene, A. Legakis, D. Vokou, and P. Lebrun. 2004. Testing the Value of Six Taxonomic Groups as Biodiversity Indicators at a Local Scale. Conservation Biology 18(3):667–675.

Kauffman, J. B., R. L. Beschta, N. Otting, and D. Lytjen. 1997. An Ecological Perspective of Riparian and Stream Restoration in the Western United States. *Fisheries (Bethesda)* 22:12–24.

Kaufmann, P. R., P. Levine, E. G. Robison, C. Seeliger, and D. V. Peck. 1999. *Quantifying Physical Habitat in Streams*. U.S. Environmental Protection Agency, Washington, D.C. Available: http://www.epa.gov/emap2/html/pubs/docs/groupdocs/surfwatr/field/phyhab.pdf.

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010: Rising Stream and River Temperatures in the United States. *Frontiers in Ecology and the Environment* 8:461–466. doi:10.1890/090037.

Keeney, R. L., and H. Raiffa. 1993. *Decisions with Multiple Objectives Preferences and Value Tradeoffs*. Cambridge University Press.

Keeton, W. S., C. E. Kraft, and D. R. Warren. 2007. Mature and Old-Growth Riparian Forests: Structure, Dynamics and Effects on Adirondack Stream Habitats. *Ecological Applications* 17:852–868.

Keith, D. A., T. G. Martin, E. McDonald-Madden, and C. Walters. 2011. Uncertainty and Adaptive Management for Biodiversity Conservation. *Biological Conservation* 144(4):1175–1178.

Keller, E. A. and A. MacDonald. 1995. River Channel Change: The Role of Large Woody Debris. Pages 217–236 in A. Gurnell and G. Petts (eds.), *Changing River Channels*. John Wiley and Sons, Chichester. 217-235.

Keller, E. A., and F. J. Swanson. 1979. Effects of Large Organic Material on Channel Form and Fluvial Processes. *Earth Surface Processes* 4:361–380.

Keller, E. A., and T. Tally. 1979. Effects of Large Organic Debris on Channel Form and Fluvial Processes in the Coastal Redwood Environment. Pages 169–197 in D. D. Rhodes and G. P. Williams (eds.), *Adjustments of the Fluvial System.* Proceedings of the 10th Annual Binghamton Geomorphology Symposium. Kendal-Hunt. Dubuque, IA.

Kellndorfer, J., W. Walker, E. LaPoint, J. Bishop, T. Cormier, G. Fiske, M. Hoppus, K. Kirsch, and J. Westfall. 2012. *NACP Aboveground Biomass and Carbon Baseline Data* (NBCD 2000), U.S.A. 2000. Data set. Available: http://daac.ornl.gov from ORNL DAAC, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1081. See more at: http://www.whrc.org/mapping/nbcd/#sthash.7OB99UEf.dpuf.

Kennard, P., G. Pess, T. Beechie, B. Bilby, and D. Berg. 1998. Riparian-in-a-Box: A Manager's Tool to Predict the Impacts of Riparian Management on Fish Habitat. Pages 483-490. in M. K. Brewin and D. M. A. Monita (eds.), *Forest-Fish Conference: Land Management Practices Affecting Aquatic Ecosystems*. Proceedings of Forest-fish conference, May 1-4, 1996, Calgary, Alberta. Natural Resources Canada. North For. Cent., Edmonton, Alberta Inf. Rep. NOR-X-356.

Kennedy, B. P., K. H. Nislow, and C. L. Folt. 2008. Habitat-Mediated Foraging Limitations Drive Survival Bottlenecks for Juvenile Salmon. *Ecology* 89(9):2529–2541.

Keown, M. P., N. R. Oswalt, E. B. Perry, and E. A. Dardeau Jr. 1977. *Literature Survey and Preliminary Evaluation of Streambank Protection Methods*. Technical Report No. WES-TR-H-77-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kerans, B. L., and J. R. Karr. 1994. A Benthic Index of Biotic Integrity (B-IBI) for Rivers of the Tennessee Valley. *Ecological Applications*. 4(4):768–785.

Kingsford, R. T., K. F. Walker, R. E. Lester, W. J. Young, P. G. Fairweather, J. Sammut, and M. C. Geddes. 2011. A Ramsar Wetland in Crisis—The Coorong, Lower Lakes and Murray Mouth, Australia. *Marine and Freshwater Research* 62(3):255–265.

Kirkwood, C. W. 1997. *Strategic Decision Making. Multi-Objective Decision Analysis with Spreadsheets.* Wadsworth.

Klingeman, P. C., S. M. Kehe, and Y. A. Owusu. 1984. *Streambank Erosion Protection and Channel Scour Manipulation Using Rockfill Dikes and Gabions*. Water Resources Research Institute, Oregon State University. Salem, OR.

Kloehn, K., T. Beechie, S. Morley, H. Coe, and J. Duda, J. 2008. Influence of Dams on River-Floodplain Dynamics in the Elwha River, Washington. *Northwest Science* 82:224–235.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in Snowfall versus Rainfall in the Western United States. *Journal of Climate* 19:4545–4559. doi:10.1175/JCLI3850.1. Available: http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3850.1.

Knox, J. C. 1993. Large Increases in Flood Magnitude in Response to Modest Changes in Climate. *Nature*, 361(6411):430–432.

Knox, J. C. 2000. Sensitivity of Modern and Holocene Floods to Climate Change. *Quaternary Science Reviews*, 19(1):439–457.

Knutson, M., and P. Fealko. 2014. *Pacific Northwest Region Resource and Technical Services—Large Woody Material Risk Based Design Guidelines*. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.

Knutti, R., G. Abramowitz, M. Collins, V. Eyring, P. J. Gleckler, B. Hewitson, and L. Mearns. 2010. Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, and P.M. Midgley (eds.), *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Assessing and Combining Multi Model Climate Projections.* IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Koehn, J. D., and S. J. Nicol. 2014. Comparative Habitat Use by Large Riverine Fishes. *Marine and Freshwater Research* 65(2):164–174.

Koehn, J. D., W. G. O'Connor, P. D. Jackson. 1994. Seasonal and size-Related Variation in Microhabitat Use of a Small Victorian Stream Fish Assemblage. *Australian Journal of Marine and Freshwater Research* 45:1353–1366.

Kondolf, G. M. 1995. Five Elements for Effective Stream Restoration. *Restoration Ecology* 3:133–136.

Kondolf, G. M. 1996. A Cross Section of Stream Channel Restoration. *Journal of Soil and Water Conservation* 51(2):119–125.

Kondolf, G. M. 1998. Lessons Learned from River Restoration Projects in California. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8(1):39–52.

Kondolf, G. M. 2000. Some Suggested Guidelines for Geomorphic Aspects of Anadromous Salmonid Habitat Restoration Proposals. *Restoration Ecology* 8:48–55.

Konsoer, K. M. 2014. *Influence of Riparian Vegetation on Near-Bank Flow Structure and Rates of Erosion on a Large Meandering River.* Ph.D. Dissertation, University of Illinois, Urbana-Champaign. 236 p.

Konsoer, K. M., J. A. Zinger, and G. Parker, G., 2013. Bankfull Hydraulic Geometry of Submarine Channels Created by Turbidity Currents: Relations Between Bankfull Channel Characteristics and Formative Flow Discharge. *Journal of Geophysical Research – Earth Surface* 118:1–13. doi: 10.1029/2012JF00242.

Kraft, C. E., and D. R. Warren. 2003. Development of Spatial Pattern in Large Woody Debris and Debris Dams in Streams. *Geomorphology* 51:127–139.

Kramer, N., and E. Wohl. 2014. Estimating Fluvial Wood Discharge using Time-Lapse Photography with Varying Sampling Intervals. *Earth Surface Processes and Landforms* 39:844–852.

Kratzer, J. F., and D. R. Warren. 2013. Factors Limiting Brook Trout Biomass in Northeastern Vermont Streams. *North American Journal of Fisheries Management* 33(1):130–139.

Krause, C., and C. Roghair. 2014. *Inventory of Large Wood in the Upper Chattooga River Watershed, 2007–2013*. U.S. Forest Service Southern Research Station, Center for Aquatic Technology Transfer. Blacksburg, VA.

Krause, S., M. J. Klaar, D. M. Hannah, J. Mant, J. Bridgeman, M. Trimmer, and S. Manning-Jones. 2014. The Potential of Large Woody Debris to Alter Biogeochemical Processes and Ecosystem Services in Lowland Rivers. *Wiley Interdisciplinary Reviews (WIREs): Water* 1:263–275.

Kreutzweiser, D.P., K. P. Good, and T. M. Sutton. 2005. Large Woody Debris Characteristics and Contributions to Pool Formation in Forest Streams of the Boreal Shield. *Canadian Journal of Forest Research* 35:1213–1223.

Kruys, N., B. G. Jonsson, and G. Stahl. 2002. A Stage-Based Matrix Model for Decay-Class Dynamics of Woody Debris. *Ecological Applications* 12(3):773–781.

Kukulak, J., A. Pazdur, and T. Kuc. 2002. Radiocarbon Dated Wood Debris in Floodplain Deposits of the San River in the Bieszczady Mountains. *Geochronometria* 21:129–136.

Kuhnle, R. A., C. V. Alonso, and F. D. Shields Jr. 1999.Volume of Scour Holes Associated with 90-degree Spur Dikes. *Journal of Hydraulic Engineering* 125(9):972–978.

Kuhnle, R. A., C. V. Alonso, and F. D. Shields Jr. 2002. Local Scour Associated with Angled Spur Dikes. *Journal of Hydraulic Engineering* 128(12):1087–1093.

Lagasse, P. F., P. E. Clopper, J. E. Ortiz-Page, L. W. Zevenbergen, L. A. Ameson, J. D. Schall, and L. G. Girard. 2009. *Bridge Scour and Stream Instability Countermeasures Experience, Selection and Design Guidance Volumes 1 and 2.* HEC-23, Third Edition. Federal Highway Administration. Washington, D.C.

Lagasse, P. F., P. Clopper, L. Zevenbergen, W. Spitz, and L. G. Girard.2010. *Effects of Debris on Bridge Pier Scour*. Federal Highway Administration. Washington, D.C.

Lagasse, P. F., L. W. Zevenbergen, W. J. Spitz, and L. A. Arneson 2012. *Stream Stability at Highway Structures, Fourth Edition. Hydraulic Engineering Circular No. 20*. Publication No. FHWA-HR-12-004. Office of Technology, Federal Highway Administration, Washington, DC.

Lakowicz, J. R., and G. Weber. 1973. Quenching of Fluorescence by Oxygen. Probe for Structural Fluctuations in Macromolecules. *Biochemistry* 12(21): 4161–4170.

Lampert, W. 1978. Release of Dissolved Organic-Carbon by Grazing Zooplankton. *Limnology and Oceanography* 23(4):831–834.

Lancaster, S. T., S. K. Hayes, and G. E. Grant. 2001. Modeling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds. *Geomorphic Processes and Riverine Habitat, Water Science and Application Volume 4*:85–102. American Geophysical Union.

Landres, P. B., J. Verner, and J. W. Thomas. 1988. Ecological Uses of Vertebrate Indicator Species: A Critique. *Conservation Biology* 2(4):316–328.

Langbien, W. B., and S. B. Schumm. 1958. Yield of Sediment in Relation to Mean Annual Precipitation. *American Geophysical Union Transactions* 39:1076–1084.

Lange-Bertalot, H. 1979. Pollution Tolerance of Diatoms as a Criterion for Water Quality Estimation. *Nova Hedwigia, Beih.* 64:285–304.

Lansdown, K., and seven others. 2012. Characterization of Key Pathways of Dissimitory Nitrate Reduction and Their Response to Complex Organic Substrates in Hyporheic Sediments. *Limnology and Oceanography* 57:387–400.

Lassettre, N. S. and R. R. Harris 2001. *The Geomorphic and Ecological Influence of Large Woody Debris in Streams and Rivers*. University of California, Berkeley, CA.

Lassettre, N.S., and G.M. Kondolf. 2003. *Process Based Management of Large Woody Debris at the Basin Scale, Soquel Creek, California*. Report Presented to California Department of Forestry and Fire Protection and Soquel Demonstration State Forest. Available: http://www.fire.ca.gov/resource_mgt/downloads/reports/LWDinSoquelCreek.pdf.

Lassettre, N. S., and G. M. Kondolf. 2012. Large Woody Debris in Urban Stream Channels: Redefining the Problem. *River Research and Applications* 28(9):1477–1487.

Lassettre, N., and H. Piégay. 2008. Decadal Changes in Distribution and Frequency of Wood in a Free Meandering River, the Ain River, France. *Earth Surface Processes and Landforms* 1112:1098–1112.

Latterell, J. J., and R. J. Naiman. 2007. Sources and Dynamics of Large Logs In a Temperate Floodplain River. *Ecological Applications* 17:1127–1141.

Latterell, J. J., J. S. Bechtold, T. C. O'Keefe, R. Van Pelt, and R. J. Naiman. 2006. Dynamic Patch Mosaics and Channel Movement in an Unconfined River Valley of the Olympic Mountains *Freshwater Biology* 51(3):523–544*.*

Lautz, L. K., and R. M. Fanelli. 2008. Biogeochemical Hotspots in the Streambed around Restoration Structures. *Biogeochemistry* 91:85–104.

Lautz, L. K., D. I. Siegel, and R. L. Bauer. 2006. Impact of Debris Dams on Hyporheic Interaction along a Semi-Arid Stream. *Hydrological Processes* 20:183–196.

Lautz, L. K., R. M. Fanelli, N. Kranes, and D. I. Siegel. 2007. Abstract. Sediment distribution around Debris Dams: Impacts on Streambed Hydrology, Biogeochemistry and Temperature Dynamics in Small Streams. *Geological Society of America Annual Meeting* (28–31 October 2007), Paper No. 180-4.

Lautz, L. K., N. T. Kranes, and D. I. Siegel. 2010. Heat Tracing of Heterogeneous Exchange Adjacent to In-Stream Geomorphic Features. *Hydrological Processes* 24:3074–3086.

Ledger, M. E. and M. J. Winterbourn. 2000. Growth of New Zealand Stream Insect Larvae in Relation to Food Type. *Archiv fur Hydrobiologie* 149:353–364.

Lee, K. N. 1999. Appraising Adaptive Management. *Conservation Ecology* 3(2):3.

Lee, P. C., C. Smyth, and S. Boutin. 2004. Quantitative Review of Riparian Buffer Width Guidelines from Canada and the United States. *Journal of Environmental Management* 70:165–189.

Lehane, B. M., P. S. Giller, J. O'Halloran, C. Smith, J. Murphy. 2002. Experimental Provision of Large Woody Debris in Streams as a Trout Management Technique. *Aquatic Conservation-Marine and Freshwater Ecosystems* 12:289–311.

Lemly, A. D., and R. H. Hilderbrand. 2000. Influence of Large Woody Debris on Stream Insect Communities and Benthic Detritus. *Hydrobiologia* 421:179–185.

Leopold, L. B. 1973. River Channel Change with Time: An Example. *Geological Society of America Bulletin* 84:1845–1860.

Lester, R. E. and A. J. Boulton. 2008. Rehabilitating Agricultural Streams in Australia with Wood: A Review. *Environmental Management* 42(2):310–326.

Lester, R. E., and W. Wright. 2009. Reintroducing Wood to Streams in Agricultural Landscapes: Changes in Velocity Profile, Stage and Erosion Rates. *River Research and Applications* 25(4):276–392.

Levi, P. S., J. L. Tank, S. D. Tiegs, J. Rüegg, D. T. Chaloner, and G. A. Lamberti. 2011. Does Timber Harvest Influence the Dynamics of Marine-Derived Nutrients in Southeast Alaska Streams? *Canadian Journal of Fisheries and Aquatic Sciences* 68(8):1316–1329.

Li, R., and H. W. Shen. 1973. Effect of Tall Vegetation on Flow and Sediment. *Journal of the Hydraulic Division, ASCE* 99(5):793–814.

Li, S., L. T. Martin, S. R. Pezeshki, and F. D. Shields Jr. 2005. Responses of Black Willow (*Salix nigra*) Cuttings to Herbivory and Flooding. *Acta Oecologica* 28(2):173–180.

Lichatowich, J. A., L. E. Mobrand, L. Lestelle, and T. Vogel. 1995. An Approach to the Diagnosis and Treatment of Depleted Pacific Salmon Populations in Freshwater Ecosystems. *Fisheries* 20(1):10–18.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of Large Woody Debris in Streams in Old-Growth Douglas-Fir Forests. *Canadian Journal of Forest Research* 17:150–156.

Linkov, I., and E. Moberg. 2011. *Multi-Criteria Decision Analysis: Environmental Applications and Case Studies*. Boca Raton, FL: CRC Press.

Linkov. I., and E. Moberg. 2012. *Multi-Criteria Decision Analysis: Environmental Applications and Case Studies*. CRC Press. ISBN: 978-1-4398-5318-4.

Linkov, I., A. Varghese, S. Jamil, T. P. Seager, G. Kiker, and T. Bridges. 2005. Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites. In I. Linkov and A. Bakr Ramadan (eds.), *Comparative Risk Assessment and Environmental Decision Making*. NATO Science Series Volume 38 2005ISBN: 978-1-4020-1895-4 (Print) 978-1-4020-2243-2 (Online).

Lisle, T. 1995. Effects of Coarse Woody Debris and its Removal on a Channel Affected by the 1980 Eruption of Mount St. Helens, Washington*.* *Water Resources Research* 31:1797–1808.

Lisle, T. E., Y. Cui, G. Parker, J. E. Pizzuto, and A. M. Dodd. 2001. The Dominance of Dispersion in the Evolution of Bed Material Waves in Gravel-Bed Rivers. *Earth Surface Processes and Landforms* 26:1409–1420.

Lister, D. B., and H. S. Genoe. 1970. Stream Habitat Utilization by Cohabiting Underyearlings of Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*) Salmon in the Big Qualicum River, British Columbia. *Journal of the Fisheries Research Board of Canada* 27:1215–1224.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The Velocity of Climate Change. *Nature* 462:1052–1055. doi:10.1038/nature08649.

Lockaby, B. G., J. A. Stanturf, and M. G. Messina. 1997. Effects of Silvicultural Activity on Ecological Processes in the Floodplain Forests of the Southern United States: A Review of Existing Reports. *Forest Ecology and Management* 90:93–100.

Logan, J. A., W. W. Macfarlane, and L. Willcox. 2010. White-Bark Pine Vulnerability to Climate Change Induced Mountain Pine Beetle Disturbance in the Greater Yellowstone Ecosystem. *Ecological Application* 20:895–902. doi:10.1890/09- 0655.1. Available: http://www.esajournals.org/doi/pdf/10.1890/09-0655.1.

Long, S. L., and C. R. Jackson. 2014. Variation of Stream Temperatures Among Mesoscale Habitats within Stream Reaches: Southern Appalachians. *Hydrological Processes* 28:3041–3052.

Lowe, R. L. 1974. *Environmental Requirements and Pollution Tolerance of Freshwater Diatoms.* National Environmental Research Center, Office of Research and Development, U.S. Environmental Protection Agency.

Lunetta, R. S., B. L. Cosentino, D. R. Montgomery, E. M. Beamer, and T. J. Beechie. 1997. GIS-Based Evaluation of Salmon Habitat in the Pacific Northwest. *Photogrammetric Engineering & Remote Sensing* 63(10):1219–1229.

Lyell, C. 1830. *Principles of Geology*, Volume I. London, UK: John Murray. Published in 1990 by University of Chicago Press. Chicago, IL.

Lyons, J. E., M. C. Runge, H. P. Laskowski, and W. L. Kendall. 2008. Monitoring in the Context of Structured Decision-Making and Adaptive Management. *The Journal of Wildlife Management* 72(8):1683–1692.

MacFarlane, W. A., and E. Wohl. 2003. Influence of Step Composition on Step Geometry and Flow Resistance in Step-Pool Streams of the Washington Cascades. *Water Resources Research* 39:1037. doi:10.1029/2001WR001238.

Macka, Z., K. Lukas, B. Louckova, and P. Lucie. 2011. A Critical Review of Field Techniques Employed in the Survey of Large Woody Debris in River Corridors: A Central European Perspective. *Environmental Monitoring and Assessment* 181(1–4):291–316.

Mackenzie, B. D. E, and D. A. Keith. 2009. Adaptive Management in Practice: Conservation of a Threatened Plant Population. *Ecological Management & Restoration* 10(s1):S129–S135.

MacNally, R., and E, Fleishman. 2004. A Successful Predictive Model of Species Richness Based on Indicator Species. *Conservation Biology* 18(3):646–654.

MacVicar, B., and H. Piégay. 2012. Implementation and Validation of Video Monitoring for Wood Budgeting in a Wandering Piedmont River, the Ain River (France). *Earth Surface Processes and Landforms* 37:1272–1289.

Magilligan, F. J., and K. H. Nislow. 2005. Changes in Hydrologic Regime by Dams. *Geomorphology* 71:61–78.

Magilligan, F. J., K. H. Nislov, G. B. Fisher, J. Wright, G. Mackey, and M. Laser 2008. The Geomorphic Function and Characteristics of Large Woody Debris in Low Gradient Rivers, Coastal Maine, USA. *Geomorphology* 97:467–482.

Major, J., J. O'Connor, C. Podolak, M. K. Keith, G. E. Grant, K. Spicer, S. Pittman, H. M. Bragg, J. R. Wallick, D. Q. Tanner, A. Rhode, and P. Wilcock. 2012. *Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam.* U.S. Geological Survey Professional Paper 1792.

Makaske, B., D. G. Smith, and H. J. Berendsen. 2002. Avulsions, Channel Evolution and Floodplain Sedimentation Rates of the Anastomosing Upper Columbia River, British Columbia, Canada. *Sedimentology* 49(5):1049–1071.

Manga, M., and J. W. Kirchner. 2000. Stress Partitioning in Streams by Large Woody Debris. *Water Resources Research* 36:2373–2379.

Manly, B. F. 2002. *Resource Selection by Animals*. Springer, New York.

Manners, R. B. and Doyle, M. W. 2008. A Mechanistic Model of Woody Debris Jam Evolution and its Application to Wood-based Restoration and Management. *River Research and Applications* 24:1104-1123.

Manners, R. W., M. W. Doyle, and M. J. Small. 2007. Structure and Hydraulics of Natural Woody Debris Jams. *Water Resources Research* 43, doi:10.1029/2006WR004910.

Manners, R. B., J. C. Schmidt, and M. L. Scott, M.L. 2014. Mechanisms of Vegetation-Induced Channel Narrowing on an Unregulated Canyon Bound River: Results from a Natural Field-Scale Experiment. *Geomorphology* 211:100–115.

Mao, L., and F. Comiti. 2010. The Effects of Large Wood Elements During an Extreme Flood in a Small Tropical Basin of Costa Rica. *WIT Transactions on Engineering Sciences* 67:225–236.

Marcus, W. A., R. A. Marston, C. R. Colvard, and R. D. Gray. 2002. Mapping the Spatial and Temporal Distributions of Woody Debris in Streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology* 44:323–335.

Marcus, W. A., J. Rasmussen, and M. A. Fonstad. 2011. Response of the Fluvial Wood System to Fire and Floods in Northern Yellowstone. *Annals of the Association of American Geographers* 101:21–44.

Marschall, E. A., T. P. Quinn, D. A. Roff, J. A. Hutchings, N. B. Metcalfe, T. A. Bakke, R. L. Saunders, and N. L. Poff. 1998. A Framework for Understanding Atlantic Salmon (*Salmo salar*) Life History. *Canadian Journal of Fisheries and Aquatic Sciences* 55(S1):48–58.

Marston, R. A. 1982. The Geomorphic Significance of Log Steps in Forested Streams. *Annals of the Association of American Geographers* 72:99–108.

Martin, D. J., and L. E. Benda. 2001. Patterns of Instream Wood Recruitment and Transport at the Watershed Scale. *Transactions of the American Fisheries Society* 130:940–958.

Martin, L. T., S. R. Pezeshki, and F. D. Shields Jr. 2004. High Oxygen Level in a Soaking Treatment Improves Early Root and Shoot Development of Black Willow Cuttings. *The Scientific World Journal* 4:899–907.

Maser, C. and J. R. Sedell, J.R. 1994. *From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans.* St. Lucie Press.

Maser, C., and J. R. Sedell. 1988. From the Forest to the Sea: the Ecology of Wood in Streams, Rivers, Estuaries and Oceans. Delray Beach, FL: St. Lucie Press.

Maser, C., and J. M. Trappe (eds.). 1984. *The Seen and Unseen World of the Fallen Tree*. Gen. Tech. Rep. PNW-164. Portland, OR: U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (eds.). 1988. *From the Forest to the Sea: A Story of Fallen Trees*. General Tech. Report PNW-GTR-229. USFS.

Massachusetts Department of Transportation (MassDOT). 2010. *Design of Bridges and Culverts for Wildlife Passage at Freshwater Streams.* Highway Division, Environmental, Bridge, Construction, and Hydraulics Sections, Boston, MA.

Masterman, R., and C. R. Thorne. 1992. Predicting Influence of Bank Vegetation on Channel Capacity. *Journal of Hydraulic Engineering* 118:1052–1058.

Matheussen, B., R. L. Kirschbaum, I. A. Goodman, G. M. O'Donnell, and D. P. Lettenmaier. 2000. Effects of Land Cover Change on Streamflow in the Interior Columbia River Basin (USA and Canada). *Hydrological Processes* 14:867–885.

Mathur, D., W. H. Bason, E. J. Purdy, and C. A. Silver. 1985. A Critique of Instream Flow Incremental Methodology. *Canadian Journal of Fisheries and Aquatic Science* 42(4):825–831.

May, C. L., and R. E. Gresswell. 2003a. Large Wood Recruitment and Redistribution in Headwater Streams in the Southern Oregon Coast Range, USA. *Canadian Journal of Forest Research* 33:1353–1362.

May, C. L., and R. E. Gresswell. 2003b. Processes and Rates of Sediment and Wood Accumulation in Headwater Streams of the Oregon Coast Range, USA. *Earth Surface Processes and Landforms* 28:409–424.

May, C. L., E. B. Welch, R. R. Horner, J. R. Karr, and B. W. Mar, B.W. 1997. *Quality Indices for Urbanization Effects on Puget Sound Lowland Streams.* Water Resource Series Tech Report 154. Seattle, Washington.

McCall, E. 1984. *Conquering the Rivers*. Louisiana State University Press. Baton Rouge, LA.

McClain, M. E., and 11 others. 2003. Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems. *Ecoystems* 6:301-312.

McCormick, F. H. 1993. Fish Communities as Indicators of Stream Condition. In R. M. Hughes (ed.), *EMAP Streams Bioassessment Workshop.* Report of the Proceedings. EPA/600/R-93/138. U.S. Environmental Protection Agency, Corvallis, OR.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source Distances for Coarse Woody Debris Entering Small Streams in Western Oregon and Washington. *Canadian Journal of Forest Research* 20:326–330.

McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. *Viable Salmonid Populations and the Recovery of Evolutionary Significant Units*. U.S. Department of Commerce, Seattle, WA. NOAA Tech. Memo NMFS-NWFSC-42.

McHenry, M. L., E. Shott, R. H. Conrad, and G. B. Grette. 1998. Changes in the Quantity and Characteristics of LWD in Streams of the Olympic Peninsula, Washington, USA (1982-1993). *Canadian Journal of Fisheries and Aquatic Sciences* 55(6):1395–1407.

McMahon, T. E. 1983. *Habitat Suitability Index Models: Coho Salmon*. U.S. Fish and Wildlife Service.

McMillan, LLC. 2014. *Fourth of July Creek Stream Restoration Draft Design Report*. Prepared for Pend Oreille County Public Utility District. February 14, 2014.

McNeely, C., and M. E. Power. 2007. Spatial Variation in Caddisfly Grazing Regimes Within a Northern California Watershed. *Ecology* 88(10):2609–2619.

Means, J. E., K. Cromack Jr., and P. C. MacMillan, 1986, Comparison of Decomposition Models Using Wood Density of Douglas-Fir Logs. *Canadian Journal of Forestry Research* 15:1092–1098.

Meile, T., J. Boillat, and A. Schleiss. 2011. Flow Resistance Caused by Large-Scale Bank Roughness in a Channel. *Journal of Hydraulic Engineering* 137(12):1588–1597.

Meleason, M. A., R. J. Davies-Colley, and G. M. J. Hall. 2007. Characterizing the Variability of Wood in Streams: Simulation Modelling Compared with Multiple-Reach Surveys. *Earth Surface Processes and Landforms* 32:1164–1173.

Melillo, J. M., R. J. Naiman, J. D. Aber, and K. N. Eshleman. 1983. The Influence of Substrate Quality and Stream Size on Wood Decomposition Dynamics. *Oecolgia (Berlin)* 58:281–285.

Melillo, J. M., T. C. Richmond, and G. W. Yohe (eds.). 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment.* U.S. Global Change Research Program. doi:10.7930/J0Z31WJ2.

Mellina, E. and S. G. Hinch. 2009. Influences of Riparian Logging and in-Stream Large Wood Removal on Pool Habitat and Salmonid Density and Biomass: A Meta-Analysis. *Canadian Journal of Forest Research* 39:1280–1301.

Meredith, C., B. Roper, and E. Archer. 2014. Reductions in Instream Wood in Streams near Roads in the Interior Columbia River Basin. *North American Journal of Fisheries Management* 34(3):493–506.

Merten, E., J. Finlay, L. Johnson, R. Newman, R., H. Stefan, and B. Vondracek. 2010. Factors Influencing Wood Mobilization in Stream. *Water Resources Research* 46:W10514.

Merritt, D. M., N. L. R. Poff. 2010. Shifting Dominance of Riparian Populus and Tamarix Along Gradients of Flow Alteration in Western North American Rivers. *Ecological Applications* 20:135–152.

Merten, E. C., P. G. Vaz, J. A. Decker-Fritz, J. C. Finlay, and H. G. Stefan. 2013. Relative Importance of Breakage and Decay as Processes Depleting Large Wood from Streams. *Geomorphology* 190:40–47.

Merz, J., and P. B. Moyle. 2006. Salmon, Wildlife and Wine: Marine-Derived Nutrients in Human-Dominated Ecosystems of Central California. *Ecological Applications* 13(3):999–1009.

Meyer, J. L., J. B. Wallace, and S. L. Eggert. 1998. Leaf Litter as a Source of Dissolved Organic Carbon in Streams. *Ecosystems* 1:240–249.

Micheli, E. R., J. W. Kirchner, and E. W. Larsen. 2003. Quantifying the Effect of Riparian Forest Versus Agricultural Vegetation on River Meander Migrations Rates, Central Sacramento River, California, USA. *River Research and Applications* 19:1–12.

Mikuś, P., B. Wyżga, R. J. Kaczka, E. Walusiak, and J. Zawiejska. 2013. Islands in a European Mountain River: Linkages with Large Wood Deposition, Flood Flow and Plant Diversity. *Geomorphology* 202:115–127.

Miles, P. D., and W. B. Smith. 2009. *Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America*. U.S. Forest Service, Newtown Square, PA.

Miller, D., C. Luce, and L. Benda. 2003. Time, Space, and Episodicity of Physical Disturbance in Streams. *Forest Ecology and Management* 178(1):121–140.

Miller, S. W., P. Budy, and J. C. Schmidt. 2010. Quantifying Macroinvertebrate Responses to In-Stream Habitat Restoration. *Applications of Restoration Ecology* 18:8–19.

Millward, A. A., C. E. Kraft, and D. R. Warren. 2010. Ice Storm Damage Greater Along the Terrestrial-Aquatic Interface in Forested Landscapes. *Ecosystems* 13:249–260.

Minakawa, N., and R. I. Gara. 2005. Spatial and Temporal Distribution of Coho Salmon Carcasses in a Stream in the Pacific Northwest, USA. *Hydrobiologia* 539:163–166.

Minore, D. 1979. The Wild Huckleberries of Oregon and Washington: A Dwindling Resource. *USDA Forest Service Research Paper 143*.

Montgomery, D. R. 1999. Process Domains and the River Continuum. *Journal of the American Water Resources Association* 35:397–410.

Montgomery, D. R., and T. B. Abbe. 2006. Influence of Logjam-Formed Hard Points on the Formation of Valley-Bottom Landforms in an Old-Growth Forest Valley, Queets River, Washington, USA. *Quaternary Research* 65:147–155.

Montgomery, D. R., and J. M. Buffington. 1993. *Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition*. TFW-SH10-93-002. Washington State Timber, Fish & Wildlife.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-Reach Morphology in Mountain Drainage Basins. *Geological Society of America Bulletin* 109:596–611.

Montgomery, D. R., and J. M. Buffington. 1998. Channel Processes, Classification and Response. Pages 13–42 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion.* New York: Springer.

Montgomery, D. R. and H. Piégay 2003. Wood in Rivers: Interactions with Channel Morphology and Processes. *Geomorphology* 51:1–5.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1995a. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995b. Pool Spacing in Forest Channels. *Water Resources Research* 31:1097–1105.

Montgomery, D. R., J. M. Buffington, N. P. Peterson, D. Schuett-Hames, and T. P. Quinn. 1996a. Streambed Scour, Egg Burial Depths and the Influence of Salmonid Spawning on Bed Surface Mobility and Embryo Survival. *Canadian Journal of fisheries and Aquatic Sciences* 53:1061–1070.

Montgomery, D. R., T. Abbe, N. P. Peterson, J. M. Buffington, K. M. Schmidt, and J. D. Stock 1996b. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. *Nature* 381:587–589.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Geomorphic Effects of Wood in Rivers. Pages 21–47 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society.

Moore, M. K. 1977. Factors Contributing to Blowdown in Streamside Leave Strips on Vancouver Island. *Land Management Report No. 3.* Victoria, BC: Province of British Columbia Ministry of Forests, Information Division.

Morris, A. E. L., P. C. Goebel, and B. J. Palik. 2010. Spatial Distribution of Large Wood Jams in Streams Related to Stream-Valley Geomorphology and Forest Age in Northern Michigan. *River Research and Applications* 26:835–847.

Morrison, M. L., B. G. Marcot, and R. W. Mannon. 1998. *Wildlife-Habitat Relationships. Concepts and Applications*. Madison, WI: University of Wisconsin Press.

Moscrip, A. L., and D. R. Montgomery. 1997. Urbanization, Flood Frequency, and Salmon Abundance in Puget Lowland Streams. *Journal of the American Water Resources Association* 33(6):1289–1297.

Mossop, B., and M. J. Bradford. 2004. Importance of Large Woody Debris for Juvenile Chinook Salmon Habitat in Small Boreal Forest Streams in the Upper Yukon River Basin, Canada. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 34:1955–1966.

Moulin, B., E. R. Schenk, and C. R. Hupp. 2011. Distribution and Characterization of In-Channel Large Wood in Relation to Geomorphic Patterns on a Low-Gradient River. *Earth Surface Processes and Landforms* 36:1137–1151.

Moussalli, E., and R. Hilborn. 1986. Optimal Stock Size and Harvest Rate in Multistage Life History Models. *Canadian Journal of Fisheries and Aquatic Sciences* 43(1):135–141.

MTZ Associates. 2000. *River Corridor Recreation Safety Study: Sacramento River Bank Protection Project.* Prepared for the U.S. Army Corps of Engineers, Contract 42E, Sacramento, CA.

Muir, J. 1878. Forests of California, the New Sequoia. *Harper's New Monthly Magazine* LVII (CCCXLII):813–827.

Mulholland, P. J., and J. R. Webster. 2010. Nutrient Dynamics in Streams and the Role of J-NABS. *Journal of the North American Benthological Society* 29:100–117.

Mulholland, P. J., J. D. Newbold, J. W. Elwood, L. A. Ferren, and J. R. Webster. 1985. Phosphorus Spiraling in a Woodland Stream - Seasonal-Variations. *Ecology* 66:1012–1023.

Mulholland, P. J., and 33 others. 2009. Nitrate Removal in Stream Ecosystems Measured by 15N Addition Experiments: Denitrification. *Limnology and Oceanography* 54:666–680.

Munn, N. L., and J. L. Meyer. 1990. Habitat-Specific Solute Retention in Two Small Streams: An Intersite Comparison. *Ecology* 71:2069–2082.

Murphy, D. D., and P. S. Weiland. 2010. The Route to Best Science in Implementation of the Endangered Species Act's Consultation Mandate: The Benefits of Structured Effects Analysis. *Environmental Management* 47(2):161–172.

Murphy, M. L. 1995. Forestry Impacts on Freshwater Habitat of Anadromous Salmonids in the Pacific Northwest and Alaska—Requirements for Protection and Restoration. *U.S. Department of Commerce Coastal Ocean Program, NOAA. Decision Analysis Series No. 7*.

Murphy, M. L., and K. V. Koski. 1989. Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. *North American Journal of Fisheries Management* 9(4):427–436.

Murphy, M. L., J. Heifetz, S. W. Johnson, K. V. Koski, and J. F. Thendinga. 1986. Effects of Clear-Cut Logging with and without Buffer Strips on Juvenile Salmonids in Alaskan Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 43:1521–1533.

Mutz, M. 2003. Hydraulic Effects of Wood in Streams. *American Fisheries Society Symposium* 37:93–107.

Mutz, M., E. Kalbus, and S. Meinecke. 2007. Effect of Instream Wood on Vertical Water Flux in Low-Energy Sand Bed Flume Experiments. *Water Resources Research* 43:W10424.

Nagayama, S., and F. Nakamura. 2010. Fish Habitat Rehabilitation Using Wood in the World. *Landscape and Ecological Engineering* 6(2):289–305.

Nagayama, S., F. Nakamura, Y. Kawaguchi, and D. Nakano. 2012. Effects of Configuration of Instream Wood on Autumn and Winter Habitat Use by Fish in a Large Remeandering Reach. *Hydrobiologia* 680:159–170.

Naiman, R. J., T. J. Beechie, L. E. Benda, P. A. Bisson, L. H. MacDonald, M. D. O'Conner, P. L. Olsen, and E. A. Steel. 1992. Fundamental Elements of Ecologically Healthy Watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127–188 in R. J. Naiman (ed.), *Watershed Management: Balancing Sustainability and Environmental Change*. Springer: New York.

Naiman, R. J., K. L. Fetherston, S. McKay, and J. Chen. 1998. Riparian Forests. Pages 289–323 in R. J. Naiman and R. E. Bilby (eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag: New York.

Naiman, R. J., R. E. Bilby, and P. Bisson. 2000. Riparian Ecology and Management in the Pacific Coastal Rain Forest. *Bioscience* 50:996–1011.

Naiman, R. J., E. V. Balian, K. K. Bartz, R. E. Bilby, and J. J. Latterell. 2002a. Dead Wood Dynamics in Stream Ecosystems. Pages 23–48 in W. F. Laudenslayer Jr., P. J. Shea, B. E. Valentine, C. P. Weatherspoon, and T. E. Lisle (eds.), *Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests*. Gen. Tech. Rep. PSW-GTR-181. U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station.

Naiman R. J., S. E. Bunn, and C. Nilsson. 2002b. Legitimizing Fluvial Ecosystems as Users of Water. *Environmental Management* 30:455–467.

Naiman, R. J., R. E. Bilby, D. E. Schindler, and J. M. Helfield. 2002c. Pacific Salmon, Nutrients, and the Dynamics of Freshwater and Riparian Ecosystems. *Ecosystems* 5:399–417.

Naiman, R. J., J. S. Becthold, T. J. Beechie, J. J. Laterell, and R. Van Pelt. 2010. A Process-Based View of Floodplain Forest Patterns in Coastal River Valleys of the Pacific Northwest. *Ecosystems* 13:1–31.

Nakamura, F., and F. J. Swanson. 1993. Effects of Coarse Woody Debris on Morphology and Sediment Storage of a Mountain Stream System in Western Oregon. *Earth Surface Processes and Landforms* 18:43–61.

Nanson, G. C., M. Barbetti, and G. Taylor. 1995. River Stabilisation due to Changing Climate and Vegetation During the late Quaternary in Western Tasmania, Australia. *Geomorphology* 13.1(1995):145–158.

National Institute for Occupational Safety and Health. 2012. *Logging Safety.* Centers for Disease Control and Prevention. Atlanta, GA. Available: http://www.cdc.gov/niosh/topics/logging/. Accessed: July 10, 2014.

National Marine Fisheries Service. 1996. *Making Endangered Species Act Determinations of Effect for Individual or Grouped Actions at the Watershed Scale*. Environmental and Technical Services Division, Habitat Conservation Branch.

National Research Council. 1999. Committee on Health Risks of Exposure to Radon*. Health Effects of Exposure to Radon*. Vol. 6. National Academies Press.

National Research Council. 2004. *Adaptive Management for Water Resources Planning*, The National Academies Press. Washington, D.C.

Natural Resources Conservation Service (NRCS). 2007a. Streambank Soil Bioengineering. Technical Supplement TS 41I in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

Natural Resources Conservation Service (NRCS). 2007b. Use and Design of Soil Anchors*.* Technical Supplement TS 41E in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

National Resources Conservation Service (NRCS). 2007c. Chapter 15—Project Implementation. In Part 654, *Stream Restoration Design National Engineering Handbook*. U.S. Department of Agriculture, Washington, D.C.

National Resources Conservation Service (NRCS). 2007d. Technical Supplement 14I—Streambank Soil Bioengineering. In Part 654, *Stream Restoration Design National Engineering Handbook*. U.S. Department of Agriculture, Washington, D.C.

National Resources Conservation Service (NRCS) 2007e. Use of Large Woody Material for Habitat and Bank Protection - Technical Supplement 14j of Part 654. *The National Engineering Handbook*. 210–VI–NEH, August 2007. U.S. Department of Agriculture, Washington, D.C.

Natural Resources Conservation Service (NRCS). 2007f. Stream Hydrology. Chapter 5 in *Stream Restoration Design, National Engineering Handbook* Part 654. USDA-NRCS, Washington, D.C. CD-ROM.

Navel, S., C. Piscart, F. Meermillod-Blondin, and P. Marmonier. 2013. New Methods for the Investigation of Leaf Litter Breakdown in River Sediments. *Hydrobiologia* 700:301–312.

Neumann, R. M., and T. L.Wildman. 2002. Relationships Between Trout Habitat Use and Woody Debris in Two Southern New England Streams. *Ecology of Freshwater Fish* 11:240–250.

New York State Department of Environmental Conservation (NYSDEC). 2014. Removal of Woody Debris and Trash from Rivers and Streams. In *Post-Flood Stream Reconstruction: Guidelines and Best Practices*. Albany, NY.

Nichols, R. A. and S. G. Sprague. 2003. The Use of Long-Line Cabled Logs for Stream Bank Rehabilitation. Pages 422–442 in D. R. Montgomery, S. M. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers.* University of Washington Press: Seattle.

Nickelson, T. E., and P. W. Lawson. 1998. Population Viability of Coho Salmon, *Oncorhynchus kisutch*, in Oregon Coastal Basins: Application of a Habitat-Based Life Cycle Model. *Canadian Journal of Fisheries and Aquatic Sciences* 55:2383–2392.

Nickelson, T. E., M. F. Solazzi, S. L. Johnson, and J. D. Rodgers. 1992. Effectiveness of Selected Stream Improvement Techniques to Created Suitable Summer and Winter Rearing Habitat for Juvenile Coho Salmon (*Oncorhynchus kisutch*) in Oregon Coastal Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 49:790–794.

Nickelson, T. E., M. F. Solazzi, S. L. Johnson, and J. D. Rodgers. 1993. An Approach to Determining Stream Carrying Capacity and Limiting Habitat For Coho Salmon (*Oncorhynchus kisutch*). Paper read at *Proceedings of the Coho Workshop*, May 1992, Nanaimo, B.C.

Niezgoda, S., and P. Johnson. 2007. Case Study in Cost-Based Risk Assessment for Selecting a Stream Restoration Design Method for a Channel Relocation Project. *Journal of Hydraulic Engineering* 133(5):468–481

Nilsson, C., and K. Berggren. 2000. Alterations of Riparian Ecosystems Caused by River Regulation. *Bioscience* 50:783–792.

Nooksack Tribe. 2013. *ELJ Assessment*.

Norris, R. H. 1995. Biological Monitoring: The Dilemma of Data Analysis." *Journal of the North American Benthological Society*:440–450

North American Forest Commission. 2011. *Forests of North America*. Vector Digital Data. Food and Agriculture Organization of the United Nations. Commission for Environmental Cooperation. Montreal, Quebec, CA.

Noss, F., and R. L. Peters. 1995. *Endangered Ecosystems – A Status Report on America'sVanishing Habitat and Wildlife*. 133 Pages. Defenders of Wildlife, 1101 Fourteenth Street, NW, Suite 1400, Washington, DC 20005.

Nowinski, J. D., M. B. Cardenas, A. F. Lightbody, T. E. Swanson, and A. H. Sawyer. 2012. Hydraulic and Thermal Response of Groundwater-Surface Water Exchange to Flooding in an Experimental Aquifer. *Journal of Hydrology* 472–473:184–192.

Oakley, K. L., L. P. Thomas, and S. G. Fancy. 2003. Guidelines For Long-Term Monitoring Protocols. *Wildlife Society Bulletin* 31(4):1000–1003.

Occupational Safety and Health Administration (OSHA). Undated a. *Logging eTool*. Occupational Safety and Health Administration. Washington, D.C. Available: https://www.osha.gov/SLTC/etools/logging/index.html. Accessed: July 10, 2014.

Occupational Safety and Health Administration (OSHA). Undated b. *Trenching and Excavation Safety*. Fact Sheet. Occupational Safety and Health Administration. Washington, D.C. Available: https://www.osha.gov/SLTC/trenchingexcavation/construction.html. Accessed: July 10, 2014.

O'Connor, J. E., M. A. Jones, and T. L. Haluska. 2003. Flood Plain and Channel Dynamics of the Quinault and Queets Rivers, Washington, U.S.A. *Geomorphology* 51:31–59.

O'Connor, M., and G. Watson, 1998. *Geomorphology of Channel Migration Zones and Implications for Riparian Forest Management.* Available: http://www.oei.com/Reports/Geomorph_of_CMZ.htm.

O'Connor, R. R., and F. J. Rahel. 2009. A Patch Perspective on Summer Habitat Use by Brown Trout *Salmo trutta* in a High Plains Stream in Wyoming, USA. *Ecology of Freshwater Fish* 18(3):473–480.

Oglethorpe, J. 2002. *Adaptive Management: From Theory to Practice*. The World Conservation Union (IUCN).

Oliver, C. D. 1980/1981. Forest Development in North America Following Major Disturbances. *Forest Ecology and Management* 3:153–168.

Opperman, J. J., and A. M. Merenlender. 2004. The Effectiveness of Riparian Restoration for Improving Instream Fish Habitat in Four Hardwood-Dominated California Streams. *North American Journal of Fisheries Management* 24(3):822–834.

Oppermanh, J. J., and A. M. Merenlender. 2007. Living Trees Provide Stable Large Wood in Streams. *Earth Surface Processes & Landforms* 32(8):1229–1238.

Opperman, J. J., A. M. Merenlender, and D. Lewis. 2006. *Maintaining Wood in Streams: A Vital Action for Fish Conservation.* Davis, CA: University of California. Publication 8157.

Oregon Department of Fish and Wildlife (ODFW). 2010. *Guide to Placement of Wood, Boulders, and Gravel for Habitat Restoration*. Oregon Departments of Forestry and Fish and Wildlife. Salem, OR.

Oregon Department of Forestry. 1995. *A Guide to Placing Large Wood in Streams*. Salem, OR, Forest Practices Section.

Oregon Department of Transportation (ODOT). 2011. *Hydraulics Manual, Engineering and Asset Management*. Unit Geo-Environmental Section. Salem, OR.

Oswald, E. B., and E. Wohl. 2008. Wood-Mediated Geomorphic Effects of a Jökuhlaup in the Wind River Mountains, Wyoming. *Geomorphology* 100:549–562.

Pahl-Wostl, C. 1995. *The Dynamic Nature of Ecosystems: Chaos and Order Entwined*. Chichester: Wiley.

Palik, B., S. W. Golladay, P. C. Goebel, and B. W. Taylor. 1998. Geomorphic Variation in Riparian Tree Mortality and Stream Coarse Woody Debris Recruitment from Record Flooding in a Coastal Plain Stream. *Ecoscience* 5:551–560.

Pariset, E., R. Hausser, and A. Gagnon. 1966. Formation of Ice Covers and Ice Jams in Rivers. *Journal of the Hydraulics Division* 92(6):1–24.

Parrish, R. M. and P. B. Jenkins. 2012. *Natural Log Jams in the White River: Lessons for Geomimetic Design of Engineered Log Jams*. U.S. Fish and Wildlife Service, Leavenworth, WA.

Pastorok, R. A., A. MacDonald, J. R. Sampson, P. Wilber, D. J Yozzo, and J. P Titre. 1997. An Ecological Decision Framework for Environmental Restoration Projects. *Ecological Engineering* 9(1–2):89–107.

Paukert, C. P., and A. S. Makinster. 2008. Longitudinal Patterns in Flathead Catfish Relative Abundance and Length at Age Within a Large River: effects of an urban gradient. *River Research and Applications*. Available: www.interscience.wiley.com. DOI: 10.1002/rra.1089.

Pealer, S. 2012. *Lessons from Irene – Building Resiliency as We Rebuild.* Vermont Agency of Natural Resources Climate Change Team, Montpelier, VT. Available: http://www.anr.state.vt.us/anr/climatechange/Pubs/Irene_Facts.pdf.

Pearsons, T. D., and H. W. Li. 1992. Influence of Habitat Complexity on Resistance to Flooding and Resilience of Stream Fish Assemblages. *Transactions of the American Fisheries Society* 121:427–436.

Pelto, M. S. 2011. *North Cascade Glacier Retreat*. Nichols College, Dudley, MA. Available: http://www.nichols.edu/departments/glacier/bill.htm.

Pess, G. R., D. R. Montgomery, E. A. Steel, R. E. Bilby, B. E. Feist, and H. M. Greenberg. 2002. Landscape Characteristics, Land Use, and Coho Salmon (*Oncorhynchus kisutch*) Abundance, Snohomish River, Washington, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 59:613–623.

Pess, G. R., M. C. Liermann, M. L. Mchenry, R. J. Peters, and T. R. Bennett. 2012. Juvenile Salmon Response to the Placement of Engineered Log Jams (ELJs) in the Elwha River, Washington State, USA. *River Research and Applications* 28(7):872–881.

Peters, P. 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, North Pacific Coast Ecoregion. Western Washington Office, Aquatic Resources Division. Lacey, WA.

Petersen, M. S. 1986. *River Engineering*. Englewood Cliffs, NJ: Prentice-Hall.

Pettit, N. E., and R. J. Naiman. 2006. Flood-Deposited Wood Creates Regeneration Niches for Riparian Vegetation on a Semi-Arid South African River. *Journal of Vegetation Science* 17:615–624.

Pettit, N. E., R. J. Naiman, K. H. Rogers, and J. E. Little. 2005. Post-Flooding Distribution and Characteristics of Large Woody Debris Piles Along the Semi-Arid Sabie River, South Africa. *River Research and Applications* 21:27–38.

Petts, G. E., A. L. Roux, and H. Moller (eds.). 1989. *Historical Changes of Large Alluvial Rivers, Western Europe*. Chichester: John Wiley.

Phillips, E. C. 2003. Habitat Preference of Aquatic Macroinvertebrates in an East Texas Sandy Stream. *Journal of Freshwater Ecology* 18(1):1–11.

Phillips, J. D. 2012. Log-Jams and Avulsions in the San Antonio River Delta, Texas. *Earth Surface Processes and Landforms* 37:936–950.

Phillips, J. D., and L. Park. 2009. Forest Blowdown Impacts of Hurricane Rita on Fluvial Systems. *Earth Surface Processes and Landforms* 34:1069–1081.

Pickett, S. T. A., and K. H. Rogers. 1997. Patch Dynamics: The Transformation of Landscape Structure and Function. Pages 101–127 in J. A. Bissonette (ed.), *Wildlife and Landscape Ecology.* New York: Springer-Verlag.

Pianka, E. R. 1994. *Evolutionary Ecology*. Harper-Collins.

Pickett, S. T. A., and K. H. Rogers. 1997. Patch Dynamics: The Transformation of Landscape Structure and Function. Pages 101–127 in J. A. Bissonette (ed.), *Wildlife and Landscape Ecology*. New York: Springer-Verlag.

Piégay, H. 1993. Nature, Mass and Preferential Sites of Coarse Woody Debris Deposits in the Lower Ain Valley (Mollon Reach), France. *Regulated Rivers: Research and Management* 8:359–372.

Piégay, H., and J. P. Bravard. 1997. Response of a Mediterranean Riparian Forest to a 1 in 400 Year Flood, Ouveze River, Drome-Vaucluse, France. *Earth Surface Processes and Landforms* 22(1):31–43.

Piégay, H., A. and R. A. Marston. 1998. Distribution of Coarse Woody Debris Along the Concave Bank of a Meandering River (the Ain River, France). *Physical Geography* 19(4):318–340.

Piégay, H., A. Thevenet, and A. Citterio. 1999. Input, Storage and Distribution of LWD Along a Mountain River Continuum, the Drôme River, France. *Catena* 35:19–39.

Pittman, S. E., and M. E. Dorcas. 2009. Movements, Habitat Use, and Thermal Ecology of an Isolated Population of Bog Turtles (*Glyptemys muhlenbergii*). *Copeia*(4):781–790.

Plafkin, J. L., Barbour, M. T., Porter, K. D., Gross, S. K. and Hughes, R. M. 1992. R*apid Bioassessment Protocols for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish.* Washington, D.C.: EPA.

Poff, N. L., and H. K. H. Zimmerman. 2010. Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshwater Biology* 55:194–205.

Poff, N. L., J. D. Allan, M. A. Palmer, D. D. Hart, B. D. Richter, A. H. Arthington, K. H. Rogers, J. L. Meyer, and J. A. Stanford. 2003. River Flows and Water Wars: Emerging Science for Environmental Decision Making. *Frontiers in Ecology and the Environment* 1:298–306.

Poff, N. L., B. P. Bledsoe, and C. O. Cuhaciyan. 2006. Hydrologic Variation with Land Use across the Contiguous United States: Geomorphic and Ecological Consequences for Stream Ecosystems. *Geomorphology* 79:264–285. doi:10.1016/ j.geomorph.2006.06.032.

Pohl, M. M. 2002. Bringing Down Our Dams: Trends in American Dam Removal Rationales. *Journal of the American Water Resources Association* 38:1511–1519.

Pokrefke, T. J. (ed.) 2013. *Inland Navigation: Channel Training Works*. ASCE Manual of Practice 124. American Society of Civil Engineers. Reston, VA.

Pollen-Bankhead, N., and A. Simon. 2010. Hydrologic and Hydraulic Effects of Riparian Root Networks on Streambank Stability: Is Mechanical Root-Reinforcement the Whole Story? *Geomorphology* 116(3):353–362.

Pollock, K. H., J. D. Nichols, T. R. Simons, G. L. Farnsworth, L. L. Bailey, and J. R. Sauer. 2002. Large Scale Wildlife Monitoring Studies: Statistical Methods for Design and Analysis. *Environmetrics* 13:105–119.

Pollock, M. M., and T. J. Beechie. 2014. Does Riparian Forest Restoration Thinning Enhance Biodiversity? The Ecological Importance of Large Wood. *JAWRA Journal of the American Water Resources Association* 50(3):543–559. Online publication date: June 1, 2014.

Pollock, M. M., R. J. Naiman, and T. A. Hanley. 1998. Plant Species Richness in Riparian Wetlands—A Test of Biodiversity Theory. *Ecology* 79:94–105.

Pollock, M. M., T. J. Beechie., M. Liermann, and R. E. Bigley. 2009. Stream Temperature Relationships to Forest Harvest in Western Washington. *Journal of the American Water Resources Association* 45(1):141–156.

Poole, G. C., J. A. Stanford, S. W. Running, and C. A. Frissell. 2006. Multiscale Geomorphic Drivers of Groundwater Flow Paths: Subsurface Hydrologic Dynamics and Hyporheic Habitat Diversity. *Journal of the North American Benthological Society* 25:288–303.

Power, M. E., and W. E. Dietrich. 2002. Food Webs in River Networks. *Ecological Research* 17:451–471.

Power, M. E., A. Sun, G. Parker, W. E. Dietrich, and J. T. Wootton. 1995. Hydraulic Food Chain Models. *BioScience* 45:159–167.

Prato, T. 2003. Adaptive Management of Large Rivers with Special Reference to the Missouri River. *Journal of the American Water Resources Association* 39(4):935–946.

Prowse, T. D. 2001. River Ice Ecology. 1: Hydrologic, Geomorphic, and Water Quality Aspects. *Journal of Cold Regions Engineering* 15(1):1–16.

Ptolemy, R. A. 1993. Maximum Salmonid Densities in Fluvial Habitats in British Columbia. Paper read at Proceedings of the Coho Workshop, May 26–28, 1992, at Nanaimo, B.C.

Quinault Indian Nation (QIN). 2008. *Salmon Habitat Restoration Plan for the Upper Quinault River.* Quinault Indian Nation Department of Fisheries. Taholah, Washington. Prepared by T. Abbe and others.

Quinn, T. P., S. M. Carlson, S. M. Gende, and H. B. Rich. 2009. Transportation of Pacific Salmon Carcasses from Streams to Riparian Forests by Bears. *Canadian Journal of Fisheries and Aquatic Science* 87:195–203.

Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-Scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *Bio-Science* 58:501–517. doi:10.1641/b580607. Available: http://www.jstor.org/stable/pdfplus/10.1641/B580607. pdf.

Raikow, D. F., S. A. Grubbs, and K. W. Cummins. 1995. Debris Dam Dynamics and Coarse Particulate Organic Matter Retention in an Appalachian Mountain Stream. *Journal of the North American Benthological Society* 14:535–546.

Railsback, S. F., and J. Kadvany. 2008. Demonstration Flow Assessment: Judgment and Visual Observation in Instream Flow Studies. *Fisheries* 33:217–227.

Railsback, S. F., H. Stauffer, and B. Harvey. 2003. What can Habitat Preference Models Tell Us? Tests using a Virtual Trout Population. *Ecological Applications* 13(6):1580–1594.

Ralph, S. C., G. C. Poole, L. L. Conquest, and R. J. Naiman. 1991. Stream Channel Morphology and Woody Debris in Logged and Unlogged Basins of Western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51:37–51.

Rapp, C., and T. Abbe. 2003. A *Framework for Delineating Channel Migration Zones*. Washington State Department of Ecology Publication Number 03-06-027. Final Draft.

Raup, H. M. 1957. Vegetation Adjustment to the Instability of Sites. *Proceedings and Papers of the 6th Technical Meeting of the International Union for Conservation of Nature and Natural Resources*. Edinburgh. Pages 36–48.

Ravazzolo, D., L. Mao, L. Picco, and M. A. Lenzi 2015. Tracking Log Displacement During Floods in the Tagliamento River Using Rfid and Gps Tracker Devices. *Geomorphology* 228:226-233.

Reeves, G. H., F. H. Everest, and T. E. Nickelson. 1989. *Identification of Physical Habitats Limiting the Production of Coho Salmon in Western Oregon and Washington*. Portland, OR: USDA Forest Service.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991. Rehabilitating and Modifying Stream Habitats. Pages 519–557 in *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication* 19.

Reich, P. B., I. Wright, J. Cavender-Bares, J. Craine, J. Oleksyn, M. Westoby, and M. B. Walters. 2003. The Evolution of Plant Functional Variation: Traits, Spectra, and Strategies. *International Journal of Plant Sciences* 164:s143–s164.

Reid, L. M., and T. Dunne. 1996. *Rapid Evaluation of Sediment Budgets*. Reiskirchen, Germany: Catena Verlag (GeoEcology paperback).

Reid, L. M., and S. Hilton. 1998. Buffering the Buffer. Pages 71–80 in R. R. Ziemer (ed.), *Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story*; held May 6, 1998, in Ukiah, California. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-168.

Reisenbichler, R. R. 1989. Utility of Spawner-Recruit Relations for Evaluating the Effect of Degraded Environment on the Abundance of Chinook Salmon, *Oncorhynchus tshawytscha*. Pages 21–32 in C. D. Levings, L. B. Holtby, and M. A. Henderson (eds.), *Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks: Canadian Special Publication on Fisheries and Aquatic Sciences* 105.

Resh, V. H., R. H. Norris, and M. T. Barbour. 1995. Design and Implementation of Rapid Assessment Approaches for Water Resource Monitoring Using Benthic Macroinvertebrates. *Australian Journal of Ecology* 20(1):108–121.

Reynoldson, T. B., R. C. Bailey, K. E. Day, and R. J. Norris. 1995. Biological Guidelines for Freshwater Sediment Based on BEnthic Assessment of SedimenT (the BEAST) Using a Multivariate Approach for Predicting Biological State. *Australian Journal of Ecology* 20(1):198–219.

Rheinhardt, R., M. Brinson, G. Meyer, and K. Miller. 2012. Integrating Forest Biomass and Distance from Channel to Develop an Indicator of Riparian Condition. *Ecological Indicators* 23:46–55.

Richards, K. 1982. *Rivers: Form and Process in Alluvial Channels.* New York: Methuen.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and Function of Large Woody Debris in Subalpine Rocky Mountain Streams in Northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Rigon, E., F. Comiti, and M. A. Lenzi. 2012. Large Wood Storage in Streams of the Eastern Italian Alps and the Relevance of Hillslope Processes. *Water Resources Resea*rch 48:W01518, doi:10.1029/2010WR009854 18 p.

Riley, A. L. 1998. *Restoring Streams in Cities: A Guide for Planners, Policymakers, and Citizens*. Washington, D.C. Island Press.

Riley, S. C. and K. D. Fausch. 1995. Trout Population Response to Habitat Enhancement in Six Northern Colorado Streams. *Canadian Journal of Fisheries and Aquatic Sciences*. 52:34–53.

Roadway Safety Alliance. 2005. *Internal Traffic Control Plans. Laborers' Health and Safety Fund of North America*. Washington, D.C.

Roadway Safety Alliance. Undated. *Internal Traffic Control Plans*. Developed under a contract with the Centers for Disease Control and Prevention contract No. 212-2003-M-02677, Laborers' Health and Safety Fund of North America, Washington, D.C.

Robert, A. 1997. Characteristics of Velocity Profiles Along Riffle-Pool Sequences and Estimates of Bed Shear Stresses. *Geomorphology* 19:89–98.

Robison, E. G. and R. L. Beschta. 1990. Identifying Trees in Riparian Areas that can Provide Coarse Woody Debris to Streams. *Forest Science* 36:790–801.

Roloff, G. J., G. F. Wilhere, T. Quinn, and S. Kohlmann. 2001. An Overview of Models and Their Role in Wildlife Management. Pages 521–536 in T. J. Johnson and T. A. O'Neil (eds.), *Wildlife-Habitat Relationships in Oregon and Washington*. Corvallis, OR: Oregon State University.

Roni, P. 2002. Habitat Use by Fishes and Pacific Giant Salamanders in Small Western Oregon and Washington Streams. *Transactions of the American Fisheries Society* 131(4):743–761.

Roni, P. (ed.). 2005. *Monitoring Stream and Watershed Restoration*. American Fisheries Society, Bethesda, MD.

Roni, P., and T. P. Quinn. 2001. Density and Size of Juvenile Salmonids in Response to Placement of Large Woody Debris in Western Oregon and Washington Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 58:282–292.

Roni, P., M. Liermann, and A. Steel. 2003. Monitoring and Evaluating Fish Response to Instream Restoration. In D. Montgomery, S. Bolton, D. Booth, and L. Wall (eds.), *Restoration of Puget Sound Rivers*. Center for Water and Watershed Studies. University of Washington Press: Seattle.

Roni, P., T. Bennett, S. Morley, G. R. Pess, K. Hanson, D. Van Slyke, and P. Olmstead. 2006. Rehabilitation of Bedrock Stream Channels: The Effects of Boulder Weir Placement on Aquatic Habitat and Biota. *River Research and Applications* 22(9):967–980.

Roni, P., K. Hanson, and T. Beechie. 2008. Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management* 28(3):856–890.

Roni, P., G. Pess, T. Beechie, and S. Morley. 2010. Estimating Changes in Coho Salmon and Steelhead Abundance from Watershed Restoration: How Much Restoration is Needed to Measurably Increase Smolt Production? *North American Journal of Fisheries Management* 30(6):1469–1484.

Roni, P., T. J. Beechie, G. R. Pess, and K. M. Hanson. 2014a. Wood Placement in River Restoration: Fact, Fiction and Future Direction. *Canadian Journal of Fisheries and Aquatic Sciences.*

Roni, P., G. R. Pess, and T. J. Beechie. 2014b. *Fish-Habitat Relationships and Effectiveness of Habitat Restoration.* National Marine Fisheries Service. Seattle, WA. NOAA Technical Memorandum NMFS-NWFSC-127.

Rood, S. B., and J. M. Mahoney. 1990. Collapse of Riparian Poplar Forests Downstream from Dams in Western Prairies: Probable Causes and Prospects for Mitigation. *Environmental Management* 14:451–464.

Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppettone, S. Swanson, and P. L. Wagner. 2003. Flows for Floodplain Forests: A Successful Riparian Restoration. *Bioscience* 53:647–656.

Roper, B. B., J. M. Buffington, S. Bennett, S. H. Lanigan, E. Archer, S. T. Downie, J. Faustini, T. W. Hillman, S. Hubler, K. Jones, C. Jordan, P. K. Kauffman, G. Merritt, C. Moyer, and A. Pleus. 2010. A Comparison of the Performance and Compatibility of Protocols Used by Seven Monitoring Groups to Measure Stream Habitat in the Pacific Northwest. *North American Journal of Fisheries Management* 30:565–587.

Rose, K. A. 2000. Why are Quantitative Relationships Between Environmental Quality and Fish Populations so Elusive? *Ecological Applications* 10(2):367–385.

Rose, S. and N. E. Peters. 2001. Effects of Urbanization on Streamflow in the Atlanta Area (Georgia, USA): A Comparative Hydrological Approach. *Hydrological Processes* 15:1441–1457.

Rosenberg, D. M., and V. H. Resh (eds.). 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrate*s. Springer.

Rosenfeld, J. 2003. Assessing the Habitat Requirements of Stream Fishes: an Overview and Evaluation of Different Approaches. *Transactions of the American Fisheries Society* 132:953–968.

Rosenfeld, J. S. 2014. Modelling the Effects of Habitat on Self-thinning, Energy Equivalence, and Optimal Habitat Structure for Juvenile Trout. *Canadian Journal of Fisheries and Aquatic Sciences.* 71(9):1395–1406.

Rosenfeld, J. S., and S. Boss. 2001. Fitness Consequences of Habitat Use for Juvenile Cutthroat Trout: Energetic Costs and Benefits in Pools and Riffles. *Canadian Journal of Fisheries and Aquatic Sciences* 58(3):585–593.

Rosenfeld, J., and T. Hatfield. 2006. Information Needs for Assessing Critical Habitat of Freshwater Fish. *Canadian Journal of Fisheries and Aquatic Sciences 63:*683–698.

Rosenfeld, J. S., and L. Huato. 2003. Relationship Between Large Woody Debris Characteristics and Pool Formation in Small Coastal British Columbia Streams. *North American Journal of Fisheries Management* 23:928–938.

Rosenfeld, J. S., and R. Ptolemy. 2012. Modelling Available Habitat Versus Available Energy Flux: Do PHABSIM Applications that Neglect Prey Abundance Underestimate Optimal Flows for Juvenile Salmonids? *Canadian Journal of Fisheries and Aquatic Sciences* 69(12):1920–1934.

Rosgen, D., and H. L. Silvey 1996. *Applied River Morphology.* Pagosa Springs, CO: Wildland Hydrology.

Rot, B. 1993. *Windthrow in Stream Buffers on Coastal Washington Streams*. ITT-Rayonier Inc.

Rot, B. W., R. J. Naiman, and R. E. Bilby. 2000. Stream Channel Configuration, Landform, and Riparian Forest Structure in the Cascade Mountains, Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 57:699–707.

Ruffner, E. H. 1886. *The Practice of the Improvement of the Non-Tidal Rivers of the United States, with an Examination of the Results Thereof*. New York, NY: John Wiley and Sons.

Ruiz-Villanueva, V., A. Díez-Herrero, J. M. Bodoque, and E. Bladé. 2014a. Large Wood in Rivers and its Influence on Flood Hazard. *Cuadernos de Investigación Geográfica* 40:229–246.

Ruiz-Villanueva, V., M. Stoffel, H. Piegay, V. Gaertner, and F. Perret. 2014b. Wood Density Assessment to Improve Understanding of Large Wood Buoyancy in Rivers. Pages 2503–2508 in A. Schleiss, G. De Cesare, M. Franca, and M. Pfister (eds.), *River Flow*. London, England: Taylor and Francis.

Rumpff, L., Duncan, D. H., P. A. Vesk, D. A. Keith, and B. A. Wintle. 2011. State-and-Transition Modelling for Adaptive Management of Native Woodlands. *Biological Conservation* 144(4):1224–1236.

Russell, I. C. 1898. *Rivers of North America*. New York: G.P. Putnams Sons.

Russell, I. C. 1909. *Rivers of North America*. New York, NY: G.P. Putnam and Sons.

Russell, K., and E. Holburn. 2009. Field Evaluation of Engineered Large Woody Debris for Structure Performance and Habitat Value. Pages 3234–3243 in *World Environmental and Water Resources Congress 2009.* American Society of Civil Engineers.

Rutherford, I., B. Anderson, and A. Ladson. 2007. Managing the Effects of Riparian Vegetation on Flooding. In S. Lovett and P. Price (eds.), *Principles for Riparian Lands Management*. Land & Water Australia, Canberra.

Ryan, S. E., E. L. Bishop, and J. M. Daniels. 2014. Influence of Large Wood on Channel Morphology and Sediment Storage in Headwater Mountain Streams, Fraser Experimental Forest, Colorado. *Geomorphology* 217:73–88.

Sabater, S., V. Acuña, A. Giorgi, E. Guerra, I. Muñoz, and A. M. Romaní, 2005. Effects of Nutrient Inputs in a Forested Mediterranean Stream Under Moderate Light Availability. *Archiv für Hydrobiologie* 163:479–496.

Saldi-Caromile, K., K. Bates, P. Skidmore, J. Barenti, and D. Pineo. 2004. *Stream Habitat Restoration Guidelines: Final Draft*. Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. Olympia, Washington.

Salmon Recovery Funding Board (SRFB). 2013. *Manual 18 Salmon Recovery Grants*. Washington State Recreation and Conservation Office. Salmon Recovery Funding Board. January.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish Community and Food Web Responses to a Whole-Lake Removal of Coarse Woody Habitat. *Fisheries* 31:321–330.

Sauer, V. B. 1974. *Flood Characteristics of Oklahoma Streams Techniques for Calculating Magnitude and Frequency of Floods in Oklahoma, with Compilations of Flood Data Through 1971.* U.S. Geological Survey Water-Resources Investigations Report 73–52. 307 p.

Sauer, V. B., and D. P. Turnipseed. 2010. *Stage Measurement at Gaging Stations: U.S. Geological Survey Techniques and Methods Book 3*, Chapter A7.

Saunders, J. W. and M. W. Smith. 1955. Physical Alteration of Stream Habitat to Improve Brook Trout Production. *Canadian Fish Culturist* 16:185–188.

Sawyer, A. H., and M. B. Cardenas. 2009. Hyporheic Flow and Residence Time Distributions in Heterogeneous Cross-Bedded Sediment. *Water Resources Research* 45:W08406.

Sawyer, A. H., and M. B. Cardenas. 2012. Effect of Experimental Wood Addition on Hyporheic Exchange and Thermal Dynamics in a Losing Meadow Stream. *Water Resources Research* 48:W10537.

Sawyer, A. H., M. B. Cardenas, and J. Buttles. 2011. Hyporheic Exchange due to Channel-Spanning Logs. *Water Resources Research* 47(8):W08502.

Sawyer, A. H., M. B. Cardenas, and J. Buttles. 2012. Hyporheic Temperature Dynamics and Heat Exchange Near Channel-Spanning Logs. *Water Resources Research* 48:W01529.

Schaff, S. D., S. R. Pezeshki, and F. D. Shields Jr. 2002.The Effect of Pre-Planting Soaking on Growth and Survival of Black Willow (*Salix nigra*) Cuttings. *Restoration Ecology* 10(2):267–274.

Scheffer, T. C. 1971. A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground. *Forest Products Journal* 21(10):25–31.

Scheiner S. M., and J. Gurevitch (eds.). 2001. *Design and Analysis of Ecological Experiments.* Oxford University Press.

Schenk, E. R., J. W. McCargo, B. Moulin, C. R. Hupp, and J. M. Richter. 2014a. The Influence of Logjams on Largemouth Bass (*Micropterus salmoides*) Concentrations on the lower Roanoke River, a Large Sand-Bed River. *River Research and Applications* 2014(DOI: 10.1002/rra.2779).

Schenk, E. R., B. Moulin, C. R. Hupp, and J. M. Richter. 2014b. Large Wood Budget and Transport Dynamics on a Large River Using Radio Telemetry. *Earth Surface Processes and Landforms* 39:487–498.

Scherer, R. 2004. Decomposition and Longevity of In-Stream Woody Debris: A Review of Literature from North America. Pages 127–133 in *Forest Land–Fish Conference–Ecosystem Stewardship through Collaboration*. Proceedings of Forest-Land-Fish Conference II.

Scheuerell, M. D., R. Hilborn, M. H. Ruckelshaus, K. K. Bartz, K. M. Lagueux, A. D. Haas, and K. Rawson. 2006. The Shiraz Model: A Tool for Incorporating Anthropogenic Effects and Fish–Habitat Relationships in Conservation Planning. *Canadian Journal of Fisheries and Aquatic Sciences* 63(7):1596–1607.

Schiff, R., J. S. Clark, G. Alexander, and M. Kline 2008a. *The Vermont Agency of Natural Resources Reach Habitat Assessment (RHA).* Prepared by Milone & MacBroom, Inc. with the Vermont Agency of Natural Resources, Departments of Environmental Conservation and Fish and Wildlife, Waterbury, VT.

Schiff, R., J. S. Clark, and S. Jaquith 2008b. *The Vermont Culvert Geomorphic Compatibility Screening Tool.* Prepared by Milone & MacBroom, Inc. with the VT DEC River Management Program, Waterbury, VT.

Schiff, R., E. Fitzgerald, J. MacBroom, M. Kline, and S. Jaquith 2014. *The Vermont Standard River Management Principles and Practices (Vermont SRMPP): Guidance for Managing Vermont's Rivers Based on Channel and Floodplain Function*. Prepared by Milone & MacBroom and Fitzgerald Environmental Associates for and in collaboration with the Vermont Rivers Program, Montplelier, VT.

Schlosser, I. J. 1991. Stream Fish Ecology: A Landscape Perspective. *BioScience* 41:704–712.

Schlosser, I. J., and P. L. Angermeier. 1995. Spatial Variation in Demographic Processes of Lotic Fishes: Conceptual Models, Empirical Evidence, and Implications for Conservation. Pages 392–401 in J. L. Nielsen and D. A. Powers (eds.), *Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation.* Bethesda, MD: American Fisheries Society.

Schmetterling, D. A., and R. W. Pierce. 1999. Success of Instream Habitat Structures After a 50-Year Flood in Gold Creek, Montana. *Restoration Ecology* 7(4):369–375.

Schmidt, J. C., and P. R. Wilcock. 2008. Metrics for Assessing the Downstream Effects of Dams. *Water Resources Research* 44:W04404. doi:10.1029/2006WR005092.

Scott, M. L., J. M. Friedman, G. T. Auble. 1996. Fluvial Process and the Establishment of Bottomland Trees. *Geomorphology* 14:327–339.

Schuett-Hames, D., A. E. Pleus, J. Ward, M. Fox, and J. Light. 1999. *TFW Monitoring Program Methods Manual for the Large Woody Debris Survey*. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-004. DNR #106. March.

Schumm, S. A. 1999. Causes and Controls of Channel Incision. Pages 19–34 in S. E. Darby and A. Simon (eds.), *Incised River Channels.* Chichester, UK: Wiley.

Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. *Incised Channels: Morphology, Dynamics and Control.* Water Resources Publication. Littleton, CO.

Scott, S. E., and Y. Zhang. 2012. Contrasting Effects of Sand Burial and Exposure on Invertebrate Colonization of Leaves. *American Midland Naturalist* 167:68–78.

Scottish Environment Protection Agency. 2009. *Engineering in Water Environment Good Practice Guide: Temporary Construction Methods.* First edition.

Sear, D. A., C. E. Millington, D. R. Kitts, and R. Jeffries. 2010. Logjam Controls on Channel:Floodplain Interactions in Wooded Catchments and Their Role in the Formation of Multi-Channel Patterns. *Geomorphology* 116:305–319.

Sedell, J. R., and J. L. Frogatt. 1984. Importance of Streamside Forests to Large Rivers: The Isolation of the Willamette River, Oregon, U.S.A., from its Floodplain by Snagging and Streamside Forest Removal. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1828–1834.

Sedell, J. R., and K. J. Luchessa. 1981. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. Symposium *on Acquisition and Utilization of Aquatic Habitat Inventory Information*. October 23–28, Portland, OR.

Sedell, J. R., and K. J. Luchessa. 1982. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. Pages 222–245 in N. B. Armantrout (ed.). *Acquisition and Utilization of Aquatic Habitat Inventory Information.* Proceedings of a Symposium October 28–30, 1981. Billings, MT: The Hague Publishing.

Sedell, J. R., and F. J. Swanson. 1984. Ecological Characteristics of Streams in Old-Growth Forests of the Pacific Northwest. Pages 9–16 in W. R. Meehan, T. R. Merrell Jr., and T. A. Hanley (eds.), *Fish and Wildlife Relationships in Old-Growth Forests*. Juneau, AK: American Institute of Fisheries Research Biologists.

Sedell, J. R., F. H. Everest, and F. J. Swanson. 1982. Fish Habitat and Streamside Management: Past and Present. Pages 244–255 in *Proceedings of the 1981 Convention of the Society of American Foresters, September 27–30, 1981*. Society of American Foresters, Publication 82–01, Bethesda, Maryland.

Sedell, J. R., F. J. Swanson, and S. V. Gregory. 1984. Evaluating Fish Response to Woody Debris. Pages 191–221 in T. J. Hassler (ed.). *Proceedings of the Pacific Northwest Streams Habitat Management Workshop*. American Fisheries Society. Humboldt State University. Arcata, CA.

Sedell, J. R., J. E. Richey, and F. J. Swanson. 1989. The River Continuum Concept: A Basis for the Expected Ecosystem Behavior of Very Large Rivers? *Canadian Special Publication of Fisheries and Aquatic Sciences* 106:49–55.

Seehorn, M. E. 1985. *Fish Habitat Improvement Handbook: Atlanta, Georgia*. U.S. Forest Service, Southern Region. Technical Publication R8-TP-16. 30 pp.

Seitzinger, S., and seven others. 2006. Denitrification across Landscapes and Waterscapes: A Synthesis. *Ecological Applications* 16:2064–2090.

Senter, A. E., and G. B. Pasternack. 2010. Large Wood Aids Spawning Chinook Salmon (*Oncorhynchus Tshawytscha*) in Marginal Habitat on a Regulated River in California. *River Research and Applications* 27:550–565.

Sharma, R., A. B. Cooper, and R. Hilborn. 2005. A Quantitative Framework for the Analysis of Habitat and Hatchery Practices on Pacific Salmon. *Ecological Modeling* 18:231–250.

Shields, F. D., Jr. 2007. *Scour Calculations. Technical Supplement 14B in Stream Restoration Design.* National Engineering Handbook Part 654. USDA-NRCS. Washington, D.C. CD-ROM.

Shields, F. D., Jr., and C. V. Alonso. 2012. Assessment of Flow Forces on Large Wood in Rivers. *Water Resources Research* 48(4):W04156.

Shields, F. D., Jr., and C .J. Gippel. 1995. Prediction of Effects of Woody Debris Removal on Flow Resistance. *Journal of Hydraulic Engineering* 121 (4):341–354.

Shields, F. D., and R. H. Smith. 1992. Effects of Large Woody Debris Removal on Physical Characteristics of a Sand-Bed River. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:145–163.

Shields, F. D., Jr. and A. D. Wood. 2007. *The Use of Large Woody Material for Habitat and Bank Protection.* Technical Supplement 14J in *Stream Restoration Design, National Engineering Handbook Part 654*. USDA-NRCS Washington, D.C. CD-ROM.

Shields, F. D., Jr., A. J. Bowie, and C. M. Cooper. 1995. Control of Streambank Erosion due to Bed Degradation with Vegetation and Structure. *Water Resources Bulletin* 31(3):475–489.

Shields, F. D., Jr., R. Copeland, P. Klingeman, M. Doyle, and A. Simon. 2003. Design for Stream Restoration. *Journal of Hydraulic Engineering* 129(8):575–584.

Shields, F. D., Jr., N. Morin, and C. M. Cooper. 2004. Large Woody Debris Structures for Sand-Bed Channels. *Journal of Hydraulic Engineering* 130(3):208–217.

Shields, F. D. Jr., S. S. Knight, and J. M. Stofleth. 2006. Large Wood Addition for Aquatic Habitat Rehabilitation in an Incised, Sand-Bed Stream, Little Topashaw Creek, Mississippi. *River Research and Applications* 22:803–817.

Shields, F. D., Jr., S. R. Pezeshki, G. V. Wilson, W. Wu, and S. M. Dabney. 2008. Rehabilitation of an Incised Stream with Plant Materials: The Dominance of Geomorphic Processes. *Ecology and Society* 13 (2):54.

Shirvell, C. S. 1990. Role of Instream Rootwads as Juvenile Coho Salmon (*Oncorhynchus kisutch*) and Steelhead Trout (*O. mykiss*) Cover Habitat Under Varying Streamflows. *Canadian Journal of Fisheries and Aquatic Sciences* 47(5):852–861.

Sidle, R. C. 1991. A Conceptual Model of Changes in Root Cohesion in Response to Vegetation Management. *Journal of Environmental Quality* 20:43–52.

Sigura, C., and Booth, D. B. 2010. Effects of Geomorphic Setting and Urbanization on Wood, Pools, Sediment Storage, and Bank Erosion in Puget Sound Streams. *JAWRA Journal of the American Water Resources Association* 46(5):972–986.

Simon, A. 1989. A Model of Channel Response in Disturbed Alluvial Channels. *Earth Surface Processes and Landforms* 14:11–26.

Simon, A. 1994. *Gradation Processes and Channel Evolution in Modified West Tennessee Streams: Process, Response and Form*. U.S. Geological Survey Professional Paper 1470. Washington D.C.

Simon, A., and A. J. C. Collison. 2002. Quantifying the Mechanical and Hydrological Effects of Riparian Vegetation on Stream-Bank Stability. *Earth Surface Processes and Landforms* 27(5):527–546.

Simon, A., and M. Rinaldi. 2006. Disturbance, Stream Incision, and Channel Evolution: The Roles of Excess Transport Capacity and Boundary Materials in Controlling Channel Response. *Geomorphology* 79:361–383.

Simon, A., A. Curini, S. E. Darby, and E. J. Langendoen. 2000. Bank and Near-Bank Processes in an Incised Channel. *Geomorphology* 35(3):193–217.

Simon, A., A. Brooks, and N. Bankhead. 2012. Effectiveness of Engineered Log Jams in Reducing Streambank Erosion to the Great Barrier Reef: The O'Connell River, Queensland, Australia. Pages 2570–2577 in *World Environmental and Water Resources Congress 2012: Crossing Boundaries*. Reston, VA: ASCE.

Simon, A., R. Thomas, A. Curini, and N. Bankhead. 2014. *Development of the Bank-Stability and Toe-Erosion Model* (BSTEM version 5.4). Available: www.kwo.org/reports_publications/Presentations/pp_Development_of_BSTEM_012811_sm.pdf.

Simon, T. P., and J. Lyons. 1995. Application of the Index of Biotic Integrity to Evaluate Water Resource Integrity in Freshwater Ecosystems. Chapter 16 in W. S. Davis and T. P. Simon. *Bioassessment and Criteria: Tools for Water Resources Planning and Decision Making*. CRC Press.

Simpson, W. and A. TenWolde. 1999. Physical Properties and Moisture Relations of Wood. Chapter 3 in *Wood Handbook: Wood as an Engineering Material.* Report FPL-GTR-113. U.S. Department of Agriculture Forest Service. Forest Products Laboratory. Madison, WI.

Singer, S., and M. L. Swanson. 1983. *The Soquel Creek Storm Damage Recovery Plan with Recommendations for Reduction of Geologic Hazards in Soquel Village, Santa Cruz County, California.* Unpublished USDA Soil Conservation Service report to the Santa Cruz County Board of Supervisors.

Sinsabaugh, R. L., M. P. Osgood, and S. Findlay. 1994. Enzymatic Models for Estimating Decomposition Rates of Particulate Detritus. *Journal of the North American Benthological Society*. 13:160–169.

Skidmore, P. B., C. R. Thorne, B. L. Cluer, G. R. Pess, J. M. Castro, T. J. Beechie, and C. C. Shea. 2011. *Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals*. U.S. Department of Commerce. NOAA Tech. Memo. NMFS-NWFSC-112.

Sklar, L. S., J. Fadde, J. G. Venditti, P. Nelson, M. A. Wydzga, Y. Cui, and W. E. Dietrich. 2009. Translation and Dispersion of Sediment Pulses in Flume Experiments Simulating Gravel Augmentation Below Dams. *Water Resources Research* 45:W08439, doi:10.1029/2008WR007346.

Sleeter, B., T. Wilson, W. Acevedo, W. 2012. *Status and Trends of Land Change in the Western United States—1973–2000.* U.S. Geological Survey Professional Paper 1794-A.

Smith, D. G. 1979. Effects of Channel Enlargement by River Ice Processes on Bankfull Discharge in Alberta, Canada. *Water Resources Research*, 15(2):469–475.

Smith, D. G., and C.M. Pearce. 2000. River Ice and its Role in Limiting Woodland Development on a Sandy Braid-Plain, Milk River, Montana. *Wetlands,* 20(2):232–250.

Smith, D. G., and D. M. Reynolds. 1983. Tree Scars to Determine the Frequency and Stage of High Magnitude River Ice Drives and Jams, Red Deer, Alberta. *Canadian Water Resources Journal* 8(3):77–94.

Smith, D. L., J. B. Allen, O. Eslinger, M. Valenciano, J. Nestler, and R. A. Goodwin. 2011. Hydraulic Modeling of Large Roughness Elements with Computational Fluid Dynamics for Improved Realism in Stream Restoration Planning. *Geophysical Monograph Series* 194:115–122.

Smith, J. D.. 2004. The Role of Riparian Shrubs in Preventing Floodplain Unraveling Along the Clark Fork of the Columbia River in the Deer Lodge Valley, Montana. Pages 71–85 in S. J. Bennett. and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8*. American Geophysical Union, Washington, D.C.

Smith, M. P., R. Schiff, A. Olivero, and J. G. MacBroom 2008. The *Active River Area: A Conservation Framework to Protect Rivers and Streams.* Boston, MA: The Nature Conservancy.

Smith, R. D., R. C. Sidle, and P. E. Porter. 1993. Effects on Bedload Transport of Experimental Removal of Woody Debris from a Forest Gravel-Bed Stream. *Earth Surface Processes and Landforms* 18:455–468.

Smock, L. A., G. M. Metzler and J. E. Gladden. 1989. Role of Debris Dams in the Structure and Functioning of Low Gradient Headwater Streams. *Ecology* 70:764–775.

Smokorowski, K. E., and T. C. Pratt. 2007. Effect of a Change in Physical Structure and Cover on Fish and Fish Habitat in Freshwater Ecosystems - A Review and Meta-Analysis. *Environmental Reviews* 15:15–41.

Sobczak, W. V., and S. Findlay. 2002. Variation in Bioavailability of Dissolved Organic Carbon among Stream Hyporheic Flowpaths. *Ecology* 83:3194–3209.

Sobota, D. J., S. V. Gregory, S. V., and S. L. Johnson. 2007. Influence of Wood Decomposition on Nitrogen Dynamics in Stream Ecosystems: Interactive Effects of Substrate Quality and Nitrogen Loading. *North American Benthological Society 55th Annual Meeting.* Available: https://nabs.confex.com/nabs/2007/techprogram/P1365.HTM.

Society for Ecological Restoration. 2002. *SER International Primer on Ecological Restoration*. Science & Policy Working Group, Version 2, October. Available: http://www.ser.org/resources/resources-detail-view/ser-international-primer-on-ecological-restoration.

Society for Ecological Restoration. 2004. *The SER International Primer on Ecological Restoration*. Available: http://www.ser.org.

Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of Increasing Winter Rearing Habitat on Abundance of Salmonids in Two Coastal Oregon Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 57:906–914.

Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of Log Decay in Old-Growth Douglas-Fir Forests, *Canadian Journal of Forest Research* 17:1585–1595.

Southerland, B. S., and F. Reckendorf. 2010. Performance of Engineered Log Jams in Washington State—Post Project Appraisal. In *Joint Federal Interagency Conferences 2010: Book of Abstracts.* Joint Fed. Interagency Conf., 2010, Conference on Sedimentation and Hydrologic Modeling, June 27–July 1, Las Vegas, Nev., Government Printing Office, Washington, D. C.

Southwide Safety Committee. 2010. *Timber Harvesting Safety Manual*. Rockville, MD. National Timber Harvesting and Transportation Safety Foundation. Available: http://loggingsafety.com/content/timber-harvesting-safety-manual. Accessed: July 10, 2014.

Southwood, T. R. E. 1977. Habitat, the Template for Ecological Strategies? *Journal of Animal Ecology* 46:337–365.

Spänhoff, B., and E. Cleven. 2010. Wood in Different Stream Types: Epixylic Biofilm and Wood-Inhabiting Invertebrates in a Lowland Versus an Upland Stream. *Annales De Limnologie-International Journal of Limnology* 46(3):169–179.

Spänhoff, B., and E. I. Meyer. 2004. Breakdown Rates of Wood in Streams. *Journal of the North American Benthological Society* 23(2):189–197.

Spänhoff, B., C. Alecke, and E. Irmgard Meyer. 2001. Simple Method for Rating the Decay Stages of Submerged Woody Debris. *Journal of the North American Benthological Society* 20(3):385–394.

Spies, T. A., and J. F. Franklin. 1991. The Structure of Natural Young, Mature, and Old-Growth Douglas Fir Forests in Oregon and Washington. Pages 91–109 in L. F. Ruggiero, K. B. Aubrey, A. B. Carey, and M. H. Huff (technical coordinators), *Wildlife and Vegetation of Unmanaged Douglas Fir Forests*. USDA Forest Service. General Technical Report PNW-GTR-285.

Spies, T. A., J. F. Franklin, and T. B. Thomas. 1988. Coarse Woody Debris in Douglas-Fir Forests of Western Washington and Oregon. *Ecology* 69:1689–1702.

Spooner, D. E., M. A. Xenopoulos, C. Schneider, and D. A. Woolnough. 2011. Coextirpation of Host-Affiliate Relationships in Rivers: The role of Climate Change, Water Withdrawal, and Host-Specificity. *Global Change Biology* 17:1720–1732. doi:10.1111/j.1365-2486.2010.02372.x.

Stahle, D. W., M. K. Cleaveland, R. D. Griffin, M. D. Spond, F. K. Fye, R. B. Culpepper, and D. Patton. 2006. Decadal Drought Effects on Endangered Woodpecker Habitat. *Eos, Transactions American Geophysical Union* 87(12):121–125.

Stanford, J. A., and G. C. Poole. 1996. A Protocol for Ecosystem Management. *Ecological Applications*:741–744.

Stanford, J. A. and J. V. Ward. 1988. The Hyporheic Habitat of River Ecosystems. *Nature* 335:64–66.

Stanford, J. A., and J. V. Ward. 1993. An Ecosystem Perspective of Alluvial Rivers: Connectivity and the Hyporheic Corridor. *Journal of the North American Benthological Society* 12(1):48–60.

Stanford, J. A., and J. V. Ward. 1995. The Serial Discontinuity Concept: Extending the Model to Floodplain Rivers. *Regulated Rivers: Research and Management:*159–168.

Statzner, B., and B. Higler. 1985. Questions and Comments on the River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Science* 42:1038–1044.

Steinhart, G. S., G. E. Likens, and P. M. Groffman. 2000. Denitrification in Stream Sediments in Five Northeastern (USA) Streams. *Verhandlungen Internationale Vereinigung für Theorertische und Angewandte Limnologie* 27:1331–1336.

Stelzer, R. S., L. A. Bartsch, W. B. Richardson, and E. A. Strauss. 2011. The Dark Side of the Hyporheic Zone: Depth Profiles of Nitrogen and its Processing in Stream Sediments. *Freshwater Biology* 56:2021–2033.

Stewart, G. B., H. R. Bayliss, D. A. Showler, W. J. Sutherland, and A. S. Pullin. 2009. Effectiveness of Engineered In-Stream Structure Mitigation Measures to increase Salmonid Abundance: A Systematic Review. *Ecological Applications* 19(4):931–941.

Stewart, P. M., S. Bhattarai, M. W. Mullen, C. K. Metcalf, and E. G. Reategui-Zirena. 2012. Characterization of Large Wood and its Relationship to Pool Formation and Macroinvertebrate Metrics in Southeastern Coastal Plain Streams, USA. *Journal of Freshwater Ecology* 27(3):351–365.

Stewart, T. L., and J. F. Martin. 2005. Energy Model to Predict Suspended Load Deposition Induced by Woody Debris: Case Study. *Journal of Hydraulic Engineering-ASCE* 131:1011–1016.

Stewart-Oaten, A., J. R. Bence, and C. W. Osenberg. 1992. Assessing Effects of Unreplicated Perturbations: No Simple Solutions. *Ecology*:1396–1404.

Stiehl, R. B. 1998. *Habitat Evaluation Procedures Workbook.* Fort Collins, CO: U.S. Geological Survey.

Stock, J. D., D. R. Montgomery, B. D. Collins, W. E. Dietrich, and L. Sklar. 2005. Field Measurements of Incision Rates Following Bedrock Exposure: Implications for Process Controls on the Long Profiles of Valleys Cut by Rivers and Debris Flows. *Geological Society of America Bulletin* 117(11/12):174–194.

Stockner, J. G. (ed.). 2003. *Nutrients in Salmonid Ecosystems: Sustaining Production and Biodiversity.* Bethesda, MD: American Fisheries Society.

Stofleth, J. M., F. D. Sheilds, Jr., and G. A. Fox. 2004 Organic Carbon Concentrations in Hyporheic Zone Sediments: A Tool for Measuring Stream Integrity. In *Proceedings of the 2004 World Water and Environmental Resources Congress*, G. Shhlke, D. F. Hayes, and D. K. Stevens (eds.). *Critical Transitions in Water and Environmental Resources, American Society of Civil Engineers*: CD ROM.

Stofleth, J. M., F. D. Shields, Jr., and G. A. Fox. 2007. Hyporheic and Total Transient Storage in Small, Sand-Bed Streams. *Hydrological Processes* 22:1885–1894.

Subramanya, K., 2008. *Engineering Hydrology*. New York: McGraw-Hill.

Suding, K. N., and R. J. Hobbs. 2009. Threshold Models in Restoration and Conservation: A Developing Framework. *Trends in Ecology & Evolution* 24 (5):271–279.

Sullivan, K. J., J. Tooley, K. Doughty, J. E. Caldwell, and P.A. Knudsen. 1990. *Evaluation of Prediction Models and Characterization of Stream Temperature Regimes in Washington*. TFW-WQ3-90-006, Timber Fish & Wildlife, Department of Natural Resources, Olympia, WA.

Sundbaum, K. and I. Naslund. 1998. Effects of Woody Debris on the Growth and Behavior of Brown Trout in Experimental Stream Channels. *Canadian Journal of Zoology* 76:56–61.

Svoboda, C. D. and K. Russell, K. 2011. Flume Analysis of Engineered Large Wood Structures for Scour Development and Habitat. Pages 2572–2581 in *Proceedings, World Environmental and Water Resources Congress*, ASCE, Reston, VA.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land-Water Interactions: The Riparian Zone. Pages 267–291 on R. L. Edmonds (ed.), *Analysis of Coniferous Forest Ecosystems in the Western United States*. US/IBP Synthesis Series, Hutchinson Ross Publishing Company: Stroudsburg, PA.

Swanson, F. J., T. K. Kranz, N. Caine, and R. G. Woodmansee. 1988. Landform Effects on Ecosystem Patterns and Processes. *BioScience* 38:92–98.

Sylte, T., and C. Fischenich. 2000. *Rootwad Composites for Streambank Erosion Control and Fish Habitat Enhancement*. U.S. Army Corps of Engineers. Vicksburg, MS.

Tappeiner, J. C., D. Huffman, D. Marshall, T. A. Spies, and J. D. Bailey. 1997. *Density, Ages, and Growth Rates in Old-Growth and Young-Growth Forests in Coastal Oregon*. Paper 3166 of the Forest Research Laboratory, Oregon State University, Corvallis.

Tarzwell, C. M. 1934. *The Purpose and Value of Stream Improvement Method. Stream Improvement.* Bulletin R-4. Presented at the Annual Meeting of the American Fisheries Society. Ogden, UT.

Tarzwell, C. M. 1936. Experimental Evidence of the Value of Trout Stream Improvements. *Transactions of the American Fisheries Society* 66:177–187.

Teels, B. M., and T. Danielson. 2001. *Using a Regional IBI to Characterize Condition of Northern Virginia Streams, with Emphasis on the Occoquan Watershed*. USDANRCS. Technical Note 190-13-1. December 2001

Thomas, H., and T. R. Nisbet. 2006. An Assessment of the Impact of Flood Plain Woodland on Flood Flows. *Water and the Environment Journal* 21(2):114–126.

Thompson, D. M. 1995. The Effects of Large Organic Debris on Sediment Processes and Stream Morphology in Vermont. *Geomorphology* 11(3):235–244.

Thompson, D. M. 2002. Channel-bed Scour with High Versus Low Deflectors. *Journal of Hydraulic Engineering* 128(6):640–643.

Thompson, D. M. 2002. Long-term Effect of Instream Habitat-improvement Structures on Channel Morphology along the Blackledge and Salmon Rivers, Connecticut, USA. *Environmental Management* 29(1):250–265.

Thompson, D. M. 2005. The History of the Use and Effectiveness of Instream Structures in the United States. *Geological Society of America Reviews in Engineering Geology* XVI:35–50.

Thompson, D. M. 2006. Did the Pre-1980 Use of In-Stream Structures Improve Streams? A Reanalysis of Historical Data. *Ecological Applications* 16(2):784–796.

Thompson, D. M., and Stull, G. N. 2002. The Development and Historic Use of Habitat Structures in Channel Restoration in the United States: The Grand Experiment in Fisheries Management. *Géographie physique et Quaternaire* 56(1):45–60.

Thorne, S. D., and D. J. Furbish. 1995. Influences of Coarse Bank Roughness on Flow Within a Sharply Curved River Bend. *Geomorphology* 12(3):241–257.

Thorne, C., J. Townsend, and T. Ashley. 2014a. *Geomorphic and Ecological Assessment and Evaluation of Grade Building Structures on the SRS Sediment Plain, North Fork Toutle River Final Report*. Performed for the U.S. Army Corps of Engineers, Portland District, OR.

Thorne, C., J. Castro, B. Cluer, P. Skidmore, and C. Shea. 2014b. Project Risk Screening Matrix for River Management and Rrestoration. *River Research and Applications,* April 2014, DOI: 10.1002/rra.2753.

Tillman, D. C., A. H. Moerke, C. L. Ziehl, and G. A. Lamberti. 2003. Subsurface Hydrology and Degree of Burial Affect Mass Loss and Invertebrate Colonization of Leaves in a Woodland Stream. *Freshwater Biology* 48:98–107.

Tonglao, P., and D. Eckberg. 2012. *FAQ's about Wood Placements in Rivers*. March Bulletin, Skellenger Bender Attorneys, Seattle, Washington. Available: http://www.hallandcompany.com/php_uploads/resources/library/2012%20March%20Bulletin%20-%20FAQ%27s%20About%20Wood%20Placements%20in%20Rivers%20%283%29%202012.pdf .

Tonina, D., and J. M. Buffington. 2009. Hyporheic Exchange In Mountain Rivers I: Mechanics and Environmental Effects. *Geography Compass* 3:1063–1086.

Torgersen, C. E., J. L. Ebersole, and D. M. Keenan. 2012. *Primer for Identifying Cold-Water Refuges to Protect and Restore Thermal Diversity in Riverine Landscapes*. U.S. EPA 910-C-12-001.

Townsend, C. R. 1989. The Patch Dynamics Concept of Stream Community Ecology. *Journal of the North American Benthological Society* 8(1):36–50.

Treadwell, S., J. Koehn, S. Bunn, and A. Brooks. 2007. Wood and Other Aquatic Habitat. Chapter 7 in S. Lovett and P. Price (eds.), *Principles for Riparian Lands Management*. Land and Water Australia, Canberra.

Trinity River Restoration Program. 2015. Main Web Page. Available: http://www.trrp.net/. Accessed: February 28, 2015.

Triska, F. J. 1984. Role of Large Wood in Modifying Channel Morphology and Riparian Areas of a Large Lowland River under Pristine Conditions: A Historical Case Study. *Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie* 22:1876–1892.

Triska, F. J., and K. Cromack, Jr.. 1979. The Role of Wood Debris in Forests and Streams. In R. H. Waring, Forests: Fresh Perspectives from Ecosystem Analysis. Pages 171–190 in *Proceedings of the 40th Annual Biology Colloquium*. Corvallis, OR: Oregon State University Press. Corvallis, OR.

Trotter, E. H. 1990. Woody Debris, Forest-Stream Succession, and Catchment Geomorphology. *Journal of the North American Benthological Society* 9(2):141–156.

Tsukamoto, Y. 1987. Evaluation of the Effect of Tree Roots on Slope Stability. *Bulletin of the Experimental Forests*. 23:65–124.

Tufekcioglu, A., J. W. Raich, T. M. Isenhart, and R. C. Schultz. 2003. Biomass, Carbon and Nitrogen Dynamics of Multi-Species Riparian Buffers within an Agricultural Watershed in Iowa, USA. *Agroforestry Systems* 57(3):187–198.

Tullos, D., and C. Walter. 2014. Fish Use of Turbulence Around Wood in Winter: Physical Experiments on Hydraulic Variability and Habitat Selection by Juvenile Coho Salmon, *Oncorhynchus kisutch*. *Environmental Biology of Fishes*:1–15.

Turnipseed, D. P., and V. B. Sauer. 2010. *Discharge Measurements at Gaging Stations: U.S. Geological Survey Techniques and Methods Book 3*, Chapter A8, U.S. Geological Survey.

Turowski, J. M., A. Badoux, K. Bunte, C. Rickii, N. Federspiel, and M. Jochner. 2013. The Mass Distribution of Coarse Particulate Matter from an Alpine Headwater Stream. *Earth Surface Dynamics* 1:1–14.

Tyler, R. N. 2011. *River Debris: Causes, Impacts, and Mitigation Techniques*. Prepared for Ocean Renewable Power Company by the Alaska Center for Energy and Power, Fairbanks, Alaska.

Umazano, A.M., R.N. Melchor, E. Bedatou, E.S. Bellosi, and J.M. Krause. 2014. Fluvial Response to Sudden Input of Pyroclastic Sediments During the 2008–2009 Eruption of the Chaitén Volcano (Chile): The Role of Logjams. *Journal of South American Earth Sciences* 54:140–157.

U.S. Army Corps of Engineers, 1981. *The Streambank Erosion Control Evaluation and Demonstration Act of 1974*. Final Report to Congress, Main Report. Washington, D.C.

U. S. Army Corps of Engineers. 1992. *Engineering and Design: Bearing Capacity of Soils*. EM 1110-1-1905. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U. S. Army Corps of Engineers. 1994. *Engineering and Design: Hydraulic Design of Flood Control Channels.* EM 1110-2-1601. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U. S. Army Corps of Engineers. 2005. *Engineering and Design: Stability Analysis of Concrete Structures.* EM 1110-2-2100. Department of the Army, U.S. Army Corps of Engineers. Washington, D.C.

U.S. Army Corps of Engineers. 2008. *Safety and Health Requirements*. Engineer Manual 385-1-1. U.S. Army Corps of Engineers Headquarters, Washington, D.C

U.S. Army Corp of Engineers Institute for Water Resources (USACE IWR). 2010. *IWR Planning Suite MCDA Module User's Guide*. U.S. Army Corp of Engineers Institute for Water Resources.

U.S. Bureau of Reclamation. 2005. *Watershed Conditions and Seasonal Variability for Select Streams within WRIA 20, Olympic Peninsula, Washington*. Available: http://www.ecy.wa.gov/programs/eap/wrias/planning/docs/opendraft_wria20_final4.pdf.

U.S. Climate Change Science Program (CCSP). 2008a. *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (S. H. Julius and J.M. West [eds.], J. S. Baron, B. Griffith, L. A. Joyce, P. Kareiva, B. D. Keller, M. A. Palmer, C. H. Peterson, and J. M. Scott [Authors]). U.S. Environmental Protection Agency. Washington, D.C.

U.S. Climate Change Science Program (CCSP). 2008b. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B. A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. G. Ryan, S. R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, B. Peterson, and R. Shaw). U.S. Department of Agriculture. Washington, D.C.

U.S. Climate Change Science Program (CCSP). 2008c. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (M. J. Savonis, V. R. Burkett, and J. R. Potter [eds.]). U.S. Department of Transportation. Washington, D.C.

U.S. Department of Agriculture (USDA). 1980. *Ecoregions of the United States*. U.S. Forest Service, Washington, D.C. Miscellaneous Publication No. 1391

U.S. Department of Agriculture (USDA), Agricultural Research Service. 2013. *Bank Stability and Erosion Model*. Available: http://www.ars.usda.gov/Research/docs.htm?docid=5044&page=1.

U.S. Department of Health and Human Services. 2002. *Toxicological Profile for Wood Creosote, Coal Tar Creosote, Coal Tar, Coal Tar Pitch, and Coal Tar Pitch Volatiles*. September.

U.S. Department of the Interior – Bureau of Reclamation. 2011. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*. Technical Memorandum No. 86-68210–2011-01

U.S. Environmental Protection Agency (EPA). 1995. *A Decision-Making Guide for Restoration in Ecological Restoration*. EPA 841-F-95-007 (November)

U.S. Environmental Protection Agency (EPA). 2000. *Principles for the Ecological Restoration of Aquatic Resources*. EPA841-F-00-003. Available: http://www.epa.gov/owow/wetlands/restore/.

U.S. Environmental Protection Agency (EPA). 2008. *Handbook for Developing Watershed Plans to Restore and Protect our Water*.

U.S. Environmental Protection Agency. 2009. *Valuing the Protection of Ecological Systems and Services*. May. Available: http://yosemite.epa.gov/sab%5CSABPRODUCT.NSF/F3DB1F5C6EF90EE1852575C500589157/$File/EPA-SAB-09-012-unsigned.pdf. Accessed: October 8, 2014

U.S. Environmental Protection Agency. 2011. *Aquatic Indicators*. Available: http://www.epa.gov/nheerl/arm/indicators/indicators.htm.

U.S. Environmental Protection Agency (EPA). 2013. *A Quick Guide to Developing Watershed Plans to Restore and Protect Our Waters.*

U.S. Environmental Protection Agency (EPA). 2014. *Green Infrastructure*. Available: http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm.

U.S. Environmental Protection Agency, Office of Water. 2013. *Climate Change Adaptation Implementation Plan*. Available: http://epa.gov/climatechange/Downloads/impacts-adaptation/office-of-water-plan.pdf.

U.S. Forest Service (USFS). 2008. *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*. Forest Service Stream-Simulation Working Group. San Dimas, CA. May. Available: http://www.stream.fs.fed.us/fishxing/publications/PDFs/AOP_PDFs/08771801.pdf. Accessed: February 27, 2015.

U.S. Fish and Wildlife Service (USFWS). 2008. *SDM Fact Sheet*. Available: http://www.fws.gov/science/doc/structured_decision_making_factsheet.pdf. Accessed: May 15, 2015.

U.S. Global Change Research Program (USGCRP). 2009. *Global Climate Change Impacts in the United States*. Edited by T. R. Karl, J. M. Melillo, and T. C. Peterson. Cambridge, MA: Cambridge University Press.

University of New Hampshire (UNH). 2009. *New Hampshire Stream Crossing Guidelines.* University of New Hampshire, Durham, NH.

Vail, L. W., and R. L. Skaggs. 2002. *Adaptive Management Platform for Natural Resources in the Columbia River Basin*. Pacific Northwest National Laboratory. Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13875.pdf.

Valett, H. M., C. L. Crenshaw, and P. F. Wagner. 2002. Stream Nutrient Uptake, Forest Succession, and Biogeochemical Theory. *Ecology* 83:2888–2901.

Valverde, R. S. 2013. *Roughness and Geometry Effects of Engineered Log Jams on 1-D Flow Characteristics.* M. S. Thesis, Civil Engineering, Oregon State University, Corvallis.

Van Cleef, J. S. 1885. How to Restore Our Trout Streams. *Transactions of the American Fisheries Society* 14:50–55.

Van Horne, B. 1983. Density as a Misleading Indicator of Habitat Quality. *Journal of Wildlife Management* 47:893–901.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Science* 37(1):130–137.

Vanoni, V. 1975. *Sedimentation Engineering, ASCE Manuals and Reports on Engineering Practice—No. 54*. American Society of Civil Engineers, New York, NY.

Van Sickle, J., and S. V. Gregory. 1990. Modeling Inputs of Large Woody Debris to Streams from Falling Trees. *Canadian Journal of Forest Research* 20(10):1593–1601.

Van Wilgen, B. W., and H. C. Biggs. 2011. A Critical Assessment of Adaptive Ecosystem Management in a Large Savanna Protected Area in South Africa. *Biological Conservation* 144(4):1179–1187.

Veatch, A. C. 1906. Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas. Washington D.C. *United States Geological Survey Professional Paper* 46.

Veilleux, A. G., T. A. Cohn, K. M. Flynn, R. R. Mason, and P. R. Hummel. 2013. *Fact Sheet 2013-3108: Estimating Magnitude and Frequency of Floods Using the PeakFQ 7.0 Program*. 2327-6932, U.S. Geological Survey.

Vermont Agency of Natural Resources (VTANR). 2014. V*ermont Stream Alteration General Permit.* Department of Environmental Conservation, Montpelier, VT.

Vermont Agency of Transportation (Vtrans). 2001. *Hydraulics Manual*. Montpelier, VT.

Vidon, P., and A. R. Hill. 2004. Denitrification and Patterns of Electron Donors and Acceptors in Eight Riparian Zones with Contrasting Hydrogeology. *Biogeochemistry* 71:259–283.

Vidon, P., and nine others. 2010. Hot Spots and Hot Moments in Riparian Zones: Potential for Improved Water Quality Management. *Journal of the American Water Resources Association.* DOI: 101111/j.1752-1688.2010.00420.x.

Viessman, W. J., and G. L. Lewis. 2003. *Introduction to Hydrology.* Prentice Hall.

Volkman, J. M., and W. E. McConnaha. 1993. Through a Glass, Darkly: Columbia River Salmon, the Endangered Species Act, and Adaptive Management. *Environmental Law* 23:1249–1272.

Wadsworth, A. H., Jr. 1966. Historical Deltation of the Colorado River, Texas. Pages 99–105 in *Deltas in Their Geologic Framework.* American Association of Petroleum Geologists.

Wallace, J. B., and A .C. Benke. 1984. Quantification of Wood Habitat in Subtropical Coastal Plain Streams. *Canadian Journal of Fisheries and Aquatic Sciences* 41:1643–1652.

Wallace, J. B., J. R. Webster, and J. L. Meyer. 1995a. Influence of Log Additions on Physical and Biotic Characteristics of a Mountain Stream. *Canadian Journal of Fisheries and Aquatic Sciences* 52:2120–2137.

Wallace, J. B., M. R. Whiles, S. Eggert, T. F. Cuffney, G. H. Lugthart, and K. Chung. 1995b. Long-Term Dynamics of Coarse Particulate Organic-Matter in 3 Appalachian Mountain Streams. *Journal of the North American Benthological Society* 14(2):217–232.

Wallace, J. B., S. L. Eggert, J. L. Meyer, and J. R. Webster. 1997. Multiple Trophic Levels of a Forest Stream Linked to Terrestrial Litter Inputs. *Science* 277:102–104.

Wallerstein, N. P., and C. R. Thorne. 2004. Influence of Large Woody Debris on Morphological Evolution of Incised, Sand-Bed Channels. *Geomorphology* 57:53–73.

Wallerstein, N., C. R. Thorne, and M. W. Doyle. 1997. Spatial Distribution and Impact of Large Woody Debris in Northern Mississippi. Pages 145–150 in C. C. Wang, E. J. Langendoen, and F. D. Shields (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision.* University of Mississippi. Oxford, MI.

Wallerstein, N. P., C. V. Alonso, S. J. Bennett, and C. R. Thorne. 2001. Distorted Froude-Scaled Flume Analysis of Large Woody Debris. *Earth Surface Processes and Landforms* 26:1265–1283.

Walsh, C., and A. Roy. 2005. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. *Journal of the North American Benthological Society* 24:706–723.

Walter, R. C., and D. J. Merritts. 2008. Natural Streams and the Legacy of Water-Powered Mills. *Science* 319(5861):299–304.

Walters, C. 2002. *Adaptive Management of Renewable Resources*. The Blackburn Press.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of Floodplain River Ecosystems: Ecotones and Connectivity. *Regulated Rivers Research and Management* 15:125–139.

Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. 2002. Riverine Landscape Diversity. *Freshwater Biology* 47:517–539.

Warner, M. D., C. F. Mass, E. P. Salathé Jr. 2012. Wintertime Extreme Precipitation Events along the Pacific Northwest Coast: Climatology and Synoptic Evolution. *Monthly Weather Review*, 140(7):2021–2043.

Warren, D. R., and C. E. Kraft. 2003. Brook Trout (*Salvelinus fontinalis*) Response to Wood Removal from High-Gradient Streams of the Adirondack Mountains (NY, USA). *Canadian Journal of Fisheries and Aquatic Sciences* 60(4):379-389.

Warren, D. R., and C. E. Kraft. 2008. Dynamics of Large Wood in an Eastern US Mountain Stream. *Forest Ecology and Management* 256(4):808–814.

Warren, D. R., E. S. Bernhardt, R. O. Hall Jr., and G. E. Likens. 2007. Forest Age, Wood and Nutrient Dynamics in Headwater Streams of the Hubbard Brook Experimental Forest. *N.H. Earth Surface Processes & Landforms* 32(8):1154–1163.

Warren, D. R., C. E. Kraft, W. S. Keeton, J. S. Nunery, and G. E. Likens. 2009. Dynamics of Wood Recruitment in Streams of the Northeastern US. *Forest Ecology and Management* 258:804–813.

Warren, D. R., J. D. Dunham, and D. Hockman-Wert. 2014. Geographic Variability in Elevation and Topographic Constraints on the Distribution of Native and Nonnative Trout in the Great Basin. *Transactions of the American Fisheries Society* 143:205–218.

Washington Department of Fish and Wildlife (WDFW). 2012. *Stream Habitat Restoration Guidelines*. Washington Department of Fish and Wildlife, Olympia, Washington, 2012.

Washington Department of Transportation. 2012. *WSDOT Fish Exclusion Protocols and Standards*. Available: http://www.wsdot.wa.gov/Environment/Biology/BA/BAtemplates.htm. Washington DOT, Olympia.

Washington State Legislature. Undated. *Safety Standards—Logging Operations*. Chapter 296-54 WAC. Available: http://apps.leg.wa.gov/WAC/default.aspx?cite=296-54. Accessed: July 10, 2014. Washington State Legislature. Olympia, Washington.

Watts, R. J., B. D. Richter, J. J. Opperman, and K. H. Bowmer. 2011. Dam Reoperation in an Era of Climate Change. *Marine and Freshwater Research* 62:321–327.

Webb, A. A., and W. D. Erskine. 2003. Distribution, Recruitment, and Geomorphic Significance of Large Woody Debris in an Alluvial Forest Stream: Tonghi Creek, Southeastern Australia. *Geomorphology* 51:109–126.

Webster, J. R., and E. F. Benfield. 1986. Vascular Plant Breakdown in Freshwater Ecosystems. *Annual Review of Ecology and Systematics* 17(1):567–594.

Webster, J. R., J. L. Tank, J. B. Wallace, J. L. Meyer, S. L. Eggert, T. P. Ehrman, B. R. Ward, B. L. Bennet, P. F. Wagner, and M. E. McTammy. 2000. Effects of Litter Exclusion and Wood Removal on Phosphorus and Nitrogen Retention in A Forest Stream. *Verhandlungen der Internationale Vereinigung für Limnologie* 27:1337–1340.

Webster, J. R., J. A. Stanford, J. L. Chaffin, and Field Ecology Class. 2002. Large Wood Jam in a Fourth Order Rocky Mountain Stream. *Verhandlungen der Internationale Vereinigung für Limnologie* 28:1–4.

Welber, M., W. Bertoldi, and M. Tubino. 2013. Wood Dispersal in Braided Streams: Results from Physical Modeling. *Water Resources Research* 49:7388–7400.

Wellnitz, T., S. Y. Kim, and E. Merten. 2014. Do Installed Stream Logjams Change Benthic Community Structure? *Limnologica* 49:68–72.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002. Riparian Aquatic Interaction Simulator (RAIS): A Model of Riparian Forest Dynamics for the Generation of Large Woody Debris and Shade. *Forest Ecology and Management* 162:299–318.

Wemple, B. C., and J. A. Jones 2003. Runoff Production on Forest Roads in a Steep, Mountain Catchment. *Water Resources Research* 39(8). doi:10.1029/2002WR001744

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young, M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams. 2011. Flow Regime, Temperature, and Biotic Interactions Drive Differential Declines of Trout Species under Climate

Change. *Proceedings of the National Academy of Sciences* 108:14175–14180. doi:10.1073/pnas.1103097108. Available: http://www.pnas.org/content/108/34/14175.full.pdf+html.

Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger. 2003. Climate and Wildfire in the Western United States. *Bulletin of the American Meteorological Society* 84:595–604. doi:10.1175/BAMS-84-5-595. Available: http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-84-5-595.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science* 313: 940–943. doi:10.1126/science.1128834.

Western Wood Products Association (WWPA). 1995. *Ponderosa Pine Species Facts*. Available: www.wwpa.org/ppine.htm.

White, R. J., and O. M. Brynildson. 1967. *Guidelines for Management of Trout Stream Habitat in Wisconsin*. Wisconsin Department of Natural Resources Technical Bulletin 39. Madison, WI.

White, P. S., and S. T. A. Pickett. 1985. Natural Disturbance and Patch Dynamics: An Introduction. Pages 3–9 in S. T. A. Pickett and P. S. White (eds.), *The Ecology of Natural Disturbance and Patch Dynamics*. San Diego, CA: Academic Press.

White, S. L., C. Gowan, K. D. Fausch, J. G. Harris, and W. C. Saunders. 2011. Response of Trout Populations in Five Colorado Streams Two Decades After Habitat Manipulation. *Canadian Journal of Fisheries and Aquatic Sciences* 68(12):2057–2063.

Whiteway, S. L., P. M. Biron, A. Zimmermann, O. Venter, and J. W. A. Grant. 2010. Do In-Stream Restoration Structures Enhance Salmonid Abundance? A Meta-Analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 67:831–841.

Whiting, P. J. 2002. Streamflow Necessary for Environmental Maintenance. *Annual Review of Earth and Planetary Sciences*. 30:181–206.

Whitney, G. G. 1996. *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present.* Cambridge University Press: Cambridge, UK.

Whittaker, R. H., S. A. Levin, and R. B. Root. 1973. Niche, Habitat and Ecotope. *American Naturalist* 107(955):321–338.

Wiegner, T. N., L. A. Kaplan, J. D. Newbold, and P. H. Ostrom. 2005. Contribution of Dissolved Organic C to Stream Metabolism: A Mesocosm Study Using C-13-Enriched Tree-Tissue Leachate. *Journal of the North American Benthological Society* 24:48–67.

Wilcock, P. R., A. F. Barta, C. C. Shea, G. M. Kondolf, W. V. Graham Matthew, and J. Pitlick. 1996. Observations of Flow and Sediment Entrainment on a Large Gravel-Bed River. *Water Resources Research* 32:2897–2909.

Wilford, D., D. Maloney, J. Schwab, and M. Geertsema. 1998. Tributary Alluvial Fans. *B.C. Ministry of Forests Extension Note* 30.

Williams, G. P. 1986. River Meanders and Channel Size. *Journal of Hydrology* 88(1-2):147–164.

Williams, G. P., and M. G. Wolman. 1984. *Downstream Effects of Dams on Alluvial Rivers*. USGS Professional Paper 1286.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2009. *Adaptive Management: The U.S. Department of the Interior Technical Guide*. Adaptive Management Working Group, U.S. Department of the Interior, Washington, D.C.

Williams, K. L., S. W. Griffiths, K. H. Nislow, S. McKelvey, and J. D. Armstrong. 2009. Response of Juvenile Atlantic Salmon, *Salmo salar*, to the Introduction of Salmon Carcasses in Upland Streams. *Fisheries Management and Ecology* 16(4):290–297.

Williams, R. N. (ed.). 2006. *Return to the River: Restoring Salmon Back to the Columbia River.* New York: Elsevier.

Wiltshire, P. E. J., and P. D. Moore. 1983, Paleovegetation and Paleohydrology in Upland Britain. Pages 433–451 in K. J. Gregory (ed.), *Background to Paleohydrology*. Chichester, UK: John Wiley.

Winemiller, K. O., A. S. Flecker, and D. J. Hoeinghaus. 2010. Patch Dynamics and Environmental Heterogeneity in Lotic Ecosystems. *Journal of the North American Benthological Society* 29:84–99.

Wing, M. G., and A. Skaugset. 2002. Relationships of Channel Characteristics, Land Ownership, and Land Use Patterns to Large Woody Debris in Oregon Streams. *Canadian Journal of Fisheries and Aquatic Science*s 59:796–807.

Wipf, T. J., B. M. Phares, and J. Dahlberg 2012. *Debris Mitigation Methods for Bridge Piers*. Iowa State University, Ames, IA.

Wipfli, M. S., and C. V. Baxter. 2010. Linking Ecosystems, Food Webs, and Fish Production: Subsidies in Salmonid Watersheds. *Fisheries* 35(8):373–387.

Wipfli, M. S., J. Hudson, and J. P. Caouette. 1998. Influence of Salmon Carcasses on Stream Productivity: Response of Biofilm and Benthic Macroinvertebrates in Southeastern Alaska, U.S.A. *Canadian Journal of Fisheries and Aquatic Science* 55:1503–1511.

Wipfli, M. S., J. Hudson, and J. P. Caouette. 2003. Marine Subsidies in Freshwater Ecosystems: Salmon Carcasses Increase the Growth Rates of Stream-Resident Salmonids. *Transactions of the American Fisheries Society* 132:371–381.

Wissmar, R. C., and R. L. Beschta. 1998. Restoration and Management of Riparian Ecosystems: A Catchment Perspective. *Freshwater Biology* 40(3):571–585.

Wohl, E. E. 2001. *Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range*. New Haven, CT: Yale University Press.

Wohl, E. 2011a. Seeing the Forest and the Trees: Wood in Stream Restoration in the Colorado Front Range, United States. Pages 399–418 in A. Simon, S. J. Bennett, and J. Castro (eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. Washington, D.C.: American Geophysical Union Press.

Wohl, E. 2011b. What Should these Rivers Look Like? Historical Range of Variability and Human Impacts in the Colorado Front Range, USA. *Earth Surface Processes and Landforms* 36:1378–1390.

Wohl, E. 2011c. Threshold-Induced Complex Behavior of Wood in Mountain Streams. *Geology* 39:587–590.

Wohl, E. 2013a. Redistribution of Forest Carbon Caused by Patch Blowdowns in Subalpine Forests of the Southern Rocky Mountains, USA. *Global Biogeochemical Cycles* 27:1205-1213.

Wohl, E. 2013b. Floodplains and Wood. *Earth-Science Reviews* 123:194–212.

Wohl, E. 2014. A Legacy of Absence: Wood Removal in US Rivers. *Progress in Physical Geography* 38:637–663.

Wohl, E., and N. Beckman. 2014a. Controls on the Longitudinal Distribution of Channel-Spanning Logjams in the Colorado Front Range, USA. *River Research and Applications* 30:112–131.

Wohl, E., and N. D. Beckman. 2014b. Leaky rivers: Implications for the loss of longitudinal fluvial disconnectivity in headwater streams. *Geomorphology* 205:27–35.

Wohl, E., and D. Cadol. 2011. Neighborhood Matters: Patterns and Controls on Wood Distribution in Old-Growth Forest Streams of the Colorado Front Range, USA. *Geomorphology* 125:132–146.

Wohl, E., and J. R. Goode. 2008. Wood Dynamics in Headwater Streams of the Colorado Rocky Mountains. *Water Resources Research* 44:W09429.

Wohl, E., and K. Jaeger. 2009. A Conceptual Model for the Longitudinal Distribution of Wood in Mountain Streams. *Earth Surface Processes and Landforms* 34:329–344.

Wohl, E., and D. J. Merritt. 2007. What is a Natural River? *Geography Compass* 1(4):871–900.

Wohl, E. and D. M. Merritt. 2008. Reach-Scale Channel Geometry of Mountain Streams. *Geomorphology* 93(3-4):168–185.

Wohl, E., and F. L. Ogden. 2013. Organic Carbon Export in the Form of Wood During an Extreme Tropical Storm, Upper Rio Chagres, Panama. *Earth Surface Processes and Landforms* 38:1407–1416.

Wohl, E., F. L. Ogden, and J. Goode. 2009. Episodic Wood Loading in a Mountainous Neotropical Watershed. *Geomorphology* 111:149–159.

Wohl E., D. A. Cenderelli, K. A. Dwire, S. E. Ryan-Burkett, M. K. Young, and K. D. Fausch. 2010. Large in-Stream Wood Studies: A Call for Common Metrics. *Earth Surface Processes and Landforms* 35:618–625.

Wohl, E., L. E. Polvi, and D. Cadol. 2011. Wood Distribution Along Streams Draining Old-Growth Forests in Congaree National Park, South Carolina, USA. *Geomorphology* 126:108–120.

Wohl, E., S. Bolton, D. Cado, F. Comiti, J. R. Goode, and L. Mao. 2012. A Two End-Member Model of Wood Dynamics in Headwater Neotropical Rivers. *Journal of Hydrology* 462-463:67–76.

Wojan, C., A. Devoe, E. Merten, and T. Wellnitz. 2014. Web-building Spider Response to a Logjam in a Northern Minnesota Stream. *American Midland Naturalist* 172(1):185–190.

Wolff, H. H. 1916. The Design of a Drift Barrier Across the White River, near Auburn, Washington. *Transactions of the American Society of Civil Engineers* 16:2061–2085.

Wondzell, S. M. 2011. The Role of the Hyporheic Zone across Stream Networks. *Hydrological Processes* 25:3525–3532.

Wondzell, S. M., and P. A. Bisson. 2003. Influence of Wood on Aquatic Biodiversity. Pages 249–263 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell (eds.), *The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37*. Bethesda, MD: American Fisheries Society.

Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards. 2009. Changes in Hyporheic Flow Following Experimental Removal of a Small, Low-Gradient Stream. *Water Resources Research* 45:W05406.

Wood, A. D., and A. R. Jarrett. 2004. *Design Tool for Rootwads in Streambank Restoration.* Paper 042047, Annual International Meeting, Ottawa. American Society of Agricultural Engineers. St. Joseph, MI.

Wright, L. D. (ed.). 1995. *Morphodynamics of Inner Continental Shelves.* CRC Press.

Wuehlisch, G. Von. 2011. Evidence for nitrogen-Fixation in the Salicaceae Family. *Tree Planters' Notes* 54(2):38–41.

Wyant, J. G., R. A. Meganck, and S. H. Ham. 1995. A Planning and Decision-Making Framework for Ecological Restoration. *Environmental Management* 19(6):789–796.

Wyżga, B., and J. Zawiejska. 2005. Wood Storage in a Wide Mountain River: Case Study of the Czarny Dunajec, Polish Carpathians. *Earth Surface Processes and Landforms* 30:1475–1494.

Yoccoz, N. G., J. D. Nichols, and T. Boulinier. 2001. Monitoring of Biological Diversity in Space and Time. *Trends in Ecology & Evolution* 16(8):446–453.

Young, M. K., E. A. Mace, E. T. Ziegler, and E. K. Sutherland. 2006. Characterizing and Contrasting Instream and Riparian Coarse Wood in Western Montana Basins. *Forest Ecology and Management* 226:26–40.

Zarnetske, J. P., R. Haggerty, S. M. Wondzell, and M. A. Baker. 2011a. Labile Dissolved Organic Carbon Supply Limits Hyporheic Denitrification. *Journal of Geophysical Research* 116:G04036.

Zarnetske, J. P., R. Haggerty, S. M. Wondzell, and M. A. Baker. 2011b. Dynamics of Nitrate Production and Removal as a Function of Residence Time in the Hyporheic Zone. *Journal of Geophysical Research* 116:G04025.

Zeng, H., J. Q. Chambers, R. I. Negron-Juarez, G. C. Hurtt, D. B. Baker, and M. D Powell. 2009. Impacts of Tropical Cyclones on U.S. Forest Tree Mortality and Carbon Flux from 1851 to 2000. *Proceedings of the National Academy of Sciences* 106(19), 7888–7892.

Zimmerman, R. C., J. C. Goodlett, and G. H. Comer. 1967. The Influence of Vegetation on Channel Form of Small Streams, Symposium on River Morphology. *International Association of Science Hydrology Publication, Gentbrugge, Belgium* 75:255–275.

Zobel, D. B., A. McKee, G. M. Hawk, and C. T. Dyrness. 1976. Relationships of Environment to Composition, Structure, and Diversity of Forest Communities of the Central Western Cascades of Oregon. *Ecological Monographs* 46:135–156.

Appendix A

Sample Implementation Contracts

A-1: Types of Federal Contracts Useful for Large Wood Projects **A-1**

A-2: Sample Documents for Hybrid Contracts **A-3**

A-3: Sample Contract Language for Separate Harvest and Hauling Contract **A-9**

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A-1: Types of Federal Contracts Useful for Large Wood Projects

Described below are types of contracts that may be used by federal entities for large wood placement projects. Federal procurement is government by Federal Acquisition Regulation (FAR) protocol and procedures (http://www.acquisition.gov/far/). Often the contracting phase is a challenging step in the implementation process, but project success may be enhanced using knowledge of the attributes of available contracting arrangements.

Applicable contract types may be classified as follows:

- Firm fixed price
- Time and materials or labor-hour
- Hybrid (fixed price with time and materials tasks)
- Design-build

Fixed Price Contracts

Large wood (LW) restoration projects are most commonly implemented with fixed-price contracts. Fixed price contracts allow for the contractor to determine the best method to use in order to meet the requirements identified in the scope of work and specifications. The government can only accept or reject work and at no time can the government direct the contractor's labor force or equipment operators. Fixed-price contracts place the maximum risk and full responsibility on the contractor for all costs and resulting profit or loss associated with the work. This type of contract provides the maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden on project sponsors.

A fixed-price contract requires the contractor to understand, in detail, what is to be constructed before bidding to do the work. This requires a design that includes detailed drawings, specifications, and a bid schedule containing items for each major project component. The designer must provide a cost estimate by bid item so that the contracting officer can assess the reasonableness of the bids. Most fixed-price contracts are awarded after contractors have submitted a sealed bid in response to an Invitation for Bids (IFB). The IFB includes the drawings and specifications for the work and specific contract requirements. The design effort and level of detail may be the same for simplified fixed-price contracts as it is for formal fixed-price contracts.

Time and Materials Contracts

Time-and-materials contracts (we include labor-hour contracts within this category) are used to procure supplies or services on the basis of direct labor and materials costs. Time-and-materials contracts may be used only when it is not possible for the contracting agency to accurately estimate the extent or duration of the work or to anticipate costs with any reasonable degree of confidence (FAR 16.601(c)). These types of contracts provide no positive profit incentive to the contractor for cost control or labor efficiency; therefore, appropriate government surveillance of contractor performance is required to give reasonable assurance that efficient methods and effective controls are being used.

These contracts include a ceiling price that the contractor exceeds at his own risk. Such contracts may be the best choice for stream restoration projects, allowing for the most flexibility to direct the contractor's work. Field implementation decisions may be made as long as the scope of the contract is not modified. It is essential to have experienced on-site construction support personnel and a field inspection/surveillance team to support implementation of a time-and-materials contract.

Hybrid Contracts

The recommended approach for many stream restoration projects is a hybrid contract that balances the flexibility of a time-and-materials contract with the reduced risk of a fixed-price contract. When the project requires an activity for which it is difficult to write detailed specifications, a time-and-materials task built in to a fixed-price framework is often the best option. One of the most important aspects of stream restoration projects is flexibility during the construction phase. This flexibility is important for implementation of tasks that contain a large degree of variability or intricacies that are often difficult to define in LW projects.

Typically the scope of work details the number and type of equipment and the number and type of personnel required present for each hourly unit of the specified task. The bid schedule will provide the number of hours within the task.

For example,

> "Typical equipment and crew composition utilized on past projects has included a Class 300 excavator with operator, a front end loader with operator, and an off-road dump truck with operator/laborer. The above typical crew/equipment is the basis for estimation in determining hourly units for this task, and each hour includes three pieces of equipment operating for each individual hourly unit. Contractor must have available all applicable support equipment available during the implementation of Task I. Examples of support equipment and hand tools are: chainsaw, choker cable, chaps, gas/oil, etc."

Examples of wording for specification packages, bid schedules, and scopes of work for hybrid contracts are provided in Section A-2 below.

Design-Build Contracts

Design-build two-phase contracts are described in FAR Part 36.3 (http://www.acquisition.gov/FAR/97/pdf/36.pdf). Design-build contracts accomplish design and construction implementation through one contract mechanism. This type of contract reduces the overall duration of the project development by eliminating a second procurement process for construction. Furthermore, integrating the design and construction activities can reduce the potential for design errors and discontinuities between the design and construction efforts. Design-build contracts may yield cost efficiencies by enabling the design-builder to propose alternate approaches to realize the performance objectives of the project, including innovative technologies and methodologies that leverage available government resources. By greater use of performance-based specifications that promote creativity, design-build contracts may open opportunities to use value engineering more frequently than in traditional design-bid-build projects. Significantly lower cost and claim frequency for design-build projects reflect a fundamental shift in the adversarial nature of construction contracting and bodes well for the future implementation of this procurement method, particularly for high visibility projects where cooperation between contracting agencies and their design and construction contractors is essential to project success.

A-2: Sample Documents for Hybrid Contracts

Specification Package

Below is example wording for a specification package for a fixed-price contract containing a time-and-materials task.

1. Measurement and payment for miscellaneous minor changes will be made on a time-and-materials basis in accordance with FAR clause 52.232-7, "Payments under Time-and-Materials and Labor-Hour Contracts." Contract Line Item Number (CLIN) *X* is for pricing minor changes to the original contract work. The "minor changes" provision anticipates minor within-scope changes to work and creates a method within the contract to more efficiently administer such minor changes that arise during performance. It is primarily for those instances where the specifications or drawings were incomplete, inadequate, or incorrect in the number or degree of items of work to be accomplished, or something was clearly left off that needed to be included to accomplish the intended results(s).
   a. Measurement: Measurement will be made of the actual hours worked and actual cost of materials used in performing miscellaneous minor changes.
   b. Payment: Payment for miscellaneous minor changes will be made of the actual hours worked and actual cost of materials in accordance with the hourly rate and the material handling fee offered in the schedule. NOTE: The estimated hours shown in the schedule will be used for evaluation purposes only.
   c. The Contractor shall invoice the Government for actual hours worked after the work is complete. All costs of labor wages, equipment, indirect costs, general and administrative expense, and profit shall be included in the hourly rate. Only the Contracting Officer (CO) can approve overtime for work performed under the pay item for miscellaneous minor changes.
2. The Contractor will be reimbursed for the cost of materials and subcontracts in accordance with FAR clause 52.232-7, "Payments under Time-and-Materials and Labor-Hour Contracts." A material handling fee may be included to the extent that it is clearly excluded from the hourly rate. The hours and materials costs invoiced shall be only those required to perform miscellaneous minor changes as directed by the Contracting Officer's Technical Representative (COR).
3. The method that shall be used by the Contractor when a work item arises that may be addressed by CLIN *X* is as follows:
   a. Contractor shall notify the COR of the work he/she believes could be addressed under this CLIN and asks for approval to perform the work under that CLIN (generally via phone or email).
   b. The COR will contact the CO and request approval to allow the Contractor to perform this work under the time and material CLIN. The CO will evaluate the information provided, and, if the work is of minor consequence and performing the work under this CLIN would allow work to continue forward in a timely and efficient manner, authorizes the use of the rates negotiated under this CLIN to perform this work. If the CO does not believe the work is minor in nature or determines another contractual method should be used, the CO will initiate the necessary action.
   c. The COR will notify the Contractor and the Government Inspector that the element of work will be performed under CLIN 12 using the contractually established rates.
   d. The Contractor shall perform the work and include the necessary documentation to support the billed hours and materials, if any, with his/her invoice. The COR will confirm with the Government Inspector the accuracy of the proposed hours and materials, and notify the CO the bill is correct and valid for payment.

Bid Schedule

Table A-1 below contains an example bid schedule for a hybrid contract.

Table A-1. Sample Bid Schedule for Fixed Price Contract with Time-and-Materials Items[1]

Item No.	Supplies/Services	Est. Qty	Unit	Unit Price	Amount
CLIN 001	Task A1 – Reporting, Signage & Mobilization & Demobilization	1	Lump Sum	$________	$________
CLIN 002	Tasks A2 through A4	1	Lump Sum	$________	$________
CLIN 003	Task B – Project Layout & Site Surveys	1	Lump Sum	$________	$________
CLIN 004	Task C – Site Preparation	1	Lump Sump	$________	$________
CLIN 005	Task D – In-Channel (IC) Features Excavation Cut estimate: 12,200 cubic yards (cy) Boulder Estimate: 180 cy; Clean Gravel and Cobble estimate: 1,550 cy; Pit Run estimate: 3,030 cy	1	Lump Sum	$________	$________
CLIN 006	Task E – Riverine (R) Features Excavation Cut estimate: 40,765 cy Infiltration Gravel Fill: 900 cy	1	Lump Sum	$________	$________
CLIN 007	Task F – Upland (U) Features Fill & Spoil placement estimate: 47,300 cy	1	Lump Sum	$________	$________
CLIN 008	Task G – Final Site Preparation	1	Lump Sum	$________	$_______
CLIN 009	Task H – Rock Material Supply Pit Run estimate: 3,030 cy; Clean Gravel and Cobble estimate: 1,550 cy; Infiltration Rock estimate: 900 cy; Boulder estimate: 180 cy	1	Lump Sum	$________	$________
CLIN 010	Task I – Stockpiled Material Installation Hours assume crew	300	Hours	$________	$________
CLIN 011	Task J – Contour Grading	60	Hours	$________	$________
CLIN 012	Task K – Haul Large Wood	1	Lump Sum	$________	$________
CLIN 013	Task L – Turbidity Control	1	Lump Sum	$________	$________
CLIN 014	Task M – Plant Materials Supply	1	Lump Sum	$________	$________
CLIN 015	Task N – Riparian Planting	1	Lump Sum	$________	$________
CLIN 015	Task O (Optional) – Additional Rehabilitation Services	1	Lump Sum	$________	$________

[1] Shaded rows are for time-and-materials items. Specific contract language for Task I is provided below.

Scope of Work

Below is an excerpt from the scope of work for an actual LW placement contract for the Trinity River Restoration Program (TRRP). Content below corresponds to items I, J and K of the example bid schedule depicted in Table A-1 above. Note that Tasks I and J are time-and-materials types, while K is a fixed-price task.

Stockpiled Materials Installation – Task I

Contractor shall notify the Onsite Government Representative (OGR) at least 2 weeks before installing stockpiled materials. Stockpiled materials including Large Wood (LW), slash, boulders, willow clumps, topsoil, and other materials shall be placed by Contractor at locations marked by the OGR with assistance from TRRP staff, or at locations otherwise indicated in the Performance Work Statement (PWS). An accounting of stockpiled material installation per feature is included in Table A-2, Table A-3, and Table A-4. Locations can be referenced per Technical Exhibit *X* (plan view). Measurement and payment will be based on percentage completion as determined by measurement of hours.

Stockpiled materials shall be utilized to create habitat areas for the fishery, geomorphic, or riparian revegetation purposes. Typical equipment and crew composition utilized on past projects has included a Class 300 excavator with operator, a front end loader with operator, and an off-road dump truck with operator/laborer. The above typical crew/equipment is the basis for estimation in determining hourly units for this task, and each hour includes three pieces of equipment operating for each individual hourly unit. Contractor must have available all applicable support equipment available during the implementation of Task I. Examples of support equipment and hand tools are: chainsaw, choker cable, chaps, gas/oil, etc.

Table A-2. Wood Material Accounting per Feature

Location	12”–24” dbh tree stems w/ rootwad (each)	12”–24” diameter tree stem (log only) (each)	Tree Tops with Limbs (12” diameter and smaller) (each)	Wood Slash (stems, branches, brush < 4” diameter) (cubic yards)	Estimated Installation time (3-piece crew) (hours)
IC-2	25	25	25	125	40
IC-4 @ head	20	20	20	100	40
IC-3 upper	4	6	6	25	8
IC-3 middle	5	8	8	32	8
IC-3 middle	4	6	6	25	8
IC-3 end	8	10	10	45	8
R-1 entrance	8	12	12	50	8
R-1 upper	8	10	8	45	8
R-1 mid	5	6	6	28	8
R-1 outlet	8	12	12	50	8
R-2 (multiple locations loose placements)	40	60	60	250	40
W-1 Pond (multiple loose placements)	20	20	20	100	40

Table A-3. Boulder Accounting per Feature

Location	Boulder Quantity (cubic yards)	Estimated Installation Time (3 piece crew) (hours)
IC-1	30	10
IC-2	60	10
IC-4	60	10
IC-7	30	10

Table A-4. Salvaged Willow Clump Accounting per Feature

Location	Willow Clump Quantity (each)	Estimated Installation Time (3 piece crew) (hours)
IC-3	6	4
IC-4	4	4
R-1	10	6
R-4	6	6
R-2	16	8
R-5	8	4
W-1	6	4

Salvaged and Supplied Large Wood Debris (LWD) Installation

Contractor must provide an excavator operator with a minimum of 3 years' experience in placing and building large wood structures for river restoration habitat purposes, capable of working independently with minimal direction and oversight. All LW must be anchored below grade to withstand, at a minimum, base flow velocity conditions. Contractor must schedule wood installation into the overall work schedule.

Salvaged Slash Material Installation

Slash is defined as woody material less than 6 inches in diameter that is stockpiled from site preparation activities of clearing and grubbing. Slash will be used primarily in the construction of LW structures or constructed wood jams to fill voids and create habitat. All slash not utilized for this purpose will broadcast as slash mulch under Final Site Preparation – Task G. Slash mulch materials may be placed on upland terraces or floodplain surfaces under Stockpiled Materials Installation – Task I as directed by OGR.

Salvaged Boulder Installation

Contractor will place all stockpiled boulders at specified locations. Boulders may be placed in LW structures, constructed wood jams, side channels, forced meanders, alcoves, or in the mainstem Trinity River. Boulders are placed for both geomorphic and habitat purposes. Placement locations are indicated in Table A-2.

Salvaged Willow Clump Installation

Salvaged clump plantings shall be replanted as quickly as feasible after salvage or removal from the designated storage site. Clump placement locations shall comply with Technical Exhibit *X*.

Excavate a hole approximately the size of the rootwad along the low flow channel slope or surface. Any competing vegetation within a 2-foot radius of the planting hole shall be removed. When digging the hole for planting, leave a berm between the excavation and channel so not to affect turbidity. The side of the planting hole shall be vertically lightly scarified, and the bottom shall be loosened to a minimum depth of 6 inches. Each planting hole may be inspected by an OGR prior to planting. Planting holes shall be filled with water at least 1 hour but not more than 2 hours before planting transplant.

Place one clump planting in the excavated hole, burying ½ to ⅔ of willow clump with ¼ to ½ of the root mass into the groundwater. The planting hole shall be backfilled ⅔ full with the soil excavated from the planting hole. The planting hole shall be filled with water to eliminate air pockets around roots. After the hole has drained, add more soil and water until saturated backfill material covers the top of the root crown to a minimum depth of 2 inches. After water has drained, Contractor shall backfill the hole with the remaining soil to finish grade. After planting, remove ⅓ to ½ of the remaining willow stems. The stems or trunks shall be lopped off after planting to make sure enough branches are sticking out of the ground after setting the roots deep enough to reach the water table. Stems shall be lopped square across the stem using sharp, clean lopping tools. Cut stem length shall be ⅓ to ½ of original stem length. After planting, salvaged willow clumps shall be thoroughly watered.

Salvaged Topsoil Material Installation

If topsoil is encountered and stockpiled per specification, stockpiled topsoil shall be reapplied to constructed riverine features above the waterline and included in a future executed modification. Topsoil replacement minimizes the need for soil amendments associated with plantings, and grass seeds shall be placed in an optimum medium for germination and establishment. Stockpiled organic chipped/macerated material shall be spread as evenly as possible over the previously spread topsoil before constructed surfaces are ripped. Organic material shall be applied to the spread topsoil no more than 4 inches thick.

Contour Grading – Task J

Up to 6 acres of contour grading shall be utilized within riverine and upland areas to create topographic complexity and provide positive drainage to the Trinity River or other hydrologic features within the work area. The contour grading for topographic complexity and blending shall occur within disturbed areas indicated in Table A-5.

Table A-5. Contour Grading Accounting per Feature

Location	Acres	Time Estimate (hours)
C-7	2	20
C-4	2	20
C-5	1	10
W-1	1	10

Supply Large Wood – Task K

Contractor shall harvest 200 trees from within U-3 project footprint. Trees for harvest will be clearly marked by OGR. Trees taken from outside the U-3 feature footprint shall not be measured toward completion of this task. Wood materials generated from construction of other project features outside the U-3 project footprint, and wood materials generated from clearing, are incidental to those tasks and will not count to completion of task 5.11.

All trees must be removed with rootwad intact. The ground surface at the tree wells created from removing rootwads must be smoothed and graded into adjacent ground to provide downhill drainage of surface water. After removal, trees may be cut to a length between 30–40 feet without prior approval by OGR, excluding length of attached rootwad. Limbs and branches will be left intact to the greatest extent practicable. All slash generated from wood material shall be retained for use. It is anticipated that each tree will generate three distinct products: one rootwad with attached stem 30–40’ in length, one stem 30–40’ in length, and one tree-top of varying length with intact branches.

LW materials will be stockpiled for placement as described under Stockpiled Materials Installation – Task I. At least one stockpile will be created on each bank of the Trinity River and within a Contractor use area, at a location mutually agreeable to the OGR and the Contractor. On the left bank of the Trinity River, the product (rootwads with stem, stems, and tree-tops) of 90 trees will be stockpiled. On the right bank of the Trinity River, the product of 105 trees will be placed in the stockpile. Materials taken across the Trinity River must be backhauled to the greatest practical extent to reduce river crossing. Slash materials generated during performance of this task will also be placed in the stockpiles. All materials must be stored in piles or decks of similar product (i.e., one log deck of stems with rootwads, one log deck of stems, one log deck of tree-tops, and one pile of slash). Stockpiles shall be organized to allow direct access to load and transport each distinct material with a minimum of sorting and handling.

Contractor must take special care in handling wood materials so as not to damage during loading or transport. No root balls will be removed to create more efficient hauling. Measurement and payment will be based on percentage completion as determined by count of actual number of trees present in stockpile.

A-3: Sample Contract Language for Separate Harvest and Hauling Contract

Task 12: Large Wood Supply

12.1. Purpose: Under this task, the contractor will supply the TRRP with large wood logs stockpiled at a secure location along the Trinity River for later use during channel rehabilitation activities. Location is anticipated to be Douglas City or Lower Junction City Project Sites.

12.2. Statement of Work: The Contractor shall locate timber sources, secure permits, and harvest, haul, and deck large wood within a 20-mile radius of the harvest area. The following are the types of materials that will be paid for under this task:

- 32 feet long x 12”–20” diameter at breast height (DBH) with root wad
- 32 feet long x 12”–20” DBH without root wad
- 32 feet long x 20” or greater DBH with root wad
- 32 feet long x 20” or greater DBH without root wad
- Semi-end dump load of brush/limbs (slash)
- Optional – Additional haul distance greater than 20 miles from harvest site
- Optional – Secure stockpile decking location in Weaverville, CA, or Junction City, CA

Locate trees, obtain appropriate permits (federal, state, or local), fall trees, limb/stockpile slash, load/haul trees and slash, and deck/store trees and slash at a designated location for later use by the TRRP for channel rehabilitation activities. Below are the assumptions related to this task:

- Scope does not include reloading trees at stockpile area and hauling to U.S. Bureau of Reclamation (USBR)-directed sites
- Scope assumes up to a 20-mile one-way haul distance between loading site and stockpile site
- Stockpile site is at agreed-upon location that is a secured gated area.
- If USBR identifies, permits, and pays royalties for a site, then the deduction for USBR source logs is applicable. (Site must be comparable for access as other sites.)
- Basic fire equipment is included. If trees are required on short notice during high-fire season, there may be added costs for fire watch labor.
- The harvesting area and haul road will be maintained and left in good condition.

12.3. Safety: The Contractor will contact Trinity County and any other applicable local, state, or federal agency regarding constraints, weight limits, and other restrictions for roads, bridges, and other requirements to implement the job. Roads subjected to interference by the work shall be kept open. The contractor shall provide, erect, and maintain all necessary barricades, suitable and sufficient flasher lights, flagmen, danger signals, and signs, and shall take all necessary precautions for the protection of the work and the safety of the public within the roadway and when crossing the Trinity River. Specific signs, barricades, and flagmen requirements are detailed the American National Standards Institute’s “Manual on Uniform Traffic Control Devices for Streets and Highways” (ANSI 06.1). The Contractor shall fully comply with Reclamation Safety and Health Standards (RSHS).

A-4: Example—Safety and Health Provisions for Large Wood Placement Contracts

1.4.1 A Site-Specific Safety and Health Plan shall be submitted as part of the Work Plan required in Section 5.1.2, Task A2. The general requirements stated below shall be addressed in the Site-Specific Safety and Health Plan.

1.4.2 No one employed in management or performance of the contract (including subcontracts) shall be required to work under conditions that are unsanitary, hazardous, or dangerous to the employee's health or safety. The Contractor shall fully participate in a Contractor Safety Program Review meeting, according to Reclamation Safety and Health Standards (RSHS) Section 3.4.1, prior to mobilization. The Contractor shall comply with the clause titled "Accident Prevention" in the U.S. Bureau of Reclamation (USBR) RSHS. The minimum work crew at any time on the implementation site shall be no less than two people.

1.4.3 One copy of the USBR RSHS will be provided to the Contractor, at no charge, for use in accordance with the notice titled "Notice of Safety and Health Requirements and of Safety Handbook Availability – Reclamation." Additional copies may be obtained from Superintendent of Documents, item stock No. 024-003-00190-2, phone number 202-512-1800 or online at: http://www.usbr.gov/ssle/safety/RSHS/rshs.html. Implementation Safety and Health Standards promulgated by the Secretary of Labor may be obtained from any regional or area office of the Occupational Safety and Health Administration of the U.S. Department of Labor.

1.4.4 The Contractor shall be cognizant of and ensure compliance with the requirements set forth in the paragraphs above. The Contractor's responsibility applies to all operations, including those of the Contractor's Subcontractors. When violations of safety and health requirements contained in these specifications or referenced standards are called to the Contractor's attention by the Contracting Officer's Technical Representative (COR), the Contractor shall immediately correct the condition to which attention has been directed. Either oral or written notice will be deemed sufficient. When the Contractor fails or refuses to promptly correct a compliance directive, the COR may issue an order to stop all or any part of the work. When satisfactory corrective action is taken, an order to resume work will be issued. The Contractor shall not be entitled to extension of time, or to claims for damage, or to additional compensation by reason of either the directive or the stop order. Failure of the Contracting Officer (CO) or the COR to order discontinuance of any or the entire Contractor's operations will not relieve the Contractor of the responsibility for the safety of personnel and property.

1.4.5 The Contractor shall maintain an accurate record of, and report to the COR in the manner prescribed by the CO, all cases of death, occupational diseases, or traumatic injury to employees or the public involved, and property damage in excess of $2,500 occurring during the performance of work under this contract. The rights and remedies of the Government provided in this section are in addition to any other rights and remedies provided by law or under this contract. In the event there is a conflict between requirements contained in USBR RSHS, this Performance Work Statement (PWS), Contractor's reviewed Safety Program, referenced safety and health codes and standards, or the U.S. Department of Labor Implementation Safety and Health Standards, promulgated under Section 107 of the Contract Work Hours and Safety Standards Act (40 U.S.C. 327 et seq.), as amended, the more stringent requirement will prevail.

1.4.6 The Contractor shall comply with the noise levels in Table A-6 below:

Table A-6. Exterior Noise Level Standards at Rehabilitation Site Boundary

Measurement	7:00 AM to 7:00 PM	7:00 PM to 7:00 AM
Hourly equivalent sound level (L_{eq} dB)	55	45
Maximum level dB	75	45

1.4.7 The work areas described in this PWS are popular recreational destinations for rafting, kayaking, inner-tubing, and fishing. The public has, in the past, accessed the work areas by foot, horseback, mountain bike, motorized vehicles, rafts, kayaks, and drift-boats. The Contractor shall keep the public out of areas actively being worked, or in various degrees of completion, via signs or other effective means as reviewed by the COR and in accordance with requirements contained in USBR RSHS. Access through the work areas by watercraft on the Trinity River shall be available to the public continuously for the performance period of the contract. Non-motorized access to the sites shall be maintained outside of normal working hours and on weekends and holidays, when work is not being performed. The Contractor shall provide, erect, and maintain any and all necessary barricades and warning signs and take all necessary precautions to protect the work and the safety of the public. A boater warning sign placed upstream will be mandatory during in-channel implementation activities from July 15–September 15 as required in contractors Work Plan – Task A2, section 5.1.2.

1.4.8 The Contractor shall develop Job Hazard Analyses (JHA) for each distinct phase of work as directed by the Onsite Government Representative (OGR). Each JHA shall be given to the OGR for review and acceptance. Work will not begin on the phase of work until the JHA is acceptable to the OGR.

5.1.2 Work Plan – Task A2

5.1.2.1 The Contractor shall prepare and submit a Work Plan that will be used by the Contractor and the Government to plan and manage the work to be performed. The Work Plan shall include an overall description and schedule of all required activities including project tasks, milestones, and management strategies. The Work Plan shall clearly describe the overall approach for implementing and reporting on all required work. The responsibility and authority of all organizations and key personnel involved in conducting each task will be outlined. The Work Plan shall be submitted complete, and no partial submittal of Work Plan sections will be allowed. Elements of the Work Plan shall include, but not be limited to, the following:

- Description of all tasks and subtasks and overall implementation approach to complete these tasks;
- Calculations showing quantity of earthwork to be moved to meet the design digital terrain modeling (DTM) lines and grades;
- Project site drawings with representative plan views, cross sections, and profiles for each feature, and maps that will be used for implementation;
- Description of how the Contractor intends to comply with the requirements in the Water Quality Certification 401 Permit;
- Project management strategy for achieving timely completion of all required work;

- Proposed detailed Critical Path schedule, including a bar chart timeline for completion of all required tasks showing predecessor and successor relationships and critical milestone dates. Schedule shall be prepared in Microsoft Project;
- Proposed composition and individual qualifications of a technical team or teams of personnel;
- Proposed Contractor key personnel, work crew size, equipment, and supplies needed to implement the contract;
- List of sub-contractors and responsibilities;
- Site-Specific Safety and Health Plan – See Section 5.1.2.2;
- Quality Control Plan – See Section 5.1.2.4;
- River Crossing Plan – See Section 5.1.2.5; and
- Traffic Control Plan – See Section 5.1.2.6.

5.1.2.2 **Site-Specific Safety and Health Plan**: As part of the Work Plan, develop a Site-Specific Safety and Health Plan according to Section 3 of the USBR Reclamation Safety and Health Standards (RSHS) manual. Cover all aspects of onsite and applicable offsite operations and activities associated with this contract. Follow the outline in Appendix B of RSHS. The Plan will not be accepted for review unless it addresses, in order, lettered and numbered per Appendix B, a narrative for each item in the outline. Mark any item included in the outline that is not applicable to this project as N/A after the item listing. The Plan shall also provide a list of Job Hazard Analyses (JHA) anticipated throughout the project and a statement that additional JHA shall be provided as required as the project progresses. The Safety and Health Plan shall include a noise monitoring plan. Develop JHA for each distinct phase of work under the contract and as directed by OGR. Activities involving hazardous materials shall have the appropriate Material Safety Data Sheet(s) attached to the JHA. A generic Company Safety Plan is not acceptable. The Safety Program shall be sit- specific for the requirements in this PWS.